Modelling of spaceborne linear array sensors

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MODELLING OF SPACEBORNE LINEAR ARRAY SENSORS

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ABSTRACT

The topic of this research is the development of a mathematical model for the georeferencing of imagery acquired by multi-line CCD array sensors, carried on air- or spacecraft. Linear array sensors are digital optical cameras widely used for the acquisition of panchromatic and multispectral images in pushbroom mode with spatial resolution ranging from few centimeters (airborne sensors) up to hundreds meters (spaceborne sensors). The images have very high potentials for photogrammetric mapping at different scales and for remote sensing applications. For example, they can be used for the generation of Digital Elevation Models (DEM), that represent an important basis for the creation of Geographic Information Systems, and the production of 3D texture models for visualization and animation purposes.

In the classical photogrammetric chain that starts from the radiometric preprocessing of the raw images and goes to the generation of products like the DEMs, the orientation of the images is a fundamental step and its accuracy is a crucial issue during the evaluation of the entire system. For pushbroom sensors the triangulation and photogrammetric point determination are rather different compared to the standard approaches for full frame imagery and require special investigations on the sensor geometry and the acquisition mode.

Today various models based on different approaches have been developed, but few of them are rigorous and can be used for a wide class of pushbroom sensors. In general a rigorous sensor model aims to describe the relationship between image and ground coordinates, according to the physical properties of the image acquisition. The functional model is based on the collinearity equations. The sensor model presented in this thesis had to fulfill the requirement of being rigorous and at the same time as flexible as possible and adaptable to a wide class of linear array sensors. In fact pushbroom scanners in use show different geometric characteristics (optical systems, number of CCD lines, scanning mode, stereoscopy) and for each data set specific information are available (ephemeris, GPS/INS observations, calibration, other internal parameters). Therefore the model needs to be dependent on a certain number of parameters that may change for each sensor.

According to the availability of information on the sensor internal and external orientation, the proposed model includes two different orientation approaches.

The first one, the direct georeferencing one, is based on the estimations of the ground coordinates of the points measured in the images through a forward intersection, using the external orienta-
tion provided by GPS and INS instruments or interpolated by ephemeris or computed using the orbital parameters (satellite case). This approach does not require any ground control points, except for final checking, and does not estimate any additional parameters for the correction of the interior and exterior orientation. For this reason, the accuracy of this method depends on the accuracy of the external and internal orientation data.

The alternative orientation method, based on indirect georeferencing, is used if the sensor external and internal orientation is not available or not enough accurate for high-precision photogrammetric mapping. This approach is a self-calibrating bundle adjustment. The sensor position and attitude are modelled with 2nd order piecewise polynomial functions (PPM) depending on time. Constraints on the segment borders assure the continuity of the functions, together with their first and second derivatives. Using pseudo-observations on the PPM parameters, the polynomial degree can be reduced to one (linear functions) or even to zero (constant functions). If GPS and INS are available, they are integrated in the PPM. For the self-calibration, additional parameters (APs) are used to model the lens internal parameters and distortions and the linear arrays displacements in the focal plane.

The parameters modelling the internal and external orientation, together with the ground coordinates of tie and control points, are estimated through a least-squares bundle adjustment using well distributed ground control points. The use of pseudo-observations allows the user to run the adjustment fixing any unknown parameters to certain values. This option is very useful not only for the external orientation modelling, but also for the analysis of the single self-calibration parameter's influence. The weights for the observations and pseudo-observations are determined according to the measurement accuracy. A blunder detection procedure is integrated for the automatic detection of wrong image coordinate measurement. The adjustment results are analyzed in terms of internal and external accuracy. The APs to be estimated are chosen according to their correlations with the other unknown parameters (ground coordinates of tie points and PPM parameters). A software has been developed under Unix environment in C language.

The flexibility of the model has been proved by testing it on MOMS-P2, SPOT-5/HRS, ASTER, MISR and EROS-A1 stereo images. These sensors have different characteristics (single-lens and multi-lens optical systems, various number of linear arrays, synchronous and asynchronous acquisition modes), covering a wide range of possible acquisition geometries. For each dataset both the direct and indirect models have been used and in all cases the direct georeferencing was not accurate enough for high accurate mapping. The indirect model has been applied with different ground control points distributions (when possible), varying the PPM configurations (number of segments, polynomials degree) and with and without self-calibration. Excluding EROS-A1, all the imagery has been oriented with sub-pixels accuracy in the check points using a minimum of 6 ground control points. In case of EROS-A1, an accuracy in the range of 1 to 2 pixels has been achieved, due the lack of information on the geometry of the sensor asynchronous acquisition. For the ASTER and SPOT-5/HRS datasets, a DEM has also been generated and compared to some reference DEMs.

New cameras can be easily integrated in the model, because the required sensor information are accessible in literature as well as in the web. If no information on the sensor internal orientation is available, the model supposes that the CCD lines are parallel to each other in the focal plane and perpendicular to the flight direction and estimates any systematic error through the self-calibration. The satellite's position and velocity vectors, usually contained in the ephemeris, are required in order to compute the initial approximations for the PPM parameters. If this information is not available, the Keplerian elements can be used to estimate the nominal trajectory. For pushbroom scanners carried on airplane or helicopter the GPS and INS measurements are indispensable, due to the un-predictability of the trajectory.
Il tema di questa ricerca è lo sviluppo di un modello matematico per la georeferenziazione di immagini acquisite da sensori CCD lineari, montati su aereo o satellite. I sensori lineari sono strumenti ottici digitali con metodo di acquisizione “pushbroom”. Essi sono ampiamente usati per generare immagini in pancromatico e multispettrale con risoluzione spaziale variabile da pochi centimetri (sensori su aereo) fino a centinaia di metri (sensori su satellite). Le immagini hanno grandi potenzialità per la restituzione fotogrammetrica a scale differenti e per varie applicazioni nel telerilevamento. Per esempio, esse possono essere usate per la generazione dei modelli digitali delle altezze (DEM), che rappresentano una base importante per la creazione dei sistemi d’informazione territoriale e la produzione dei modelli 3D per animazioni e di visualizzazioni. Nella classica catena fotogrammetrica che inizia con il preprocessamento radiometrico delle immagini allo stato originale e arriva alla generazione di prodotti come i DEMs, l’orientamento delle immagini è un punto basilare e cruciale per la valutazione di intero sistema. Per i sensori di tipo pushbroom la triangolazione e il posizionamento fotogrammetrico dei punti sono piuttosto differenti se confrontati ai metodi standard per i sensori digitali a matrice e richiedono indagini speciali sulla geometria e sul modo di acquisizione del sensore stesso. Oggi vari modelli matematici sono disponibili per l’orientamento di sensori pushbroom, ma pochi di loro sono rigorosi e possono essere usati per una vasta gamma di sensori. In generale, un modello rigoroso mira a descrivere il rapporto fra le coordinate immagine e quelle terreno secondo le proprietà fisiche dell’acquisizione dell’immagine. Di conseguenza il modello funzionale è basato sulle equazioni di collinearità.

Il modello matematico presentato in questa tesi deve soddisfare la condizione di essere rigoroso e nello stesso momento il più possibile flessibile ed adattabile a vari sensori lineari. In effetti gli strumenti a scansione lineare presentano diverse caratteristiche geometriche (sistemi ottici, numero di linee CCD, metodo di acquisizione, tipo di ricoprimento stereoscopico) con specifiche informazioni ausiliari (effemeridi, osservazioni da GPS/INS, parametri di calibrazione, altri parametri interni). Di conseguenza il modello deve dipendere da un determinato numero di parametri variabili per ogni sensore. A seconda della disponibilità di informazioni sull’orientamento interno ed esterno dello strumento, il modello proposto include due metodi differenti di georeferenziazione. Il primo, detto diretto, è basato sulla determinazione delle coordinate terreno dei punti misurati nelle immagini attraverso l’intersezione dei raggi omologhi, usando l’orientamento
esterno fornito dagli strumenti a bordo o interpolato dalle effemeridi o calcolato dai parametri orbitali (caso per satelliti). Questo metodo non richiede punti d’appoggio, eccetto per il controllo finale, e non estima nessun parametro supplementare per la correzione dell’orientamento interno ed esterno. Per questo motivo, l’accuratezza dei risultati dipende dall’accuratezza delle misure di orientamento interno ed esterno. L’altro metodo di orientamento, basato sulla georeferенziazione indiretta, è usato se i parametri di orientamento interno ed esterno dello strumento non sono disponibili o non abbastanza precisì per una restituzione fotografometrica di alta precisione. Il metodo indiretto è una compensazione a stelle proiettive con auto-calibrazione. La posizione e l’assetto dei centri di proiezione sono modellati con segmenti polinomiali di secondo ordine (PPM) dipendenti dal tempo. Opportuni vincoli sui bordi di ogni segmento assicurano la continuità delle funzioni, insieme alle loro derivate prime e seconde. Usando pseudo-osservazioni sui parametri PPM, il grado polinomiale può essere ridotto ad uno (funzioni lineari) o a zero (funzioni costanti). Se le osservazioni da GPS e INS sono disponibili, esse sono integrate nel PPM. Per l’autocalibrazione, parametri supplementari (APs) modellano le variazioni e le distorsioni delle lenti ed eventuali spostamenti e rotazioni delle linee CCD nel piano focale. I parametri che modellano l’orientamento interno ed esterno, insieme alle coordinate terreno dei punti d’appoggio e di legame, sono stimati con una compensazione ai minimi quadrati usando punti d’appoggio ben distribuiti nell’immagine. L’uso di pseudo-osservazioni permette all’operatore di ripetere la compensazione fissando opportuni parametri incogniti a determinati valori. Questa opzione è molto utile non soltanto per la modellazione dell’orientamento esterno, ma anche per l’analisi dell’influenza di ogni singolo parametro aggiuntivo sugli altri. I pesi per le osservazioni e le pseudo-osservazioni sono determinati dall’accuratezza delle misure. Durante la compensazione gli errori nelle misure delle coordinate immagine sono identificati automaticamente. La compensazione e’ analizzata in termini di accuratezza interna ed esterna. I parametri aggiuntivi da stimare sono scelti a seconda delle loro correlazioni con gli altri parametri incogniti (coordinate oggetto dei punti del legame e dei parametri PPM).

Basato su questo modello, un software è stato sviluppato in linguaggio C nel sistema operativo UNIX. La flessibilità del modello è stata dimostrata verificandolo su MOMS-P2, SPOT-5/HRS, ASTER-VNIR, MISR e EROS-A1. Questi sensori hanno caratteristiche differenti (sistemi ottici con una o più’ lenti, numero di linee CCD, acquisizione sincrona ed asincrona) e coprono una vasta gamma di geometrie di acquisizione. Per ogni dataset sia il metodo diretto che quello indiretto sono stati usati; in tutti i casi la georeferенziazione diretta non ha dato risultati soddisfacenti. Il metodo indiretto è stato applicato con diverse distribuzioni di punti d’appoggio (se possibile), variando le configurazioni dei PPM (numero di segmenti, grado dei polinomi), con e senza auto-calibrazione. A parte EROS-A1, tutte le immagini sono state orientate con precisione inferiore al pixel nei punti di controllo usando un numero minimo di 6 punti d’appoggio. Nel caso di EROS-A1, l’accuratezza era nell’ordine di 1 - 2 pixel, a causa della mancanza di informazioni sulla geometrica di acquisizione asincrona del sensore. Per SPOT-5/HRS e ASTER, il corrispondente DEM è stato generato e confrontato con quelli di riferimento e risultati soddisfacenti sono stati raggiunti. Nuovi sensori lineari possono essere integrati facilmente nel software, poiché’ le informazioni necessarie sul sensore sono accessibili in letteratura o in internet.

Se i parametri di calibrazione non sono disponibili, il programma suppone che le linee CCD siano parallele le une alle altre nel piano focale e perpendicolari alla direzione di volo e stima l’errore sistematico con un’auto-calibrazione. I vettori di posizione e di velocità del satellite, contenuti solitamente nelle effemeridi, sono richiesti per calcolare le approssimazioni iniziali per i parametri PPM. Se queste informazioni non sono disponibili, gli elementi di Kepler possono essere usati per valutare la traiettoria nominale. Per i sensori pushbroom montati su aereo o elicottero le misure da GPS e INS sono indispensabili, poiché’ la traiettoria non e’ completamente prevedibile.
INTRODUCTION

Linear array sensors for Earth observations are widely used for the acquisition of imagery in pushbroom mode from spaceborne and on airborne platforms. They offer panchromatic and multispectral images with spatial resolution ranging from few centimeters (airborne sensors) up to hundreds meters (spaceborne sensors). Images provided by these sensors have very high potentials for photogrammetric mapping at different scales and for remote sensing applications. For example, they can be used for the generation of Digital Elevation Models (DEM), that represent an important basis for the creation of Geographic Information Systems, and the production of 3D texture models for visualization and animation purposes (Grün et al., 2004, Poli et al., 2004b).

In the classical photogrammetric chain that starts with the radiometric preprocessing of the raw images and goes to the generation of products like the DEMs, the orientation of the images is a fundamental step and its accuracy is a crucial issue during the evaluation of the entire system. For pushbroom sensors the triangulation and photogrammetric point determination are rather different compared to standard approaches, which are usually applied for full frame imagery, and require special investigations on the sensor geometry and the acquisition mode.

In the next Section the existing approaches followed for the orientation of linear array scanners are reviewed. Then the main objectives of this research and their development in the thesis are described.

1.1 REVIEW OF EXISTING MODELS

For the georeferencing of imagery acquired by pushbroom sensors, geometric models with different complexity, rigor and accuracy have been developed, as described for example in Fritsch and Stallmann, 2000, Hattori et al., 2000, Dowman and Michalis, 2003 and Toutin, 2004.

The main approaches are based on rigorous models, Rational Polynomial Models (RPM), Direct Linear Transformations (DLT) and affine projections.
The rigorous models try to describe the physical properties of the image acquisition. As each image line is the result of a perspective projection, they are based on the collinearity equations, which are extended in order to include the external (and eventually internal) orientation modelling. Some rigorous models are designed for specific sensors, while some others are more general and can be used for different sensors. Few models are designed for both spaceborne and airborne linear scanners.

In case of spaceborne sensors, different approaches have been proposed.

In the software SPOTCHECK+, developed by Kratky (Kratky, 1989), the satellite position is derived from known nominal orbit relations, while the attitude variations are modelled by a simple polynomial model (linear or quadratic). For self-calibration two additional parameters are added: the focal length (camera constant) and the principle point correction. The exterior orientation and the additional parameters are determined in a general formulation by least-squares adjustment. The use of additional information from supplemented data files is not mandatory, but if this information is available it can be used to approximate or preset some of the unknown parameters. This model has been used for the orientation of SPOT (Baltsavias and Stallmann, 1992), MOMS-02/D2 (Baltsavias and Stallmann, 1996b), MOMS-02/Priroda (Poli et al., 2000). An advantage of this software is that it can easily integrate new pushbroom instruments, if the corresponding orbit and sensor parameters are known. The model was also investigated and extended in Fritsch and Stallmann, 2000.

At the Chair of Photogrammetry and Remote Sensing at TUM Munich the existing block adjustment program CLIC (TUM Munich, 1992) has been extended for the photogrammetric point determination of airborne and spaceborne three-line scanners (Ebner et al., 1992). For the external orientation, a polynomial approach with orbital constraints in case of spaceborne imagery is utilized. In the airborne case the exterior orientation parameters are estimated only for so-called orientation points, which are introduced at certain time intervals, e.g. every 100th readout cycle. In between, the parameters of each 3rd image-line are expressed as polynomial functions (e.g. Lagrange polynomials) of the parameters at the neighboring orientation points. For preprocessed position and attitude data, like the differential GPS and INS measurements, observation equations are formulated. Systematic errors of the position and attitude observations are modeled through additional strip- or block-invariant parameters for each exterior orientation function. 12 parameters are introduced to model a bias and a drift parameter with constant and time-dependent linear terms. For the satellite case, the model exploits the fact that the spacecraft proceeds along an orbit trajectory and all scanner positions lie on this trajectory, when estimating the spacecraft's epoch state vector. Due to the lack of a dynamic model describing the camera's attitude behavior during an imaging sequence, for the spacecraft's attitude the concept of orientation points is maintained. All unknown parameters are estimated in a bundle block adjustment using threefold stereo imagery. The model was tested on MOMS-02/D2 and P2 (Ebner et al., 1992), MEOSS (Ohlhof, 1995), HRSC and WAOSS (Ohlhof and Kornus, 1994) sensors. The same model has been adopted at DLR for the geometric in-flight calibration and orientation of MOMS-2P imagery (Kornus et al., 1999a, Kornus et al., 1999b).

The University College London (UCL) suggested a dynamic orbital parameter model (Gugan and Dowman, 1988). The satellite movement along the path is described by two orbital parameters (true anomaly and the right ascension of the ascending node) which are modelled with linear angular changes with time, and included in the collinearity equations. The attitude variations are described by drift rates. This model was successfully applied for SPOT level 1A and 1B, MOMS-02 and IRS-1C (Valadan Zoej and Foomani, 1999) imagery. In (Dowman and Michalis, 2003) this approach was investigated and extended for the development of a general sensor model for along-track pushbroom sensors. The results obtained with SPOT-5/HRS are reported in Michail and Dowman, 2004.
The IPI Institute in Hannover has developed the program BLASPO for the adjustment of satellite line scanner images (Konecny et al., 1997). Just the general information about the satellite orbit together with the view directions in-track and across-track are required. Systematic effects caused by low frequency motions are handled by self calibration with additional parameters. In this model the unknown parameters for each image are 14: 6 exterior orientation parameters which represent the uniform motion and 8 additional parameters which describe the difference between the approximate uniform movement and the reality. This program seems very flexible, because it has been used for the orientation of different pushbroom sensors carried on satellite, like MOMS-02 (Büyükosalih and Jacobsen, 2000), SPOT and IRS-1C (Jacobsen et al., 1998), IKONOS and Quickbird (Jacobsen and Passini, 2003), SPOT5-5/HRS (Jacobsen, 2004) and on airplane, like DPA (Jacobsen and Passini, 2003).

Another flexible and rigorous model for pushbroom sensors has been developed by Toutin (Toutin, 2002) and embedded in PCI Geomatica. The model takes into account the distortions relative to the platforms (position, velocity, orientation), to the sensor (orientation angles, instantaneous field of view, detection signal integration time), to the Earth (geoid-ellipsoid elevation) and the cartographic projection. The unknown parameters are two translations, a rotation related to the cartographic North, the scale factors and the levelling angles, the non-perpendicularity of the axes, as well as some 2nd order parameters when the orbital/attitude data are not known or not accurate (Toutin, 2004).

In Westin, 1990 the orbital model used is simpler than in the previous models. A circular orbit instead of elliptical orbit is used. Using SPOT data, seven unknown parameters need to be computed for each image.

O’Neill (O’Neill and Dowman, 1991) proposed a model where auxiliary data are used in order to set up the relative orientation between the scenes. Then three GCPs are needed to establish the exterior orientation. The model works accurately with both single SPOT stereo pairs and strips.

Alternative image orientation approaches are based on empirical models (Toutin, 2004). They describe the relation between image and object coordinates and vice versa through:

- 2D or 3D polynomials or
- the quotients of polynomials, usually of 3rd order (Rational Function Model -RFM- or Rational Polynomial Coefficients - RPC).

These empirical models can be used:

- to extract the 2D (or 3D) information from single (or stereo) satellite imagery without explicit reference to either a camera model or satellite ephemeris information and using a large number of ground control points (RFM-1) or
- to approximate the strict sensor model previously developed or contained in the image auxiliary files (RFM-2). A regular grid of the images terrain is first defined and the image coordinates of the 3D grid ground points are computed using the already-solved 3D physical model, like in SPOTCHECK+ (Kratky, 1989). If the image-to-ground model is available from the scene auxiliary files (like for SPOT-5/HRG and SPOT-5/HRS), the grid is firstly defined in the image space and then projected on three different heights in the object space. In both cases, the image and ground grid points are used as GCPs to resolve the functions and compute the unknown polynomial terms (Toutin, 2004).

In Grodecki and Dial, 2003 a block adjustment with RPC is proposed and applied for the orientation of high-resolution satellite stereo images, such as IKONOS. After the determination of the RPC of each image, a block adjustment is applied for the estimation of a suitable number of additional parameters. The same model has been implemented at IGP, ETH Zurich, for the orientation of IKONOS and Quickbird (Eisenbeiss et al., 2004), SPOT-5/HRS (Poli et al., 2004a) and SPOT-5/HRG stereo images (Grünn et al., 2004).
As a special case of 2D/3D empirical models are the affine transformations. Okamoto (Okamoto, 1981) proposed the affine transformation to overcome problems arising due to the very narrow field of the sensor view. Under this approach an initial transformation of the image from a perspective to an affine projection is first performed, then a linear transformation from image to object space follows, according to the particular affine model adopted. The assumption is that the satellite travels in a straight path at uniform velocity within the model space. The model utilizes local systems and ellipsoidal heights as a reference system, therefore height errors due to the Earth curvature must be compensated. The results demonstrated that 2D and 3D geopositioning to sub-pixel accuracy can be achieved with IKONOS scenes (Fraser et al., 2001). The method was applied to SPOT stereo scenes of level 1 and 2 (Okamoto et al., 1998). The theories and procedures of affine-based orientation for satellite line-scanner imagery have been integrated and used for the orientation MOMS/2P (Hattori et al., 2000) and IKONOS (Fraser et al., 2001) scenes.

The Direct Linear Transformation (DLT) approach has also been investigated. The solution is based only on ground control points and does not require the interior orientation parameters nor the ephemeris information. The DLT approach was suggested for the geometric modelling of SPOT imagery (El Manadili and Novak, 1996) and applied to IRS-1C images (Savopol and Armenakis, 1998). In (Wang, 1999) it was improved by adding corrections for self-calibration. In general, the approaches based on 2D and 3D empirical models, as those presented, are advantageous if the rigorous sensor model or the parameters of the acquisition system are not available.

Gupta (Gupta and Hartley, 1997) proposed a simple non-iterative model based on the concept of fundamental matrix for the description of the relative orientation between two stereo scenes. The model was successfully applied on SPOT scenes. The unknown parameters for each pair are: the sensor position and attitude of one scene at the time of acquisition of the first line, the velocity of the camera, the focal length and the parallax in across-track direction.

In case of pushbroom sensors carried on airplane or helicopter, GPS and INS (or IMU) observations are indispensable, because the airborne trajectories are not predictable. In many cases the original position and attitude measurements are not enough accurate for high-precision positioning and require a correction.

The IGP at ETH Zurich (Grün and Zhang, 2002a) investigated three different approaches for the external orientation modelling of the Three-Line Scanner (TLS) developed by Starlab Corporation: the Direct Georeferencing, in which the translation displacement vector between the GPS and camera systems is estimated for the correction of GPS observations, the Lagrange Polynomials, as used in (Ebner et al., 1992) for spaceborne sensors and the Piecewise Polynomials, where the sensor attitude and position functions are divided in sections and modelled with 1st and 2nd order polynomials respectively, with constraints on their continuity. The sensor self-calibration has also been integrated in the processing chain (Kocaman, 2003a). Further investigations on the models performances are in progress.

In the photogrammetric software for the LH-Systems ADS40 processing, a triangulations is applied for the compensation of systematic effects in the GPS/IMU observations (Tempelmann et al., 2000). These effects include the misalignment between IMU and the camera axes and the datum differences between GPS/IMU and the ground coordinates system. For the orientation of each sensor line the concept of orientation fixes is used. The external orientation values between two orientation fixes are determined by interpolation using the IMU/GPS observations.

From the analysis of the above literature, which is summarized in Table 1.1, we can see that nowadays approaches based on rigorous and non rigorous models are widely used. In case of rigor-
ous models the main research interests are the sensor external and internal orientation modelling. The external orientation parameters are often estimated for suitable so-called "orientation lines" and interpolated for any other lines. A self-calibration process is often recommended, at least to model the focal length variation and the first order lens distortions. In order to avoid over-paramaterization the correlation between the parameters is investigated and tests on the parameters' significance and determinability are studied. Few models can be applied for both airborne and spaceborne sensors. The orientation methods based on rational polynomials functions, affine projections and DLT transformations are mostly used for high-resolution satellite imagery. They can be a possible alternative to rigorous models when the calibration data (calibrated focal length, principal point coordinates, lens distortions) are not released by the image providers or when the sensor positions and attitudes are not available with sufficient precision (Vozikis et al., 2003).

1.2 RESEARCH OBJECTIVES

The topic of this research is the development of a mathematical model for the georeferencing of imagery acquired by multi-line CCD array sensors, carried on air- or spacecraft. The model has to fulfill the requirement of being as flexible as possible and being adaptable to a wide class of linear array sensors. In fact pushbroom scanners in use show different geometric characteristics (optical systems, number of CCD lines, scanning mode, stereoscopy) and for each data set specific information are available (ephemeris, GPS/INS observations, calibration, other internal parameters). Therefore the model needs to be dependent on a certain number of parameters that may change for each sensor.

For the orientation of CCD linear array sensors' imagery with a rigorous photogrammetric model, the collinearity equations, which describe the perspective acquisition of each image line, will be the basis of the functional model. According to the availability of information on the sensor internal and external orientation, two approaches must be investigated.

The first one, the direct georeferencing one, is based on the estimation of the ground coordinates of the points measured in the images through a forward intersection, using the external orientation provided by GPS and INS instruments or interpolated by ephemeris or computed using the orbital parameters (satellite case). The advantage of this method is that no ground information is required, but the results accuracy depends on the precision and availability of the external and internal orientation information.

On the other hand, in the indirect georeferencing approach, the parameters modelling the internal and external orientation are estimated in a bundle adjustment with least squares methods. The external orientation modelling takes into account the physical properties of satellite orbits and the integration of observations on the external orientation, provided by instruments carried on board, while the internal orientation modelling considers the lens distortions and the CCD lines (or segments) displacement in the focal plane (or planes).

As a result, a flexible model for the orientation of a wide class of pushbroom sensors will be developed.
Table 1.1. Summary of the main characteristics (basic geometry, external and internal orientation modelling, flexibility) of four approaches for the orientation of pushbroom imagery: rigorous models, RFM, DLT and affine models. Examples are also given.

<table>
<thead>
<tr>
<th></th>
<th>Rigorous</th>
<th>RFM</th>
<th>DLT</th>
<th>Affine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic geometry</td>
<td>Perspective projection in each line, parallel projection between lines</td>
<td>None</td>
<td>Camera model in auxiliary files</td>
<td>Projective geometry</td>
</tr>
<tr>
<td>Mathematical model</td>
<td>Collinearity equations extended to include internal and external orientation modeling Least squares solution GCPs required</td>
<td>Relationship between image (line, sample) and ground coordinates through quotients of polynomials (max 3rd order)</td>
<td>Relationship between image (line, sample) and ground coordinates through quotients of 1st order polynomials</td>
<td>Relationship between image and ground coordinates through 2D-3D affine transformations</td>
</tr>
<tr>
<td>Need of GCP</td>
<td>yes, variable number</td>
<td>yes, large number</td>
<td>only for refinement, min 2</td>
<td>yes, min 6</td>
</tr>
<tr>
<td>External orientation</td>
<td>Modelled with piecewise polynomials, Lagrange polynomials or with constant shifts/misalignments Same/different approach for position and attitude Metadata files required (satellite) Possible GPS/INS integration</td>
<td>Not modelled No GPS/INS integration</td>
<td>Constant shifts and misalignments compensated with block adjustment</td>
<td>No model Constant shifts and misalignments compensated No GPS/INS integration</td>
</tr>
<tr>
<td>Internal orientation</td>
<td>Not always. Main parameters: focal length, principal point displacement, line curvature</td>
<td>Effects compensated in upper-order terms</td>
<td>Residual internal orientation compensated in block adjustment</td>
<td>Not modelled</td>
</tr>
<tr>
<td>Flexibility</td>
<td>Models are usually separately implemented for spaceborne and airborne platforms Few models for both platforms</td>
<td>High flexibility Usually for high-resolution satellite imagery</td>
<td>High flexibility, because camera model and satellite ephemeris are not required</td>
<td>High flexibility, because camera model is not required</td>
</tr>
</tbody>
</table>
1.3 OUTLINE

This thesis describes the rigorous sensor model developed at IGP for the orientation of imagery acquired by linear array sensors. A software has been designed, self-implemented in C language and tested on simulated and real data. The work is described in six chapters.

Following this Introduction, in Chapter 2 the main characteristics of linear array sensors are investigated. This study is required in order to understand the geometric properties of imagery provided by linear scanners and the range of case studies that may occur.

In Chapter 3 the direct georeferencing approach for the orientation of pushbroom images without ground control points is described. The alternative approach, the indirect georeferencing model, is proposed in Chapter 4. The functional and stochastic models are both analyzed.

After the overview of the preprocessing required for the preparation of the input data (Chapter 5), in Chapter 6 the results of the orientation of pushbroom imagery from five different satellite sensors (MOMS-P2, SPOT-5/HRS, ASTER, MISR, EROS-A1) are reported. In order to demonstrate the general character and the flexibility of the model, the imagery used come from sensors with different characteristics (multi-line and single-line sensors at different ground resolution with synchronous and asynchronous acquisition modes). The internal and external accuracy obtained for each dataset are reported and commented. The results obtained with airborne pushbroom imagery are described in Poli, 2002b.

Chapter 6 will close the thesis with some conclusions and future work.

In the Appendices, after the acronyms adopted in the thesis (Appendix A), the main reference systems mentioned in the thesis are reported (Appendix B) and the software is briefly described (Appendix C).
LINEAR CCD ARRAY SENSORS

Linear array sensors are widely used for the acquisition of images at different ground resolution for photogrammetric mapping and remote sensing applications. Today a large variety of sensors observe the Earth and provide data for studies of the atmosphere, oceans and land. To classify these sensors (Figure 2.1), a first distinction can be made between active and passive acquisition modes. In passive sensors the energy leading to the received radiation comes from an external source, e.g. the Sun; on the contrary in active sensors the energy is generated within the sensor system, beamed outward, and the fraction returned is measured. Both active and passive sensors can be imaging or non-imaging, according to the production of images or not. A sensor classified as a combination of passive, non-scanning and non-imaging method is a type of profile recorder, for example a microwave radiometer. A sensor classified as passive and imaging is a camera, such as a close-range or an aerial survey or a space camera. An example of an active and non-imaging sensor is a profile recorder such as a laser spectrometer and laser altimeter, while a radar, for example synthetic aperture radar (SAR), is classified as active and imaging.

Going further in the classification of passive imaging sensors, they can be optical and non-optical, according to the presence of an optical system or not. In the class of optical sensors, the alternative is between film-based and digital cameras. Linear array sensors belong to the category of the digital optical cameras and acquire in pushbroom mode. The technology used for the digital acquisition is described in Section 2.1.

In the category of digital optical sensors we also find the point-based electromechanical and the frame sensors (Section 2.2.2). In the case of a point-based electromechanical scanning system, the image is formed by a side-to-side scanning movement as the platform travels along its path. As frame cameras concern, the images are acquired in digital form with a central perspective, like in case of film-based cameras.
In this Chapter the main characteristics of linear array sensors, or linear scanners, and their imagery are investigated, giving more attention to those aspects that must be taken into account during the geometric modelling of this kind of imagery. As the instruments concern, we will concentrate on the imaging components: the optical system and the linear arrays. The geometry of the solid-state lines and the optical systems are illustrated in Section 2.2 and Section 2.3. The geometric errors occurring both in the solid-state lines and in the optical systems are analyzed in Section 2.4, together with two examples of laboratory geometric calibration.

Linear array sensors produce strips with two possible stereo geometries: along and across the flight direction. These two modes are described in Section 2.5.

Linear array sensors are usually mounted on platforms in the air and in space. Aerial platforms are primarily stable wing aircraft, although helicopters are also used. The aircraft are often used to collect very detailed images and facilitate the collection of data over virtually any portion of the Earth's surface at any time. In space, the acquisition of images is sometimes conducted from the space shuttle or, more commonly, from satellites for Earth observation. Because of their orbits, satellites permit repetitive coverage of the Earth's surface on a continuing basis. This topic will be addressed in Section .

The geometric characteristics of the pushbroom sensors and their platforms determine the properties of the imagery described in Section 2.7. The images are available on the market at different processing levels (Section 2.8). In conclusion, the principal characteristics of the linear array sensors used in photogrammetry and remote sensing are summarized in Section 2.9.
2.1 SOLID-STATE TECHNOLOGY

George Smith and Willard Boyle invented the Charge-Coupled Device (CCD) at Bell Labs in 1969. They were attempting to create a new kind of semiconductor memory for computers and at the same time to develop solid-state cameras for use in video telephone service. They sketched out the CCD's basic structure, defined its principles of operation and outlined applications including imaging as well as memory. By 1970, the Bell Labs researchers had built the CCD into the world's first solid-state video camera. In 1975, they demonstrated the first CCD camera with image quality sharp enough for broadcast television. Today, CCD technology is pervasive not only in broadcasting but also in video applications that range from security monitoring to high-definition television, and from endoscopy to desktop videoconferencing. Facsimile machines, copying machines, image scanners, digital still cameras, and bar code readers also have employed CCDs to turn patterns of light into useful information. In general CCD technologies and image sensors have evolved towards mature products which today can be found in almost all electronic image acquisition systems (Blanc, 2001). In particular, the combination of CCD and optical technologies brought the generation of digital optical cameras. Since 1983, when telescopes were first outfitted with solid-state cameras, CCDs have enabled astronomers to study objects thousands of times fainter than what the most sensitive photographic plates could capture, and to image in seconds what would have taken hours before. Today all optical observatories, including the Hubble Space Telescope, rely on digital information systems built around "mosaics" of ultrasensitive CCD chips. CCD cameras are also used in satellite observation of the earth for environmental monitoring, surveying, and surveillance.

The Charge-Coupled Device is an electronic device made of silicon, capable of transforming a light pattern into an electric charge pattern (an electronic image). The CCD consists of several individual photosensitive elements that have the capability of collecting, storing and transporting electrical charge from one element to another. When the incoming radiation interacts with a CCD during a short time interval (exposure time), the electronic charges develop with a magnitude proportional to the intensity of the radiation. Then the charge is transferred to a readout register and amplified for the analog-to-digital converter (Figure 2.2a). Each photosensitive element will then represent a picture element (pixel). The chips contain from 3000 to more than 10000 detector elements that can occupy linear space less than 15cm in length. With semiconductor technologies and design rules, structures that form lines or matrices of pixels are made.

In photogrammetry and remote sensing the CCD technology is employed almost everywhere. In close-range the CCD cameras are used for motion capture, human body modelling and object modelling for medical, industrial, archeological and architecture applications. On airborne, helicopter and satellite platforms the CCD sensors acquire imagery for terrain models generation and object extraction.

More recently, alternative sensors based on CMOS (Complementary Metal-Oxide Semiconductor) technology have gained considerable interest. CMOS detectors operate at a lower voltage than CCDs, reducing power consumption for portable applications. Each CMOS active pixel sensor cell has its own buffer amplifier and can be addressed and read individually (Figure 2.2b). CMOS technology is advantageous for the acquisition of color and false color images. In fact one of the main difference between CCD and CMOS technology is the generation of color images. Using CCD chips different techniques can be used to obtain color images. One of the most popular is the use of an interpolation procedure in conjunction with a mosaic of tiny (pixel-sized) color filters placed over the array of detectors. However this affects the quality of the resulting image. Another commonly employed solution is to use multiple digital cameras, with each camera recording a specific spectral band to make up the final composite color or false-color image which is produced by image processing. Needless to say, having to use multiple cameras and fil-
Chapter 2. LINEAR CCD ARRAY SENSORS

ters is costly and may be inconvenient. Usually it results in the format size being reduced with consequent reduction in the ground resolution or ground coverage of the resulting aerial images. On the other hand the three-layer CMOS areal array corresponds to the three-layer color or false-color photographic emulsion.

![Figure 2.2. CCD (right) and CMOS (left) detectors. Example with frame chips.](image)

Regarding the development of CCD and CMOS technologies, CCDs have been the dominant solid-state imagers since the 1970s, primarily because CCDs gave far superior images with the fabrication technology available. CMOS image sensors required more uniformity and smaller features than silicon wafer foundries could deliver at the time. Only recently the semiconductor fabrication has advanced to the point that CMOS image sensors can be useful and cost-effective in some mid-performance imaging applications. Today the CMOS technology is mostly used in frame design for close-range applications and lately in some airborne frame cameras too. Currently CMOS are not used for space cameras.

In general, as suggested by Litwiller, 2002, CCDs offer superior image performance (as measured in quantum efficiency and noise) and flexibility at the expense of system size. They remain the most suitable technology for high-end imaging applications, such as digital photography, broadcast television, high-performance industrial imaging and most scientific and medical applications.

CMOS imagers offer more integration (more functions on the chip), lower power dissipation (at the chip level) and smaller system size at the expense of image quality and flexibility. They are the technology of choice for high-volume, space constrained applications where image quality requirements are low. This makes them a natural fit for security cameras, PC videoconferencing, wireless handheld device videoconferencing, bar-code scanners, fax machines, consumer scanners, toys, biometrics and some automotive in-vehicle uses. Costs are similar at the chip level.

The early CMOS proponents claimed that CMOS imagers would be much cheaper because they could be produced on the same high-volume wafer processing lines as mainstream logic or memory chips. Anyway, the accommodations required for good imaging performance have limited CMOS imagers to specialized, lower-volume mixed-signal fabrication processes. CMOS imagers also require more silicon per pixel and even if they may require fewer components and less power, they may also require post-processing circuits to compensate for the lower image quality. The larger issue around pricing is sustainability. The money and attention concentrated on CMOS imagers mean that their performance will continue to improve, eventually blurring the line between CCD and CMOS image quality. But for the foreseeable future, CCDs and CMOS will remain complementary. Each can provide benefits that the other cannot.

In this thesis, only sensor based on CCD technology are taken into account, because currently (September 2004) CMOS technology is not used in linear array sensors carried on airborne and satellite for Earth observation. CMOS sensors in linear arrays are used for close range applications only.
2.2 ARRAY GEOMETRIES

For the purposes of this thesis, CCDs in the form of linear arrays are investigated (Section 2.2.1). The other CCD designs will be briefly described in Section 2.2.2.

2.2.1 Linear arrays

In linear array sensors the chips (or sensor elements or detectors) are arranged in the focal plane along a line (Figure 2.3).

According to the line design, the possible configurations are:

a. the chips are placed along a single line (Figure 2.4a). The number of sensor elements in the line is not constant and depends on the desired swath path. Up to date, the maximum number of sensor elements in each line is 14,400, on Starimager SI-200 (Starlabo)
b. a line consists of 2 or more segments (Figure 2.4b). This is the case of QuickBird, which uses a CCD line of 27,000 elements, obtained by three linear arrays, each of 9,000 elements
c. two CCD segments are placed one parallel to the other on the longer side, as shown in Figure 2.4c. This design is used to increase the image resolution through a specific post-processing (Section 2.2.1.3). Examples of sensors where this configuration is adopted are the ADS40 sensor (Tempelmann et al., 2000) and the HRG on SPOT-5 (Latty and Rouge, 2003a).

The largest part of linear array sensors use (a) and (b) geometries. Using staggered lines (c), the detector line length is halved, the image field area is reduced to one quarter, the focal length is halved and the optics need to be of high quality for twice as many line pairs per millimeter with respect to the line pairs per millimeter necessary for the pixel size (Sandau, 2004).

Other linear array designs are possible. For example IRS-1C/1D combines has 3 CCD segments (called CCD1, CCD2, CCD3), each having 4096 elements; the overlap in the images between CCD1 and CCD2 is 243 pixels and between CCD2 and CCD3 is 152 pixels (Zhong, 1992 and Figure 2.5).

Figure 2.4. Possible designs of CCD lines: a) one line; b) two (or more) segments; c) two staggered segments.

Figure 2.5. Design of CCD lines in IRS-1C/1D sensor.

According to the line design, the possible configurations are:

a. the chips are placed along a single line (Figure 2.4a). The number of sensor elements in the line is not constant and depends on the desired swath path. Up to date, the maximum number of sensor elements in each line is 14,400, on Starimager SI-200 (Starlabo)
b. a line consists of 2 or more segments (Figure 2.4b). This is the case of QuickBird, which uses a CCD line of 27,000 elements, obtained by three linear arrays, each of 9,000 elements
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Chapter 2. LINEAR CCD ARRAY SENSORS

2.2.1.1 Pushbroom principle

The combination of the optical systems and the CCD lines allows the acquisition of images through the so-called pushbroom principle. A CCD linear array placed in the focal plane of the optical system acquires a scanline perpendicular to the satellite or airplane track. While the platform moves along its trajectory, successive lines are acquired and stored one after the other to form a strip (Figure 2.6). For each CCD line, a strip is generated.

![Diagram of pushbroom principle](image)

Figure 2.6. Pushbroom acquisition. Left: the sensor scans one line at each time instant while moving on its trajectory. Right: corresponding image creation.

The energy collected by each detector of each linear array is sampled electronically and digitally recorded. After sampling, the array is electronically discharged fast enough to allow the next incoming radiation to be detected independently. The time required by the system to acquire a single line is called integration time. The time interval between two samplings is usually chosen equal to the integration time. In order to generate a square sampling grid, the sampling time interval is calculated by imposing that the spacing interval in the flight direction \( a_x \), obtained by multiplying the platform velocity \( v \) with the integration time \( \Delta t_s \)

\[
a_s = v \cdot \Delta t_s
\]

is equal to the size of an elementary detector in the linear array as projected on the ground \( a_y \)

\[
a_y = \frac{p \cdot H}{f}
\]

where \( p \) is the pixel size (square, \( p_x = p_y = p \)), \( H \) is the flying height and \( f \) is the focal length of the instrument (Figure 2.7). By imposing \( a_s = a_y \), the integration time (equal to the sampling time interval) can be calculated as

\[
\Delta t_s = \frac{p \cdot H}{v \cdot f}
\]

For example, in the case of SPOT-5, each of the two HRG instrument acquires conventional panchromatic images in the so-called HM mode. In case of nadir viewing, a square, orthogonal grid with a sampling interval of 5m is generated. Considering the following characteristics:

- linear array of 12,000 square pixels with a size of \( p = 6.510 \) μm
- focal length \( f = 1.082 \) m
- altitude \( H = 832 \) km (near-polar sun-synchronous orbit)
- velocity \( v = 6.6 \) km/s
the integration time results (Latry and Rouge, 2003a)

\[ \Delta t_s = \frac{p \cdot H}{v \cdot f} = \frac{6.510 \cdot 10^{-6} \cdot 832 \cdot 10^3}{6.610 \cdot 10^3 \cdot 1.082} = 0.75210 \cdot 10^{-3} \, s \]  

(2.4)

Usually the integration time is so small that the illumination conditions may be considered constant (Eckardt and Sandau, 2003).

Taking into account Equation 2.2, we can see that for a given ground pixel size and flying height, the smaller the detector elements' size \( p \), the shorter the focal length \( f \). Of course with smaller detector sizes less energy is integrated. If the sensitivity of the pixel element is not sufficient to obtain the necessary Signal to Noise Ratio (SNR), there are two possibilities to overcome this obstacle (Sandau, 2004):

- use TDI technology with \( N \) stages in order to increase the signal \( N \)-fold and improve the SNR by the factor of \( N \) (this technology is used e.g. in the IKONOS and QuickBird missions)
- use the so-called slow-down mode in order to decrease the ground track velocity of the line projection on the surface with respect to the satellite velocity in order to obtain the necessary integration time.

From a ‘signal processing’ point of view, the signal entering the instrument is a continuous function of the spatial variables \( x \) and \( y \) and is directly proportional to the radiance entering the instrument. The signal is convolved by the point-spread function \( h(x,y) \) of the instrument, then sampled according to the given sampling grid. In case of conventional pushbroom type acquisition, the sampling grid has a square mesh.

The point-spread function is the response of the system to a point object. The imaging system behaves as a low pass filter and the Fourier transformation of the point-spread function, called the Modulation Transfer Function (MTF), characterizes the attenuation of high spatial frequencies. The 2D sampling process leads to retrieve only a low frequency area in the Fourier domain, called the reciprocal cell. In the classic case of a square grid with sampling interval \( p \), the reciprocal cell is simply the frequency square defined by (Latry and Rouge, 2003a)

\[ -\frac{1}{2p} \leq f_x \leq \frac{1}{2p} \quad \text{and} \quad -\frac{1}{2p} \leq f_y \leq \frac{1}{2p} \]  

(2.5)

Figure 2.7. Pixel dimension in the image space and on the ground.
2.2.1.2 TDI technology

The TDI, or Time Delay and Integration, technology is based on the principle of multiple exposure of the same object (Schröder et al., 2001). This principle is shown in Figure 2.8 for a three stage TDI detector.

![Figure 2.8. Exposure principle of a TDI-detector with three stages. The amount of generated charges is direct proportional to the number of stages (Source Schröder et al., 2001).](image)

Considering an N-stage TDI, the TDI-detector consists of N detector lines. After N fold integration of the image line the generated charges are transferred to a shift register. The shift register is then read out with the rate of the corresponding line frequency in parallel channels and serial with 256 pixel elements per channel. After leaving the shift register the voltages are amplified and then converted to digital numbers ranging from 0 to 255, in case of 8 bit images (Schröder et al., 2001).

2.2.1.3 Supermode: the Quincunx sampling principle

As mentioned in Section 2.2.1, the CCD arrays can be designed as the combination of two segments placed one parallel to the other on the longer side, staggered by a fraction of pixel (design numbered as “c” in Figure 2.4). The reason is that with this configuration the spatial resolution of the images produced by each segment can be improved through post-processing. In this paragraph the principle of Quincunx sampling, which is used to generate high resolution imagery from the SPOT-5 HM mode is described. The idea came by observing that in the traditional HM mode the sampling does not use all the system's capability in terms of resolution and produces aliasing phenomenon. The THR (Très Haute Résolution or very high resolution) mode uses the Quincunx sampling principle with the aim to refine the sampling without modifying the MTF support, therefore keeping the same size of the detectors and the same telescopes. The sampling density is increased by using two line arrays identical to those used in the classical mode and with an offset in the focal plane (Latry and Rouge, 2003a).

In the case of SPOT-5, the two arrays of 12000 CCDs of 6.5μm size are separated in the focal plane, along the row axis by 0.5 • 6.5μm (0.5 pixels) and along the column axis by (n+0.5) • 6.5μm with n integer. The value of n must be as small as possible to limit the time interval separating the data acquisitions of each line array, so that the spacecraft perturbations have a minimum impact (for this data n=3). Each line array produces two classical images acquired according to the 5m square grid, with the two grids with offset by 2.5m on both lines and columns (Figure 2.9). The Quincunx sampling grid, which is obtained interleaving the two images, is square but turned 45° in relation to the axis (line array, velocity) and its sampling interval is 2.5 • \(\sqrt{2} = 3.53 \text{ m}\). The reciprocal cell corresponding to this sampling is the frequency square...
with a side of $\sqrt{2}$ and turned 45° in relation to the axis. It is defined by $|\alpha| + |\beta| \leq f$.

Figure 2.9. SPOT-5 THR grid. The Quincunx grid is generated by two shifted CCD linear arrays, separated along the row axis by 0.5 pixels and along the columns axis by 3.5 pixels (Latry and Rouge, 2003a).

The ground processing chain for the generation of a THR image from two shifted HM images (called HMA and HMB) includes two main steps:

1. Interleaving and interpolation. The final image grid is built from the initial grid with a sampling interval which is halved in both directions. In other words, HMA and HMB are issued from the two linear arrays into a grid which is twice as dense. For this operation zeros are introduced for the missing pixels and two filters, whose frequency responses depend on the offset between the two images (nominally 0.5 pixels for lines and columns), are applied to the images, then the images thus obtained are summed.

2. Denoising and deconvolution. The denoising is based on the FCNR algorithm (Rougé, 1994), according to which the signal is decomposed into wavelet packets well localized in both the spatial and frequency planes. After deconvolution, it produces a desired noise level for uniform areas.

As result, the panchromatic THR image at 2.5m ground resolution is produced (THX product, Figure 2.10).

Figure 2.10. Two examples of improvement from HM to THR mode (Source Latry et Rougé, 2003b).
2.2.2 Other geometries

2.2.2.1 Frame cameras

In digital frame cameras the chips are positioned in a regular rectangular matrix. The images are acquired through a central projection, like in the case of film cameras. The processing differences are in the radiometric pre-processing, point measurements with matching and orthophoto generation.

Taking into account digital frame cameras for aerial mapping, Pétrie (Pétrie, 2003) suggested a classification based on the size of the array, which is the single most important factor that controls the suitability, availability and usage of digital frame cameras in the aerial mapping field. According to him, frame cameras for aerial mapping can be classified under three main groups:

1. small-format cameras, typically generating images with formats of 1,000 x 1,000 to 2,000 x 3,000 pixels, i.e. between 1 and 6 Megapixels;
2. medium-format cameras with image formats typically around 4,000 x 4,000 pixels = 16 Megapixels;
3. large-format cameras having a format of 6,000 x 6,000 pixels = 36 Megapixels or larger.

A brief description of the most important airborne systems of each class is reported.

![Frame camera acquisition](Figure 2.11)

**Small-format cameras.** Four different types of systems for the generation of multispectral images can be distinguished:

1. single cameras equipped with a mosaic filter and producing color or false-color images by interpolation. To this category belong the Kodak’s DCS series, the ADPS (Aerial Digital Photographic System) by GeoTechnologies consulting from Bath Spa University College, U.K., the DORIS (Differential Ortho-rectification System) by the University of Calgary, Canada, the ADAR system by Positive Systems of Whitefish, Montana, U.S. and the ADC multi-spectral camera by Tetracam, U.S.;
2. single cameras equipped with rotating filter wheels to produce multi-band images, like the ADC (Airborne Digital Camera) and AMDC (Airborne Multi-Spectral Digital Camera) by SensyTech, U.S.;
3. single cameras fitted with three CCD arrays, a beam splitter and suitable filters to produce color or false-color images, e.g. the MS (Multi-Spectral) camera by Redlake, U.S.;
4. multiple cameras coupled together and equipped with the appropriate color filters to produce multiband images from which color or false-color images can be produced. To this category

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1. For this Section the article Pétrie, 2003 on airborne digital cameras has been used as reference.
belong many examples: the TS-1 (TerraSim-1), by STI Service, US, the DAIS-1 (Digital Airborne Imaging System-1) by Space Imaging, U.S., the SpectraView from Airborne Data Systems, U.S., the AirCam multi-spectral system by Kestrl Corporation, U.S., the cameras from ImageTeck, U.S., some cameras developed by American Universities (AEROCam by the University of North Dakota and a camera at the Environment Remote Sensing Center at the University of Wisconsin) and two systems from IGN, France.

In summary, numerous small-format airborne digital cameras are operational. The technology is quite well established; the main emphasis has been on the production of true-color and false-color images for environmental monitoring and agricultural applications over relatively small areas.

Medium-Format Digital Cameras. The biggest drawback of small-format digital cameras is the very limited size of the format itself, with the resulting severe limitations in the ground coverage of a single frame image. During the late 1990s, with the commercial availability of larger CCD areal arrays of up to 4,000 x 4,000 pixels = 16 Megapixels, medium-format digital cameras have been designed in two different directions:

1. modified film cameras. They comprise digital cameras that could be fitted to existing high-quality film cameras generating 6 cm wide images. To this category belong: the AIMS (Airborne Integrated Mapping System), that was first proposed by the Center for Mapping at Ohio State University in 1995, the Digital Backs, developed by various companies such as MegaVision, Sinar, PhaseOne, Linhof and Jenoptik, the MF-DMC (Medium Format- Digital Mapping Cameras) from the GoeTechnologies consulting at Bath Spa University College, U.K., the Mamiya RZ67 Pro II camera by the Latvian mapping company, SIS Parnas and the DSS (Digital Sensor System), by Emerge.

2. medium-format digital cameras. These cameras have been specifically designed using the medium-format arrays. The most obvious example is the Kodak MegaPlus 18.8i camera. Other examples include the DATIS (Digital Airborne Topographical Imaging System), produced by the 3Di company, the RAMS (Remote Airborne Mapping System) by EnerQuest of Denver, CO, and the camera developed by EarthData mapping company.

Medium-format digital cameras offer a substantially better ground coverage than the small-format cameras. Quite a number are used in combination with airborne laser scanners that produce DEMs, on the basis of which, the digital frame images can be orthorectified (Wicks and Campos-Marquetti, 2003).

Large-Format Frame Cameras. The design of the large-format frame cameras for photogrammetric mapping and interpretation has been set using as reference the metric film frame cameras produced by Leica (RC30) and Z/I Imaging (RMK-TOP). Image size and geometry comparable to conventional film-based cameras could be achieved based on available image frames if several synchronously operating digital camera heads are combined (Hinz, 1999).

The main difference lies in the much smaller format sizes that are possible with digital frame cameras due to the small sizes of the available CCD arrays.

Current developments in large-format digital frame cameras are taking place in two main directions:

1. Large-format digital frame imagery using multiple cameras. Multiple medium-format cameras produce multiple images that are synthesized into a single large-format image. This is the approach that is being followed by the commercial vendors of large-format digital cameras: the DMC (Digital Modular Camera), renamed DMCS (Digital Modular Camera System), by Z/I Imaging and the UltraCam D camera by Vexcel Austria

2. Large-Format Digital Cameras. These are single cameras fitted with very large CCD frame sensors. So far, these cameras have all been constructed for military customers and applica-
tions. In this group belong the cameras constructed in the U.S. by Recon/Optical (CA-270) and BAE Systems (Ultra High Resolution Reconnaissance Camera).

This new generation of airborne digital cameras will produce monochrome images that are equivalent to those from film cameras utilizing a 5 inch (12.5 cm) wide film and producing images that are 4.5 x 4.5 inches (11.5 x 11.5 cm) in size.

2.2.2.2 Point-based sensors

The point-based electromechanical sensors acquire images with whiskbroom mode. They use rotating mirrors to scan the terrain surface from side to side perpendicular to the direction of the sensor platform, like a whiskbroom (Figure 2.12). The width of the sweep is referred to as the sensor swath. The rotating mirrors redirect the reflected light to a point where a single or just a few sensor detectors are grouped together. Whiskbroom scanners with their moving mirrors tend to be large and complex to build. The moving mirrors create spatial distortions that must be corrected with preprocessing by the data provider before the image data is delivered to the user. An advantage of whiskbroom scanners over other types of sensors is that they have fewer sensor detectors to keep calibrated. The main limitation of this scanning mechanism is the restricted time available to read each detector. This generally requires that such scanners have rather broad spectral bands to achieve an adequate signal-to-noise ratio. The oscillating movement of the mirror may also result in some inconsistencies in the scanning rate, leading to geometric problems in the imagery (Ames Remote, 2004).

Compared to pushbroom scanners, they are heavier, bigger and more complex, because they have more moving parts.

Well known examples of whiskbroom imagers are:

- the Multispectral Scanner (MSS), carried on LANDSAT 1-5 (NASA)
- the Thematic Mapper (TM), carried on LANDSAT 4-5 (NASA)
- the Enhanced Thematic Mapper Plus (ETM+), carried on LANDSAT 6-7 (NASA)
- the Advanced Very High Resolution Radiometer (AVHRR), carried on Polar Orbiting Environmental Satellites (POES) constellation (NOAA)
- the Sea-viewing Wide Field of view Sensor (SeaWiFS), carried on SeaStar (NASA)
- the Imagers and Sounders carried on Geostationary Operational Environmental Satellites (GOES, NOAA).

For the orientation of the imagery acquired by these sensors both 2D and 3D empirical models as well as rigorous 2D physical models (Krathy, 1971) can be used.

![Figure 2.12. Whiskbroom principle of image acquisition.](image-url)
2.3 IMAGING SYSTEM

In case of CCD linear array sensors the imaging system consists of an optical instrument (usually a lens or a telescope) and CCD lines that are placed in the focal plane. One separate CCD line is used for each spectral channel. The most common channels adopted on airborne and satellite pushbroom sensors are: the panchromatic (about 450-900 nm), the red (about 640-720 nm), the green (about 520-610 nm) and the blue (about 450-520 nm). In many cases the near infrared channel (760-900 nm) is used, mostly for the vegetation analysis. The number of lenses can be one or more. In case of one-lens sensors, we must distinguish between single-view and multi-view systems. If the sensor has simultaneous multi-view stereo capability, the CCD lines looking in different viewing directions are placed one parallel to the other in the focal plane (Figure 2.13a). This configuration is used on few space sensors (WAOSS, HRSC) and their corresponding airborne simulators (WAAC, HRSC-A/-AX) and on commercial sensors carried on airplane (ADS40) or helicopter (StarImager). If the instrument scans in one single direction at each time, the platform is able to rotate along and across the flight direction in order to provide the stereo coverage. This configuration is used only on satellite sensors, with only across-track (i.e. SPOT-5/HRG and IRS-1C/PAN) or only along-track (i.e. Orbview-3) or combined (i.e. IKONOS) stereo capability.

According to the alternative design, with multi-lens systems, more lenses are used, each one looking along a different viewing direction (Figure 2.13b). Usually the number of lenses is equal to the number of viewing directions and the CCD lines looking in the same direction are placed on the focal plane of the lens looking in that direction. Examples of sensors with these configuration are SPOT-5/IRS, ALOS, ASTER/VNIR and MISR. In few cases more lenses view in the same direction, with different spectral and geometric resolution (for example, MOMS-02). The multi-lens design is mostly chosen for sensors carried on satellite. Currently the maximum number of lenses and viewing direction is nine (MISR).

2.4 SENSOR CALIBRATION

In this section the possible geometric errors occurring in the CCD line and in the optical system are analyzed. In the proposed sensor model only some of these parameters are estimated, as discussed in Chapter 4, Section 4.4.
2.4.1 Errors in CCD lines

Referring to the linear array design described in Section 2.2.1, we consider one CCD line made of *ns* segments. Usually in airborne and satellite sensors *ns* = 1, *ns* = 2 and *ns* = 3. In this analysis the configurations *ns* = 1 and *ns* = 2 will be taken into account, because any other case (*ns* > 2) can be described as a combination of the two basic ones. We call *Np* the number of pixels contained in segment *i*.

The reference system used for this analysis is the scanline one. This system, indicated with *S* and described in Section B.2, is a 2D frame with origin in the center of the line (center of the central pixel), *y*-axis directed along the scanline and *x*-axis perpendicular to *y* (Figure 2.14).

For the representation of the geometric errors, simple drawings will be shown with the convention that the grey filled rectangles represent the arrays in the correct (ideal) position and the dashed empty rectangles represent the same arrays in the wrong (real) position, affected by geometric errors.

The geometric errors that may occur in CCD linear array sensors are:

- change of pixel dimension
- shift or rotation of the CCD segments in the focal plane with respect to their nominal position
- line bending.

These errors can be corrected by modelling them with suitable functions.

The change of the pixel size has the effect to change the image scale (Figure 2.15). In case *ns* = 1, we consider a pixel with dimensions (*p_x*, *p_y*) and a change of the pixel size *dpx* in *x* direction and *dp_y* in *y* direction. Calling *v* the coordinate of *P* along *y* axis, the error results

\[ d_{yp} = y \cdot \frac{dp_y}{p} \]  (2.6)

in *y* direction and \( d_{xp} = dp_x \) in *x* direction. The error *d_{yp}* is highly correlated to the focal length variation, the radial distortion and the scale factor in *y*-direction (Section 2.4.2).

In the following paragraphs the errors due to the shifts and rotations of the CCD segments in the focal plane are described and modelled separately for *ns* = 1 and *ns* = 2.

**ns = 1**

The CCD arrays consist of one segment only. The errors that may occur are:

- shifts in *x* - and *y* -direction (Figures 2.16 and 2.17). These errors can be modelled with a constant quantity *dx* and *dy* respectively.
Section 2.4. SENSOR CALIBRATION

- effect of horizontal rotation \( \theta \) in the CCD plane. The rotation produces the error \( dy_\theta \) in \( y_s \) direction and \( dx_\theta \) in \( x_s \) direction (Figure 2.18).

![Figure 2.18. Effects of rotation of CCD segment in the focal plane.](image)

The error in \( y_s \) direction \( (dy_\theta) \) is equal to the distance between \( P' \) (orthogonal projection of \( P \) to \( y_s \) axis) and \( P'' \) (position of \( P \) when \( \theta = 0 \))

\[
dy_\theta = y - y\cos\theta = y(1 - \cos\theta) \tag{2.7}
\]

If \( \theta \to 0 \), the error \( dy_\theta \) is negligible \( (\cos\theta \to 1) \).

On the other hand, the error in \( x_s \) direction

\[
dx_\theta = y\sin\theta \tag{2.8}
\]

is more significant and will not be neglected during the sensor modelling.

- effect of line bending in the focal plane. The straight CCD line is deformed into an arc. The size of the bending is described by the central angle \( \delta \) that subtends the arc described by the deformed line. The effect is represented in Figure 2.19. The radius of the conference that contains the arc is calculated from the CCD line length \((Np \) pixels\), the pixel size in \( y_s \) direction \((p_y)\) and the angle \( \delta \) as

\[
R = \frac{Np \cdot p_y}{2\sin\frac{\delta}{2}} \tag{2.9}
\]

This effect produces a significant error in \( x_s \) direction, indicated as \( dx_\delta \). The error depends on the pixel position in the CCD line. Considering a line bending in the plane defined by \( x_s < 0 \) in the center of the line \((y_s = 0)\) the error is maximum, with value

\[
dx_\delta = \left( r - r\cos\frac{\delta}{2} \right) \tag{2.10}
\]

while at the borders \((y_s = \pm \frac{Np \cdot p_y}{2})\) the error is null. For any other values of \( y_s \) the error can be modelled introducing the angle \( \delta' \), \( 0 \leq \delta' \leq \frac{\delta}{2} \), defined as

\[
\delta' = \frac{y_s}{r} \tag{2.11}
\]
with the formula

$$dx_s = - \left( r \cos \delta' - r \cos \frac{\delta}{2} \right) = -r \left( \cos \delta' - \cos \frac{\delta}{2} \right)$$

(2.12)

If the CCD line is bending in the plane where \(x_s > 0\), Equation 2.12 is still valid, but with opposite sign.

\[\text{Figure 2.19. Line bending in the focal plane.}\]

**\(ns = 2\)**

This is the case of CCD lines consisting of 2 segments, containing respectively \(N_{p1}\) and \(N_{p2}\) pixels. If the segments are not aligned perfectly within the focal plane, it results that the separate sub-scenes or strips that are produced may have small discontinuities or mismatches between them. If the sub-scenes have overlaps between them (like in IRS case), a single homogeneous image can be generated by measuring common points in the overlaps to eliminate any potential physical focal plane discontinuities. On the contrary, if the sub-scenes are not overlapping, a physical modelling is required. We assume that the segment numbered as 1 is fixed in the focal plane and the other one (segment 2) translates and rotates with respect to its nominal position. For the case where the segment 1 is fixed and the segment 2 moves and rotates, the formulas are easily modified. If both segments move and rotate, the single effects of each segment's movement and rotation will be added.

The systematic errors that may occur in segment 2 are:

- shifts in \(x\)- and \(y\)-direction (Figures 2.20 and 2.21). These errors are modelled with constant parameters \(dx_c\) and \(dy_c\) for the pixels belonging to the second segment (\(y_s > 0\)).

\[\text{Figure 2.20. Shift of CCD segment in } y \text{ direction in the focal plane.}\]

\[\text{Figure 2.21. Shift of CCD segment in } y \text{ direction in the focal plane.}\]
Section 2.4. SENSOR CALIBRATION

- effect of horizontal rotation $\theta$ in the CCD plane (Figure 2.22)

\[ y \cos \theta \]

\[ dy_\theta \]

\[ x_\theta \]

\[ y \]

Figure 2.22. Effects of rotation of CCD segment in the focal plane.

As in the case $ns=1$, the value of the error $dy_\theta$ in $y$ direction is negligible, due to the small size of $\theta$, while the effect of rotation $\theta$ in $x$ direction ($dx_\theta$) for $y>0$ is

\[ dx_\theta = y \sin \theta \]  

(2.13)

2.4.2 Lens distortions

The possible errors that may occur in an optical systems have been deeply investigated in close range, airborne and satellite photogrammetry (Brown, 1971, Beyer, 1992, Jacobsen, 1998). They are:

- the displacement of the lens principal point, with coordinates $(x_p, y_p)$. This error is modelled with constant shifts $\Delta x_p, \Delta y_p$ in $x$ and $y$ directions.

- the change $\Delta f$ of the focal length $f$. The effect of this error in $x$ and $y$ directions is modelled as

\[ dx_f = \frac{\Delta f}{f} x_p \]

\[ dy_f = \frac{\Delta f}{f} y_p \]  

(2.14)

where $x_p = x - x_p$ and $y_p = y - y_p$

- the symmetric lens distortion. It is described by the coefficients $k_1$ and $k_2$ and is modelled as

\[ dx_r = (k_1 r^2 + k_2 r^4) x_p \]

\[ dy_r = (k_1 r^2 + k_2 r^4) y_p \]  

(2.15)

where $r^2 = x_p^2 + y_p^2$

- the decentering lens distortion, described by $(p_1, p_2)$. It is modelled as

\[ dx_d = p_1 (r^2 + 2 \bar{x}_p) + 2 p_2 \bar{x}_p \bar{y}_p \]

\[ dy_d = 2 p_1 \bar{x}_p \bar{y}_p + p_2 (r^2 + 2 \bar{y}_p^2) \]  

(2.16)

- the scale variation in $x$ and $y$ directions ($s_x, s_y$). In case of linear array sensors only the effect in $y$ direction is considered

\[ dy_s = s_y \bar{y}_p \]  

(2.17)
2.4.3 Laboratory calibration

High precision photogrammetric cameras require high resolution geometric, spectral and radiometric laboratory calibration. An inaccurate interior orientation would consequently lead to systematic errors in the photogrammetric point determination as well as in all follow-up products. For this reason the purpose of geometry laboratory calibration is the precise measurement of object side image angles for a sufficient number of sensor elements of each single CCD array.

In the following, two systems for the laboratory geometric calibration of pushbroom sensors are briefly reported, one for a spaceborne sensor (MOMS-02) and one for an airborne sensor (StaRmager).

The first calibration facility is located at the Institute of Space Sensor Technology at DLR. It was originally developed for the calibration of spaceborne sensors in the visible range and was lately extended to the infrared spectrum. This system has been used for the calibration of spaceborne sensors like MOMS-02/D2, MOMS-P2 (Kornus et al., 1996), HRSC (Ohlhof and Kornus, 1994), WAOSS-B (Schuster et al., 2002) and the airborne camera ADS40 (Schuster and Braunecker, 2000).

The optical system to be calibrated is mounted on a turn-table with two orthogonal rotation axis; the calibration system includes a collimator support oriented along the third orthogonal axis. The vertical x-axis is pointing in the flight direction and the horizontal y-axis is directed along the sensor lines. In an initial zero-position both axes are adjusted approximately perpendicularly to a reference direction, defined by a Cassegrain collimator. In Figure 2.23 the calibration system for MOMS-P2 is shown. In the initial zero-position the x-axis, the y-axis and the collimator axis define an orthogonal cartesian coordinate system. Deviations from orthogonality introduce errors in the image angle measurements. Referring to Figure 2.24, the errors that can occur are: the non-orthogonality between x- and y- axes (angle $\beta$), the non-orthogonality between y- and collimator axes (angle $\gamma$) and the non-orthogonality between x- and collimator axes (angle $\alpha$). In order to compensate for these errors the measurements are carried out in two sequences per set, firstly in "normal" position, then in "reverse" position (the optical module is rotated 180° around the x-axis and the y-axis). The mean values of both sequences are free of errors $\beta$ and $\alpha$. Since $\gamma$ is not estimated in this way, the x-axis must be carefully adjusted orthogonally to the collimator axis prior to calibration and never be changed during the entire process. Then $\gamma$ can be determined from the y-angles measured in normal and reverse position at azimuth angle equal to 0.

From these measurements the camera model parameters and the correction tables can be derived, describing the relative location of each CCD array and the deviations of the single pixel location from the camera model. The final values of the single pixel location $(x, y)$ are compared against ideal values, which assume a straight horizontal sensor line and constant distances between the pixel centers. The deviations $dx$ and $dy$ are modelled with linear and parabolic functions depending on parameters that describe the sensor rotation and curvature, focal length and along-track displacement. These calibration parameters are estimated and used to correct the nominal values of the sensor rotation and curvature, focal length and along-track displacement. For more details about this laboratory calibration see Kornus et al., 1996 and Kornus, 1996.
The second example of laboratory geometric calibration is the one for the three-line scanner Starlmager (SI), by Starlabo Corporation, Tokyo. The sensor optical system consists of one lens and 9 or 10 CCD lines (depending on the SI version) in the focal plane for the forward, nadir and backward viewing. The parameters of the interior orientation that are calibrated include the shift of convergent stereo channels, the offsets of the multispectral line arrays, the focal length and the lens distortions (Chen et al., 2003). The camera is mounted on the stage of the collimator at the "zero position" and aligned with regard to the spatial fixed (camera) system with coordinates $x, y$ (Figure 2.23); the center of the entrance pupil coincides with the center of rotation of the stage and the longitudinal axis of the nadir-looking CCD array is parallel to the $y$-axis and perpendicular to the $x$ axis. The collimator ray from a pinhole target at the collimator focus passes through the TLS camera’s lens center at angle $\alpha$ in the $y$ direction and angle $\beta$ in the $x$ direction, and is deformed by lens distortion (Figure 2.24). The distortions $\Delta x, \Delta y$ are measured and described by three unknown parameters for each CCD line (offset of principal point and angle between the CCD line and the $y$-axis) and six unknowns for the whole camera (focal length, three parameters for symmetric distortion, two parameters for tangential distortion). Finally the tables containing the correct values $x, y$ of the position of each detector of each CCD array are produced.
Chapter 2. LINEAR CCD ARRAY SENSORS

2.5 STEREO ACQUISITION

CCD linear array sensors can acquire stereo images with two different configurations, across and along the flight direction, as described in the following paragraphs.

2.5.1 Across-track

In across-track configuration, the CCD lines and the optical system are combined with a mirror that rotates from one side of the sensor to the other across the flight direction (Figure 2.27). The along-track angle is constant and close to zero (Figure 2.28). The across-track angle is usually up to 30°, but can reach larger values (for example 45° with Orbview-3). The number of strips is equal to the number of channels (one for each CCD line), all looking in the same direction. At the next satellite pass over the area of interest, the strips are acquired with a different viewing angle. According to this configuration, the stereo images are collected from different orbits, with the overlapping area across the flight direction (Figure 2.28). Considering a pair of images of the same area acquired with viewing angles $\alpha_1$ and $\alpha_2$, the base over height ratio is

$$\frac{B}{H} = \tan \alpha_1 - \tan \alpha_2$$  \hspace{1cm} (2.18)

The most relevant consequence of this configuration is that the time interval between the acquisition of two stereo scenes can be in the order of days or more, therefore differences in the land cover, due to natural events or human actions, and in the cloud distribution may occur.

The High Resolution Visible (HRV), the High Resolution Visible InfraRed (HRVIR) and the High Resolution Geometric Resolution (HRG) sensors carried on the SPOT constellation are an example of across-track stereo scanners, with an oblique viewing capability up to ±27° relative to the vertical (Figure 2.27). Today the two HRV instruments are carried on SPOT-2 (launched in January 1990), the two HRVIR (Figure 2.29) on SPOT-4 (launched in March 1998), while two HRG are carried on SPOT-5 (launched in May 2002). They independently image the Earth in either panchromatic or multispectral mode. In HRV and HRVIR sensors, the panchromatic channels use an array of 6000 detectors, while the multispectral ones have 3000 detectors per spectral band. The nominal pixel size is of 10m in panchromatic images and 20m in multispectral images. In HRG, on the other hand, the panchromatic channels use two staggered arrays of 12000 pixels each that produce images with an original ground resolution of 5m and 2.5m after postprocessing with Quincunx sampling, as already described in Section
Section 2.5. STEREO ACQUISITION

Flight direction

Figure 2.28. Principle of across-track stereo viewing. The sensor acquires a strip with nadir viewing (left). The stereo images belong to successive passes (right) and the overlapping area (in white) is across the trajectory.

2.2.1.3. The ground pixel resolution of the multispectral channels is again 10m. In vertical viewing, the HRV, HRVIR and HRG sensors image a 60-km long line of the Earth surface perpendicular to the satellite ground track (Westin, 1990). Another sensor acquiring with this scanning principle is the PAN camera (Josef et al., 1996) carried on the 1C and 1D satellites of Indian Remote Sensing (IRS) constellation (Kasturirangan et al., 1996, Figure 2.30). IRS-1C and 1D were launched in December 1995 and September 1997 respectively. In both cases the PAN camera is a panchromatic sensor with 5.8m resolution and 6-bit radiometric resolution. This camera can be steered up to ±26°. On the focal plane there are three CCD arrays (CCD1, CCD2 and CCD3) each having 4096 elements with pixel size 7µm (Figure 2.5). They cover a swath of about 70km in the case of nadir view and up to 91km for the most inclined view (Zhong, 1992).

Figure 2.29. Telescope in HRVIR instrument mounted on SPOT-4 (Source CNES, 2004).

Figure 2.30. IRS-1C satellite with instruments carried on board (Source CEOS, 2004).
2.5.2 Along-track

In case of sensors with along-track stereo capability, the stereo images of the same area are taken along the flight direction, with a time delay in the order of seconds (Figure 2.31). Images acquired by successive orbits (satellite case) or flight path (airborne case) may have a small overlapping in the across-track direction too. The main advantage of the along-track stereo acquisition in the same date over the across-track stereo acquisition in different dates is the reduction of the radiometric image variations (temporal changes, sun illumination, etc.), thus the increase of the correlation success rate in any image matching process. This acquisition geometry can be achieved with two different sensor configurations: multi-line sensors and single-line sensors with synchronous and asynchronous acquisition.

![Figure 2.31. Principle of along-track stereo acquisition from multi-line sensors. Each point is scanned by the n-lines at different times during the same orbit (for satellites, right). The time differences between the acquisitions is smaller than with across-track stereo acquisition.](image)

2.5.2.1 Multi-line sensors

A number of CCD linear arrays view simultaneously in different looking angles along the trajectory. A point on the terrain is scanned by each line at a different time, as the platform moves. The imaging system produces strips with overlapping areas along the flight direction. The most common configuration is with three lines viewing simultaneously backward, nadir and forward the viewing direction (Figure 2.32).

A large number of three-line sensors for airborne and spaceborne applications have been designed and developed in Germany, by Daimler-Benz Aerospace AG (DASA), formerly the MBB GmbH, and by DLR (Deutsche Forschungsanstalt für Luft- und Raumfahrt - German Space Agency), often with the consulting by German Universities (University of Munich, University of Stuttgart, etc.).

One of the pioneers of this camera design was Otto Hofmann, who in the mid 70's experimented to substitute the film-based data acquisition with linear CCDs. As a result, the pushbroom sensor EOS (Electro-Optical System) was developed for experimental purposes. Then the technology improved very quickly and new three-line pushbroom systems were soon available. The multi-line pushbroom sensors (the major part of them are three-line sensors) developed by DLR and DASA are briefly described in the following and shown in Figure 2.33.

**Digital Photogrammetric Assembly (DPA).** It was constructed by DASA for image acquisitions from airplane (Hofmann, 1986); the optical system consists of one lens for panchromatic scenes in three along-track directions and additional four lenses for multi-spectral images in the nadir direction. It has been mostly used for testing and applications at DLR and at the University of Stuttgart (Fritsch and Hobbie 1997).
Section 2.5. STEREO ACQUISITION

Figure 2.32. Geometry of three-line sensors (left) and their image acquisition (right). The overlapping areas are along the flight direction.

**Monocular Electro-Optical Stereo Scanner (MEOSS).** It was designed in the mid 80's by Lanzl (*Lanzl, 1986*). MEOSS had a single lens with a focal length of 61.6mm and 3 CCD sensor arrays. Each CCD array comprised 3236 sensor elements with 10.7μm size. After some airborne test flights, MEOSS was planned to circle the Earth on an Indian satellite. Unfortunately the camera was lost in a launch failure in 1993. The photogrammetric processing of the data available from the airborne test flight in 1986 and 1989 are reported in (*Lehner and Gill, 1989*), (*Kornus, 1989*) and (*Heipke et al, 1996*).

**Modular Optoelectronic Multispectral Scanner (MOMS).** The first MOMS sensor (MOMS-01) was built by DASA and was mounted on the Shuttle PAllet Satellite (SPAS). The successor MOMS-02 was built by DASA under contract to the Deutsche Agentur für Raumfahrtangelegenheiten (DARA) and DLR. Two versions of this sensor were built. One was flown on STS-55 during the Spacelab D-2 Mission from April to May 1993 (MOMS-02/D2, *Ackermann et al., 1989*, *Seige, 1995*, *Ebner et al., 1992*) and the other one on the Russian MIR station during the Priroda mission from May 1996 to March 2003 (MOMS-02/P or MOMS-P2, *Seige et al., 1998*). The optical system of MOMS consists of 5 lenses, three for the panchromatic stereo viewing (nadir, forward and backward) and two for the multispectral acquisition in nadir viewing. In Section 6.2 more details about MOMS-02 will be described.

**Wide-Angle Optoelectronic Stereo Scanner (WAOSS).** It was developed by DLR for the MARS mission in 1994 and now a new version of WAOSS (WAOSS-B) is carried on BIRD, which is a small satellite flying at a height of 570km over the Earth surface (*Oertel et al., 1992*). WAOSS-B is a three line sensor with a single-lens optical system and produces panchromatic stereo images with viewing angles of 0 and 25°. In the BIRD mission it provides images with a ground resolution of 145m and a swath width of 753km (*Schuster et al., 2002*).

**Wide-Angle Airborne Camera (WAAC).** This sensor is the airplane version of WAOSS and has the same geometry. It was built to test WAOSS before the MARS mission (*Eckardt, 1995*).

**High Resolution Stereo Camera (HRSC).** Together with WAOSS, HRSC was developed by DLR for MARS-94 mission (*HRSC, 2004*). The design goal of HRSC was to provide high resolution imaging (10m at 250km altitude), high quality stereo imaging (panchromatic, triple stereo concept), multispectral imaging (four narrow band color channels) and multi-phase angle imaging for photometric investigations (two additional panchromatic channels yielding images at...
five different phase angles together with the nadir and stereo channels). Today a modified version of the original HRSC is carried on the Mars Express payload developed by ESA. The modification process made the camera fully compliant with the Mars Express interface requirements (low mass and power consumption). As in the original version, the camera acquires simultaneous high-resolution panchromatic stereo images in three viewing direction, together with multi-color and multi-phase imaging of the Martian surface. An additional Super Resolution Channel provides frame images imbedded in the basic HRSC swath at five times greater resolution.

**High Resolution Stereo Camera Airborne/Airborne Extended (HRSC-A/AX).** As in the case of WAAC, HRSC-A and -AX are the airborne versions of HRSC, designed for photogrammetric and general remote sensing applications. They are very similar to HRSC, but with smaller dimensions, lower mass, lower power consumption and a more robust design. The HRSC-A is practically identical in its main structural features and electronics to the system developed for Mars 96 with some additional peripheral electronics. The camera has been used by DLR for photogrammetric mapping (Wevel et al., 1999). The HRSC-AX is an optoelectronic digital airborne multispectral stereo scanner with high photogrammetric accuracy and very high spatial resolution (10cm from 2500m flight altitude). The HRSC-A and -AX systems are mounted on a Carl Zeiss T-AS stabilizing platform in their in-flight configuration. Easy handling of operations is provided by various automatic modes.

**Airborne Digital Sensor 40 (ADS40).** This airborne sensor has been built up by DLR in collaboration with LH Systems. It acquires panchromatic and multispectral images using 7 CCD lines mounted on a single focal plane (Sandau and Eckert, 1996). The instrument provides strips in three viewing directions, which are not the same in all the versions built.

![MOMS-02](image1.png) ![DPA](image2.png) ![WAOSS-B](image3.png)

**HRSC on Mars Express**

**HRSC-A**

**ADS40**

Figure 2.33. Some of the linear array sensors developed at DLR: MOMS-02 (Source *MOMS-02*, 2004), DPA (Source *Fritsch and Stallmann*, 2000), WAOSS-B (Source *Schuster et al.*, 2002), HRSC on Mars Express (Source *ESA Mars Express*, 2004), HRSC-A (Source *DLR Berlin*, 2004), ADS40 (Source *LH-Systems*, 2004).
Another sensor based on the three-line stereo acquisition was developed in 2000 by Starlabo, in collaboration with the University of Tokyo. The sensor is called **Starlmager (SI)**, shown in Figure 2.34, and is normally carried on helicopter (Murai and Matsumoto, 2000). There are three versions of this sensor: SI-100, SI-250 and SI-290. SI-100 consists of one-lens optical system (Zeiss Distagon CD with focal length 60mm) and three CCD lines of 10,200 elements each (pixel size 7μm), scanning in forward (+21.5°), nadir and backward (-21.5°) directions. There are two configurations for image acquisition. The first one ensures the stereo imaging capability, in which the three CCD arrays working in the green channels are read out with stereo angles of 21.5°. The second configuration uses the RGB CCD arrays in nadir direction to deliver color imagery (Grün and Zhang, 2002a). The next version of STARIMAGER, called SI-250, was manufactured in 2002 (Murai et al., 2003). With the same focal length of SI-100, it acquires RGB strips with CCD lines of 14,400 detectors with size 5μm. The off-nadir viewing angles are 23° (forward) and -17° (backward). Additionally, a NIR line acquires with off-nadir angle 17° (Madani et al., 2004). The last version of Starlmager, SI-290, is similar to SI-250, but with focal length of 93mm and viewing angles of 15° (forward), -23° (backward) for the RGB and -12° for the NIR (Kocaman, 2005).

The three-line principle has also been adopted in the family of the **3-DAS-1** airborne cameras, developed and manufactured by Wehrli Associates and Geosystem during the last decade. The optical systems consist of three lenses viewing in forward (+26°), nadir and backward (-16°) directions, and the lenses are available in focal lengths of 35mm, 60mm and 100mm. On each focal plane three sets of CCD lines acquire strips in RGB channels. The possible CCD lines dimensions are: 3 x 6,000 pixels with size 12μm, 3 x 8,000 pixels with size 8μm and 3 x 14,400 pixels with size 5 μm (Wehrli et al., 2004).

The stereo principle based on simultaneous three-line scanning will be also used in future missions. This is the case, for example, of the **Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM)** on board the Japanese Advanced Land Observing Satellite (ALOS), that has been developed at the Japan Aerospace EXploration Agency (JAXA) and will be launched in 2005 from the Japanese H-IIA vehicle (Tadono et al., 2003). The PRISM sensor, designed and manufactured at Goodrich (Goodrich, 2004), is supposed to acquire triplets with a ground resolution of 2.5m in panchromatic model, using three separate lenses with viewing angles 0° and ±24° (Figure 2.34).

Multi-line scanners with a number of lines different from three also exist and are currently operational.
High Resolution Stereoscopy (HRS). This sensor (Figure 2.35a) from CNES is carried on the latest satellite of SPOT constellation (SPOT-5) and acquires simultaneously two stereo strips, backward and forward the flight direction. Each CCD array contains 12000 detectors, with ground resolution of 10m (resampled at 5m in along track direction). More details about HRS and the results obtained by the georeferencing of its imagery will be presented in Section 6.3.

Visible and Near Infrared (VNIR). This instrument (Figure 2.35b) is a component of the Advanced Spaceborne Thermal Emission and Radiation Radiometer (ASTER), built by NASA and currently mounted on EOS-AM1. Similar to SPOT-5/HRS, the VNIR subsystem consists of two independent telescopes viewing nadir and backward (-15°) the satellite trajectory (Yamaguchi et al., 1998). The focal plane of the backward looking telescope contains only a single detector array (band 3B). The focal plane of the nadir telescope contains 3 line arrays (bands 1, 2 and 3N) and uses a dichroic prism and interference filters for spectral separation allowing all three bands to view the same area simultaneously (ASTER, 2004). The channels 3N and 3B acquire stereo images in the near infrared. The results obtained by the georeferencing of a stereo pair from ASTER-VNIR imagery will be presented in Section 6.4.

Multi-Angle Imaging SpectroRadiometer (MISR). Together with ASTER, MISR is carried on EOS-AM1 platform and acquires images in four different channels (blue, green, red and near infrared) along nine different symmetric viewing directions, using 36 linear arrays (Figure 2.35c). The spatial resolution is 275m (all channels in nadir direction and red channel in all off-nadir directions) and 1100m (blue, green and near infrared channels in off-nadir directions), as described in Diner et al., 1998b. The results obtained by the georeferencing of MISR imagery will be presented in Section 6.5.

Airborne Multi-angle Imaging SpectroRadiometer (AirMISR). It was derived from the MISR concept and used for testing before the MISR launch (Figure 2.35d). Today it is used by NASA for photogrammetric mapping (Diner et al., 1998a).

Figure 2.35.Multi-line pushbroom sensors: SPOT-5/HRG from CNES (CNES, 2004); b) ASTER from NASA (ASTER, 2004); c) MISR from NASA (MISR, 2004); d) AirMIRS from NASA (AirMISR, 2004).
2.5.2.2 Single-line sensors

Single line sensors have the optical system consisting of one lens and acquire one strip using a single CCD line. They have the ability to rotate on command around their cameras axes and scan the terrain with specific viewing angles. The acquisition of stereo images of a particular area of interest is programmed in advance. Thanks to their flexibility, these sensors can be programmed to acquire stereo scenes both across- and along- the flight direction, in two different methods: synchronously or asynchronously.

Synchronous acquisition mode

The acquisition mode is synchronous if the satellite speed and the scanning speed are equal. Therefore each image line is acquired with the same viewing angle (Figure 2.36a). Sensors that follow this principles are:

**IKONOS-2.** IKONOS-1 and IKONOS-2 (Figure 2.37a) are two very high resolution sensors developed by SpacelImaging, with KODAK telescopes. After the launch failure of IKONOS-1 on 27 April 1999, IKONOS-2 was successfully launched on 24 September 1999 and is still operational. IKONOS scenes cover a squared area of $121 \text{km}^2$ with a ground resolution of 1m (panchromatic) and 4m (multispectral). The large pointing capability (off-nadir viewing up to 60° in any azimuth) enables the generation of across-track stereoscopy from two different orbits (such as with SPOT-4/HRV), as well as along-track stereoscopy from the same orbit (such as with SPOT-5/HRS).

**QuickBird-2.** QuickBird-2 (Figure 2.37b) is a very high resolution sensor launched by Digital-Globe in October 2001 (Digital Globe et al., 2003). The sensor, developed by Ball Aerospace (Ball Aerospace, 2004), provides scenes covering a squared area of $262 \text{km}^2$ with a ground resolution of 0.7m (panchromatic) and 3.4m (multispectral). The CCD line contains 27,000 pixels, obtained with a combination of three linear arrays, each of 9,000 pixels. The QuickBird Basic Stereo Product includes two stereo images collected along-track on the same pass, generally at 30° off-nadir (forward - backward) and within 10° across the ground track, which provides a base to height ratio of 0.6 to 2.0, with most collections between 0.9 and 1.2.

**Orbview-3.** Orbview-3 (Figure 2.37c), manufactured by Orbital Sciences Corporation (OSC) and operated by Orbimage, was launched on 26th June 2003. The sensor provides both one-meter panchromatic imagery and four-meter multispectral imagery with a swath width of 8km. The satellite is operating in a sun-synchronous, near-polar orbit with an orbital inclination of 97.3° at an altitude of 470km and revisits each location on Earth in less than three days with an ability to turn from side-to-side up to 45°. The stereo images are acquired along the flight direction.

**Rocsat-2.** The Taiwanese ROCSAT-2 satellite (Figure 2.37d) developed by the National Space Programme Office of Taiwan (NSPO, 2004), was successfully launched on 20 May 2004 and has the main objective of acquiring images over Taiwan for civilian and scientific purposes. The satellite carries on board the Remote Sensing Instrument (RSI), that provides images with a swath width 24km and a ground resolution of 2m in panchromatic mode and 8m in multispectral mode (RGB and NIR). The satellite's agility enables very rapid pointing (up to ±45°) both along and across track (Chen and Wu, 2000).

Asynchronous acquisition mode

The acquisition mode is asynchronous if the scanning velocity and the platform velocity are not the same (Figure 2.36). An example of pushbroom sensor with asynchronous mode is the Earth
Chapter 2. LINEAR CCD ARRAY SENSORS

Resources Observation Satellite (EROS-A), launched by in December 2000 (Figure 2.37d). The EROS project has been developed by ImageSat International, with the cooperation of Elop's Elbit (Elop's Elbit, 2004) for the telescope construction. The satellite moves in a faster ground speed than its rate of imaging, ensuring a longer dwell time to allow more light to reach the CCD linear array sensor of the imager and therefore to improve the quality of the image. The sensor bends backwards to take its images in an almost constant, predetermined angular speed, providing a forward-backward pointing; at the same time it employs the across track pointing capability (Chen and Teo, 2002). The maximum off-nadir angle is 45° both in along-track and across-track directions. Each line of the images is acquired with a different viewing angle (Figure 2.37e).

![Flight direction](a) ![Flight direction](b)

Figure 2.36. Principle of along-track stereo viewing with single lines: (a) synchronous; (b) asynchronous.

2.6 PLATFORMS

CCD linear array sensors can be mounted on terrestrial, airborne and spaceborne platforms. In this context, airborne and spaceborne platforms are taken into account. Today a large part of sensors used for Earth observation and production of imagery for mapping use pushbroom sensors.

Among the airborne acquisitions, the portion occupied by linear scanners is not as large as for space-based pushbroom scanners, because other acquisition instruments (film cameras, digital frame cameras, laser scanner) represent an alternative method for airborne photogrammetric acquisitions. Nevertheless, in the last years airborne pushbroom scanners have been reaching an operational and production status.

In the next sections, the characteristics of satellite and airborne platforms that will be taken into account for the sensor modelling are described.

2.6.1 Satellite platforms

With the launch of SPUTNIK-1 on October 4, 1957 the space age began, but it took about 15 years to launch a satellite dedicated to civil spaceborne Earth surface imaging: the ERTS (Earth Resources Technology Satellite) spacecraft, later renamed to Landsat-1. The CCD line detector technology was introduced with MSU-E (Multispectral Scanning Unit-Electronic), that was first flown on Meteor-Priroda-5 in 1980 and provided a spatial resolution of 28m and a swath width of 28km. The spaceborne stereoscopic along-track imaging was introduced by MOMS-02 (Modular Optoelectronic Multispectral Scanner), that was flown in 1993 on the Shuttle STS-55 and in 1996 on the MIR station during Priroda mission (Sandau, 2004).
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Figure 2.37. Single-line pushbroom sensors: (a) Ikonos-2 (Source SpacelMaging), (b) Quickbird-2 (Source Ball Aerospace), (c) Orviev-3 (Source Novosti-Kosmonavtiki, 2004), (d) Roc-sat-2 (Source EADS Astrium, 2004) (e) EROS-A1 (Source ImageSat International, 2005).

Today hundreds of satellites fly for Earth observation. Among them, we will provide information on those satellite platforms that carry linear array sensors for photogrammetric applications. According to their dimension, the satellites can be classified in small satellites, standard satellites and space stations.

Standard satellites are some meters large and fly at a height between 400 and 700km on the Earth surface. If constructed by private companies, they usually carry one instrument only, while if they are financed by national space agencies, they carry different sensors for specific observations. Small satellites are smaller and lighter with a shorter expected life. An example of a small satellite carrying pushbroom sensors is the Bi-Spectral Infra-Red Detection BIRD by DLR (Schuster et al., 2002), with three instruments for Earth observations on board: the three-line stereo camera WAOSS-B (Wide Angle Optoelectronic Stereo Scanner), the optional sensor HORUS (High Optical Resolution Utility Sensor) for verification tasks and HSRS (Hot Spot Recognition Sensor) for middle and thermal infrared imagery. For an overview on small satellites see Small Satellites, 2004. A space station is a manned satellite designed to revolve in a fixed orbit and to serve as a base for scientific observation and experiments, for refueling spacecraft or for launching satellites and missiles. One of the most successful space station was the MIR, launched by the Soviets on 20th February 1986 and destroyed in March 2001. The station had six docking
ports for cargo transports, visiting manned spacecraft and expansion modules, designed to be used as research laboratories and living quarters. Among the sensors carried on board, MOMS-02/P was one of the first digital satellite sensors to provide continuous stereo-panchromatic and multispectral imagery for DEM generation and orthophoto production (Müller et al., 2001).

Satellite sensors can also be classified according to their operators: large public space agencies, large aerospace companies, space nations. Table 2.1 shows the classification proposed by Denore, 2000.

In general commercial satellites developed by private companies are designed to meet the users’ requirements, in terms of resolution, ready-to-use products and temporal coverage. They usually provide high or very high resolution imagery for terrain mapping, orthophoto generation and object extraction. The along-track or across-track stereo acquisition of a particular region of interest is planned in advance and the satellite can be manoeuvred in order to satisfy as much as possible the users’ stereo requirements. The missions planned by large public space agencies, on the other hand, have the main objective to provide the users with useful tools for land planning and resource mapping and monitoring. Small satellites, which are cheaper, are usually built by companies or agencies with a more limited budget and try to fulfill specific requirements (price, coverage, etc.) which make them competitive with respect to the other image providers.

<table>
<thead>
<tr>
<th>OPERATOR</th>
<th>SATELLITE SYSTEM TYPE</th>
<th>OBJECTIVE</th>
<th>EXAMPLES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large public space agencies</td>
<td>High resolution land resources</td>
<td>Resource mapping</td>
<td>SPOT, Landsat, IRS-1C</td>
</tr>
<tr>
<td>Large aerospace companies</td>
<td>Very high resolution</td>
<td>Detailed mapping</td>
<td>IKONOS, Quickbird, EROS-A1</td>
</tr>
<tr>
<td>Emerging space nations, University start-up companies, SME’s, etc.</td>
<td>Small-satellites, medium-high resolution</td>
<td>Science Technology development, Industrial policy, National pride, etc.</td>
<td>SunSat, Kitsat, BIRD</td>
</tr>
</tbody>
</table>

2.6.1.1 Orbit characteristics

Satellite orbits have several unique characteristics which are particularly useful for photogrammetric mapping of the Earth's surface. An orbit cycle is completed when the satellite retraces its path, passing over the same point on the Earth's surface directly below the satellite (at nadir) for a second time. The exact length of time of the orbital cycle is called orbital period.

Satellite orbits differ in terms of altitude and orientation and rotation relative to the Earth and are matched to the capability and objectives of the sensor(s) they carry.

For example meteorological and communication satellites have geostationary orbits (Figure 2.38) at very high altitudes, approximately 36,000km and revolve at speeds which match the rotation of the Earth, so they observe and collect information continuously over specific areas. Due to their high altitude, the geostationary satellites can monitor weather and cloud patterns covering an entire hemisphere of the Earth.

Usually the platforms that carry pushbroom sensors for photogrammetric mappings fly at lower heights (300-850km) along near-polar orbits (Figure 2.38). They are designed to follow an orbit (basically North-South) which, in conjunction with the Earth's rotation (West-East), allows the sensors to cover most of the Earth's surface over a certain period of time. A complete coverage of the Earth's surface is completed after one cycle of orbits. As an example of satellite coverage, in
Figure 2.39 the ground track of SPOT constellation is shown. Apart of near-polar orbits with an inclination near 90°, tilted orbits (inclinations less than 90°) are also possible, but not very frequent (MOMS-02 on MIR platform), because the corresponding Earth coverage is small (Figure 2.38).

Most satellite orbits are sun-synchronous such that they cover each area of the world at a constant local time of day (local sun time). Therefore at any given latitude, the position of the sun in the sky as the satellite passes overhead is the same within the same season. As a consequence, consistent illumination conditions when acquiring images in a specific season over successive years, or over a particular area over a series of days are ensured. This is an important characteristic for monitoring changes between multi-temporal image series or for mosaicking adjacent images together, as they do not have to be corrected for different illumination conditions.

Concerning the physical properties of the orbits, a detailed description will be given in Section 3.2.1.

Figure 2.38. Different satellite orbits: a) near-polar; b) non polar (tilted); c) geostationary.

Figure 2.39. Ground track of SPOT orbit with ground receiving stations.

2.6.1.2 List of satellite platforms

Table 2.2 summarizes some information (agency, status, launch date, sensors on board) of the satellite platforms carrying pushbroom sensors for photogrammetric mapping, together with their orbit characteristics (height, orbital period, inclination).
Table 2.2. Main characteristics of satellite platforms. In column STATUS, the following abbreviations have been used: O for operational, P for not operational, F for future.

<table>
<thead>
<tr>
<th>SATELLITE</th>
<th>AGENCY</th>
<th>LAUNCH DATE</th>
<th>STATUS</th>
<th>HEIGHT</th>
<th>ORBITAL PERIOD (min)</th>
<th>INCLINATION (deg)</th>
<th>SENSORS</th>
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<td>ALOS</td>
<td>JAXA</td>
<td>end 2005</td>
<td>F</td>
<td>692</td>
<td>99</td>
<td>98.3</td>
<td>AVNIR-2 PALSAR PRISM</td>
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<td>BIRD</td>
<td>DLR</td>
<td>22.10.2001</td>
<td>O</td>
<td>570</td>
<td>96</td>
<td>97.8</td>
<td>HORUS HSRS WAQSS-B</td>
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<tr>
<td>EOS-AM1</td>
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<td>98.2</td>
<td>ASTER CERES MISR MODIS MOPITT</td>
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<td>680</td>
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<td>98.1</td>
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<td>IRS-1C IRS-1D</td>
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<td>28.12.1995</td>
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<td>817</td>
<td>101</td>
<td>98.6</td>
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<td>11.2.1992</td>
<td>O</td>
<td>568</td>
<td>96</td>
<td>97.7</td>
<td>SAR OPS</td>
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<td>MIR</td>
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<td>89</td>
<td>51.6</td>
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<td>Orbimage</td>
<td>26.6.2003</td>
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<td>480</td>
<td>92.5</td>
<td>97.3</td>
<td>Orbview-3</td>
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<tr>
<td>QuickBird-2</td>
<td>Earth Watch</td>
<td>18.10.2001</td>
<td>O</td>
<td>450</td>
<td>93.6</td>
<td>97.2</td>
<td>QuickBird-2</td>
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<td>Rocsat-2</td>
<td>NSPO of Taiwan</td>
<td>20.5.2004</td>
<td>O</td>
<td>891</td>
<td>102.8</td>
<td>98.9</td>
<td>RSI ISUAL</td>
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<tr>
<td>SPOT-1</td>
<td>CNES</td>
<td>22.1.1990</td>
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<td>101</td>
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<td>2xHRV Vegetation</td>
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<tr>
<td>SPOT-2</td>
<td>CNES</td>
<td>24.3.1998</td>
<td>O</td>
<td>832</td>
<td>101</td>
<td>98.7</td>
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<td>SPOT-3</td>
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<td>832</td>
<td>101</td>
<td>98.7</td>
<td>2xHRG HRS Vegetation-2</td>
</tr>
</tbody>
</table>

².now JAXA
2.6.2 Airborne and helicopter platforms

In the last decade a large progress in the development of airborne linear array sensors has been made. These sensors can provide very high resolution and repeated temporal, multispectral and hyperspectral image data for mapping and GIS applications (Grün et al., 2003b).

Among the pushbroom digital systems used for airborne mapping application we can list: the MEROSS (Lanzl, 1986), DPA (Müller et al., 1994), the WAAC (Sandau and Eckert, 1996) and the HRSC-A/AX (Wevel et al., 1999), developed by DLR. As already mentioned, some airborne sensors were originally designed for simulation of the corresponding satellite-based sensors (for example WAAC, HRSC-A and AirMISR). Nowadays two commercial airborne sensors are on the market: the ADS40, by LH-Systems and the StarImager, by Starlabo. Both systems acquire strips along three different directions.

Contrary to pushbroom sensors carried on satellite, in the airborne case some sensors have fixed configurations (for example StarImager, Figure 2.40) and some others have CCD array configurations different for each camera exemplar, according to the customers requirements. This is the case of ADS40. Two configurations of this sensor are shown in Figure 2.41.

![CCD line configuration on StarImager](image)

**Figure 2.40.** CCD line configuration on StarImager (Grün and Zhang, 2002b).

![Two CCD line configurations of ADS40](image)

**Figure 2.41.** Two CCD line configurations of ADS40. The numbers represent the viewing angles in degrees of the corresponding lines below. PANF = panchromatic forward viewing; PANN = panchromatic nadir viewing; PANB = panchromatic backward viewing; NIR = near infrared; RGB = red-green-blue (Pateraki et al., 2004).
As airplanes and helicopters do not fly along an accurately predictable trajectory, for the photogrammetric point determination the direct measurement of the sensor position and attitude is required. Therefore GPS and INS instruments are always carried on board. Their observations are post-processed in order to provide the accurate sensor position and attitude of each image line. This topic will be investigated in Section 3.1.

Due to the platform instability and vibrations, the original images may be highly disturbed. As shown in Figure 2.42, the image lines stored one after the other produce straight lines that appear bent. In this case the sensor position and attitude for each image line are used for the rectification of the raw images through a projection to a ground plane at a user-specified elevation. The effect of the rectification is shown in Figure 2.42.

![Figure 2.42](image1.png)

Figure 2.42. Airborne pushbroom imagery before (left) and after (right) rectification. Example with ADS40 backward images (-14°) over Yokohama, October 2003 (Courtesy of PASCO Corp.).

In case of StarImager, the pushbroom imaging instruments are mounted together with a stabilizer to maintain a trajectory with no abrupt changes in position or orientation. In Figure 2.43 the advantage of using a stabilizer is shown.

![Figure 2.43](image2.png)

Figure 2.43. Effect of stabilizer on pushbroom imagery (Madani et al., 2004).
2.7 IMAGE CHARACTERISTICS

In the following, the main properties of the images acquired by pushbroom sensors are described.

2.7.1 Spatial resolution

The spatial resolution refers to the area on the ground that an imaging system can distinguish. It is measured as the size of a pixel on the ground, when the image is displayed at full resolution (CCRS Tutorial, 2004).

The ground resolution of satellite imagery is classified as very high (<1m), high (between 1m and 5m), mean (between 5m and 20m), low (between 20m and 50m) and very low (larger than 50m). In the last years this classification has been continuously changing according to the technology development. With the successful launch of the EROS-A1, IKONOS-2 and SPOT-5, imagery with resolution smaller than 5m could be provided for the first time. Quickbird can even acquire images with less than 1m resolution. In the next future, satellite missions carrying very high and high resolution satellites are planned (Table 2.3).

The spatial resolution of passive sensors depends primarily on their Instantaneous Field of View (IFOV). The IFOV is the angular cone of visibility of the sensor and determines the area on the Earth’s surface which is ‘seen’ from a given altitude at one particular moment in time. In the current airborne scanning systems, the IFOV is generally equal to 1.0 ~ 2.0 milliradians, while in spaceborne scanning systems the IFOV is smaller than 0.1 milliradians. Using the IFOV (indicated with the letter α) and according to the geometry shown in Figure 2.44, the length of a pixel on the ground in the CCD line direction (a_y) can be calculated with the following formula (Wang, 1990, p.524)

\[ a_y = \frac{\alpha \cdot R}{\cos Q} = \frac{\alpha \cdot H}{(\cos Q)^2} \]  \hspace{1cm} (2.19)

where R is the inclined distance between the object and the sensor, H is the flight height and Q is the scanning angle.

The size of a pixel in the flight direction (a_x) is usually equal to a_y and can be calculated as

\[ a_x = \frac{\alpha \cdot H}{\cos Q} \] \hspace{1cm} (2.20)

As expected, the ground pixel size is directly proportional to the platform flying height and to the IFOV.

For a wider analysis of the relationship between the instrument geometric parameters and the imagery ground resolution, the orbit characteristics and other factors must be taken into account. The following formula

\[ \frac{H}{f} = \frac{a_x}{p_x} = \frac{a_y}{p_y} \] \hspace{1cm} (2.21)

shows the dependency of the ground resolution (a_x and a_y) on the pixel size (p_x and p_y), the focal length f and the flight height H. By fixing the minimum pixel size to 6 μm, the ground pixel size is directly proportional to H and inversely proportional to f. This means that for high resolution sensors (small a_x and a_y) low orbits and high focal lengths are recommended. Anyway, physical constraints for the focal lengths exist and low trajectories have a small swath width, which can be improved by using more imaging elements in each line or multiple segments in one line. Moreover if lines with more CCD elements are used, a small ground pixel size cannot be guaranteed along the full image line (effect of α). The satellite systems combine these parameters in order to
satisfy the customers' requirements. Table 2.2 and Table 2.3 show some practical examples of parameter combination. Satellites like SPOT-5 at high orbits (832km) provide imagery with large swath width (120km) and medium-high ground resolution (10m) using 12000 CCD elements, while Quickbird acquires 0.6m resolution imagery from a lower trajectory (450km) with a small swath width (16km) using 3 segments of 9000 CCD elements each.

The ground resolution can be improved by placing the arrays in a staggered mode and combining the images produced by each line or with TDI technology (Section 2.2).

2.7.2 Radiometric resolution

The radiometric resolution describes the ability to discriminate very slight differences in energy and represents the sensitivity to detect small differences in reflected or emitted energy (CCRS Tutorial, 2004). It is expressed by an integer number that corresponds to the number of bits (in power of 2) used to quantize a pixel. This property is fundamental during the point measurement with matching algorithms.

Images provided by linear scanners for photogrammetric mapping may have a resolution ranging from 8 bit (256 grey values) to 16 bits (65536 grey values), according to the applications. The largest part of satellite and airborne imagery has a radiometric resolution of 8 bit and 11 bit.

2.7.3 Spectral resolution

The spectral resolution represents the capability of the sensor to distinguish fine wavelength intervals and is described by the number of bands and their wavelength ranges.

The spectral range can be selected in three different modes (Nieke et al., 1997):

- with dispersion elements (Figure 2.45a). The incoming electromagnetic radiation is separated into distinct angles with a grating or a prism. The spectrum of a single ground pixel is dispersed and focused at different locations of one dimension of the detector array. This technique is used for both whiskbroom and pushbroom image acquisition modes. Hyperspectral imagers are using mainly gratings as the dispersive element
- with filter-based systems (Figure 2.45b). A narrow band of a spectrum can be selected by applying optical bandpass filters (tunable filters, discrete filters and linear wedge filters). A linear wedge filter functions by transmitting light at a centre wavelength that depends on the spatial position of the illumination in the spectral dimension. The detector behind the device receives light at different wavelengths of the scene. In the spatial dimension each row is
detected by the same wavelength

- with Fourier Transform Spectrometers (FTS, Figure 2.45c). Spatial Domain Fourier Transform Spectrometers use the principle of the monolithic Sagnac interferometer. But unlike a conventional FTS the spectrometer for Earth observation operates with fixed mirrors. The optical design distributes the interferogram (spectrum) in one dimension of the detector. The other dimension of the area array detector corresponds with the swath width.

The most common spectral selection mode for pushbroom sensors is the filter-based one.

![Figure 2.45](image-url)

**Figure 2.45.** Three different modes for spectral selection. (a) dispersion element; (b) filter-based systems; (c) Fourier Transform Spectrometers (Source Nieke et al., 1997).

CCD linear sensors usually acquire images in panchromatic mode or in multispectral mode (Figures 2.46 and 2.47). In Table 2.3 the wavelength ranges of the spectral channels used on satellite and airborne pushbroom sensors are listed.

Advanced multi-spectral sensors for remote sensing applications are the hyperspectral sensors, which detect hundreds of very narrow spectral bands throughout the visible, near-infrared, and mid-infrared portions of the electromagnetic spectrum. Their very high spectral resolution facilitates fine discrimination between different targets based on their spectral response in each of the narrow bands (CCRS Tutorial, 2004).

In general the CCD lines corresponding to each channel are placed one parallel to each other in the focal planes and provide separate strips. The strips for each channel and for each viewing direction are stored separately. Successively, the user may combine the channels of interest for specific analysis.

In some cases the users are not interested in the single channels, but in the resulting image in true or false color. In this case the strips, one for each channel, are combined according to different principles. For example, in case of ADS40 true-color images, during the flight the red, blue and green arrays are directly optically superimposed in order to generate a color line. This is accomplished with dichroic mirrors, which divide a single light ray into its three color components without significant energy loss, followed by narrow-band filtering to increase the channel separation. The great advantage of this approach is that the color image is band registered without significant post-processing and thus results instantly in an attractive color picture. In case of airborne pushbroom imagery, without dichroic mirror arrangement, a high-quality composite from three lines with different nadir-offsets would only become available after rectification using a surface model (Tempelmann et al., 2000).
2.7.4 Temporal resolution

The concept of temporal resolution is usually applied for imagery acquired by satellite systems instead of airborne systems. It is linked to the concept of revisit period, which refers to the length of time needed by a satellite to complete one entire orbit cycle. The revisit period of a satellite sensor is usually several days. The absolute temporal resolution of a remote sensing system is the interval time between two successive acquisitions of the exact same area. In near-polar orbits (Section 2.6.1.1), areas at high latitudes will be imaged more frequently than the equatorial zone due to the increasing overlap in adjacent swaths as the orbit paths come closer together near the poles. Some satellite systems can be manoeuvred and pointed to the target area to reduce the revisit period. Thus, the actual temporal resolution of a sensor depends on a variety of factors, including the satellite/sensor capabilities, the swath overlap and the latitude (CCRS Tutorial, 2004).

The ability to collect imagery of the same area of the Earth’s surface at different periods of time is one of the most important characteristics of the remote sensors. Spectral characteristics of features may change over time and these changes can be detected by collecting and comparing multi-temporal imagery. By imaging on a continuing basis at different times we are able to monitor the changes that take place on the Earth’s surface, whether they are naturally occurring (such as changes in natural vegetation cover or flooding) or induced by humans (such as urban development or deforestation).

For photogrammetric mapping applications, a high temporal resolution (small time interval) is recommended, in order to have small variations between the stereo images. Even with some tens of seconds delay the cloud cover may quickly change and occlude some parts of the images, as shown in Figure 2.48.
2.8 PROCESSING LEVELS

Satellite and airborne images are provided at different processing levels. Taking into account that each image provider uses a different notation and processing level definitions, a general classification of the processing levels is proposed:

- **Level 0**: original data, without radiometric nor geometric processing
- **Level 1A**: radiometrically corrected images. The radiometric calibration coefficients are necessary for this correction. Usually they are calculated before the flight in laboratory experiments and then systematically in special calibration experiments during the flight period
- **Level 1B**: radiometrically and geometrically corrected images with geometric resampling (projection on a reference Ellipsoid or on a horizontal plane)
- **Level 2**: ortho-rectified scenes
- **Further levels**: specific products, according to which applications the sensor is designed for.

For sensors used for photogrammetric mapping these products include the DEM; for other Earth observation sensors, other products are available; for example, for MISR the MISR 2TC (MISR Top of atmosphere Cloud retrievals), the MISR 2AS (MISR Aerosol/Surface retrievals) are produced.

Usually the pushbroom imagery are available on the market in one of the previous processing levels. An exception is made by IKONOS scenes, that are not available at the original (raw) level. IKONOS stereo images are distributed in a quasi-epipolar geometry reference where only the elevation parallax in the scanner direction remains. For along-track stereoscopy with the IKONOS orbit, it corresponds roughly to a north-south track, with a few degrees in azimuth depending upon the across-track component of the total collection angle.

For the topic of this research, level 1A images will be used. These scenes have been only radiometrically but not geometrically corrected, therefore a rigorous model that describes their acquisition geometry can be applied for their georeferencing. As a consequence, images like IKONOS not available at level 1A, can not be oriented with our model.

2.9 LIST OF LINEAR ARRAY SENSORS

The main characteristics of a large number of linear array sensors carried on space- and aircrafts are summarized in Table 2.3 and Table 2.4 respectively.
Table 2.3. Main characteristics of pushbroom sensors carried on spaceborne platforms. L = along track, C = across-track, PAN = panchromatic, NIR = Near Infrared

<table>
<thead>
<tr>
<th>Camera</th>
<th># Cameras</th>
<th>Focal Length (mm)</th>
<th>Viewing Directions</th>
<th>Stereo Angle (deg)</th>
<th>Channels</th>
<th>Wavelength (nm)</th>
<th>Resolution (m)</th>
<th>Ground swath (km)</th>
<th># Pixels/L.</th>
<th>B.H.</th>
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<td>QuickBird-2</td>
<td>1</td>
<td>8800</td>
<td>1</td>
<td>up to ±30</td>
<td>PAN</td>
<td>450-900</td>
<td>0.6</td>
<td>16</td>
<td>27000</td>
<td>Variable</td>
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<td></td>
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<td>450-520</td>
<td>2.4</td>
<td></td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>GREEN</td>
<td>520-600</td>
<td>2.4</td>
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<td>RED</td>
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<td></td>
<td></td>
<td></td>
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<td>C</td>
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<td></td>
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### Section 2.9. LIST OF LINEAR ARRAY SENSORS

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<th>SWATH WIDTH (km)</th>
<th>GROUND RESOLUTION (m)</th>
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<th>FOCAL LENGHT (mm)</th>
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<td>510-760, 610-880</td>
<td>PAN</td>
<td>up to 27</td>
<td>C</td>
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<td>1082</td>
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<td>10</td>
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<td>10</td>
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<td>580</td>
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<td>10</td>
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<td>0.421</td>
<td>L</td>
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<td>0.6</td>
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<td>15</td>
<td>520-800, 760-880</td>
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<td>0.453</td>
<td>L</td>
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<td>215</td>
<td>1</td>
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<td>SWIR</td>
<td>0.453</td>
<td>L</td>
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<td>0.453</td>
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<td>0.453</td>
<td>L</td>
<td>1</td>
<td>215</td>
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</tr>
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<td># CAMERAS</td>
<td># VIEWING DIRECTIONS</td>
<td>STEREO</td>
<td>STEREO ANGLES (deg)</td>
<td>CHANNELS</td>
<td>WAVELENGTH (nm)</td>
<td>GROUND RESOLUTION (m)</td>
<td>SWATH WIDTH (km)</td>
<td># PIXELS/LINE</td>
<td>BH</td>
<td></td>
</tr>
<tr>
<td>-----------</td>
<td>----------------------</td>
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<td>---------------------</td>
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<tr>
<td>EOS-AM1/MISR</td>
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<td>555</td>
<td>670</td>
<td>685</td>
<td>275-1100</td>
<td>275-1100</td>
</tr>
</tbody>
</table>

a. this one-lens sensor has the ability to rotate and acquire stereo images up to a certain off-nadir angle
b. after resampling
Table 2.4. Main characteristics of pushbroom sensors carried on airborne platforms.

<table>
<thead>
<tr>
<th>COMPANY</th>
<th># CAMERAS</th>
<th>FOCAL LENGTH (mm)</th>
<th># VIEWING DIRECTIONS</th>
<th>STEREO ANGLES (deg)</th>
<th>CHANNELS</th>
<th>WAVELENGTH (nm)</th>
<th>GROUND RES. (m)</th>
<th>PLATFORM</th>
<th># PIXELS/LINE</th>
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<td>ADS-40 LH-Systems</td>
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<td>80</td>
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<td>A</td>
<td>Variable</td>
<td>465-680</td>
<td>0.24@2000m</td>
<td>Airplane</td>
<td>12000</td>
</tr>
<tr>
<td>SI-250 Starfabo</td>
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<td>60</td>
<td>3</td>
<td>A</td>
<td>17,23,40</td>
<td>N/A</td>
<td>N/A</td>
<td>Helicopter</td>
<td>14400</td>
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<td>SI-290 Starfabo</td>
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<td>93</td>
<td>3</td>
<td>A</td>
<td>15,23,38</td>
<td>N/A</td>
<td>N/A</td>
<td>Helicopter*</td>
<td>14400</td>
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<td>175</td>
<td>3</td>
<td>A</td>
<td>0.±19</td>
<td>PAN BLUE GREEN RED NIR</td>
<td>0.10@2500m</td>
<td>Airplane</td>
<td>5186</td>
</tr>
<tr>
<td>DPA DLR</td>
<td>1</td>
<td>80</td>
<td>3</td>
<td>A</td>
<td>0, ±37</td>
<td>PAN MS</td>
<td>0.30 @2300m</td>
<td>Airplane</td>
<td>12000</td>
</tr>
<tr>
<td>AirMISR NASA</td>
<td>9</td>
<td>59, 59, 73, 95, 124</td>
<td>9</td>
<td>A</td>
<td>0, ±26.1, ±55.6, ±60.0, ±70.5</td>
<td>BLUE GREEN RED NIR</td>
<td>from 7 x 6 to 21 x 55 @20000</td>
<td>Airplane</td>
<td>376/1504</td>
</tr>
<tr>
<td>3-DAS-I Wehrli Association / Geosystems</td>
<td>3</td>
<td>35 or 60 or 100</td>
<td>3</td>
<td>A</td>
<td>0, -16.26</td>
<td>BLUE GREEN RED</td>
<td>0.06@500m or 3x6000 or 3x8000 or 3x12000</td>
<td>Airplane</td>
<td></td>
</tr>
</tbody>
</table>

*Normally, some tests on airplane
2.10 CONCLUSIONS

In this Chapter the geometric acquisition of pushbroom sensors has been investigated. For the development of a rigorous orientation model for these sensors, these aspects must be taken into account:

- the optical system (single or multi-lens) and the lens distortion
- the CCD line design and systematic errors (rotations, shifts and bending in the focal plane)
- the integration of internal orientation parameters measured with laboratory calibration
- the platform and therefore the approaches for the external orientation modelling (including the integration of GPS and INS measurements).

On the market a large variety of imagery at different spatial, temporal, spectral and radiometric resolutions are potentially available for the users.

The choice of the imagery, including the processing level, depends on different factors:

- applications. This is the main issue. As Figure 2.49 shows, the combination of spatial and spectral resolutions may provide images with characteristics suitable for specific applications
- costs. In general the higher the resolution is, the higher the price is. Additionally, imagery provided by private companies are more expensive than imagery provided by national space agencies
- software availability. For the orientation of pushbroom images suitable algorithms must be implemented. An alternative is to use commercial software available on the market
- experience.

Figure 2.49. Combination of spectral and spatial resolution for the specific applications (Source LH-Systems, 2004).
As seen in Chapter 2, each image acquired by CCD linear array sensors consists of lines independently acquired at different times and with a different sensor external orientation (position, attitude). Today geopositioning systems provide the direct measurement of the sensor position and attitude at certain instants of time, then accurate interpolation techniques allow the calculation of the corresponding data at any time and for each image line. Furthermore the satellite trajectories can be predicted or simulated by using the physical properties of the satellite orbits. This information, together with suitable interpolating techniques, may be used to calculate the sensor position and attitude for the particular instants of acquisition and apply a direct georeferencing.

The principle of direct georeferencing is to estimate the ground coordinates of the homologous points measured in the images through a forward intersection using as internal orientation the results of laboratory calibrations (Section 2.4) and as external orientation the data provided by the geopositioning systems carried on the platform, or the trajectory calculated by mathematical formulas (only for satellite-based sensors). This approach does not require any ground control points, except for final checking, and does not estimate any additional parameters modeling the interior and exterior orientation. For this reason, the effectiveness and reliability of this method depend on the accuracy of the internal and external orientation data. The alternative approach, called indirect georeferencing and based on the estimation of the sensor orientation through a bundle adjustment, is treated in Chapter 4.

The sensor model developed for the orientation of pushbroom imagery includes both the direct and indirect georeferencing approaches. The former is investigated in this Chapter. After the description of the methods used for the direct measurement of the sensor external orientation (GPS/INS instruments in Section 3.1 and the analysis of satellite orbits in Section 3.2), the mathematical model for direct georeferencing is presented in Section 3.3. A special attention is paid to the integration of GPS and INS data into the photogrammetric model (Section 3.4). Finally Section 3.6 will summarize the conclusions on the direct georeferencing approach.
Chapter 3. DIRECT GEOREFERENCING

3.1 EXTERNAL ORIENTATION FROM GPS/INS

3.1.1 Background

The traditional way for the georeferencing of spaceborne and airborne imagery is to use ground control points, which represents a big cost for photogrammetric projects. The determination of the external orientation has always constituted an important topic of the photogrammetric processing. It was Seb. Finsterwalder who, about 90 years ago, called it the fundamental problem of aerophotogrammetry (Ackermann, 1986). Many attempts have been made in the past to measure and record the external orientation elements, mostly in aerial photogrammetry applications. Those efforts, however, were not or only partly successful, as the tools were either not accurate enough or too expensive. Remarkable exception are the statoscope and the APR (Airborne Profile Recorder), which succeeded in providing accurate vertical camera position or terrain elevation data (Ackermann, 1986). Today differential kinematic GPS positioning is a standard tool for determining the camera exposure centres not only for aerial triangulation (Heipke et al., 2002), but also for satellite positioning. Tests conducted in the last few years demonstrated the quasi total reduction of GCPs for aerial triangulation, if accurate GPS and INS observations are available. The OEEPE test in 2001 showed that direct georeferencing is a serious alternative to classical and GPS-assisted bundle adjustment and currently allows for the generation of orthophotos and other products with less stringent accuracy requirements. Few GCPs are essentially only necessary for calibration, for detecting and eliminating GPS errors such as cycle slips, for reliability purposes and possibly for datum transformations (see OEEPE test results in 2001, described by Heipke et al., 2001).

The importance of measurement systems like GPS and INS is even stronger in case of the georeferencing of imagery acquired by pushbroom sensors. In fact with these sensors a bundle adjustment is unrealistic, because the number of unknown external orientation parameters (six for each image line!) would be too large. Moreover in case of airborne pushbroom sensors, the aircraft trajectory cannot be predicted and modelled, as in the satellite case. Therefore the direct measurement of the sensor position and attitude is indispensable.

In the next paragraphs, the main principles of the direct measurement of the camera external orientation with GPS and INS systems are presented.

3.1.2 GPS system

The GPS (Global Positioning System), officially also known as NAVSTAR (Navigation and Satellite Timing and Ranging), is part of a satellite-based navigation system developed by the U.S. Department of Defense (DoD) and is operational since 27th April 1995.

GPS provides two levels of service: the Standard Positioning Service (SPS) and the Precise Positioning Service (PPS). The SPS is a positioning and timing service which is available to all GPS users on a continuous, worldwide basis with no direct charge, while the PPS is a highly accurate military positioning, velocity and timing service which is available on a continuous, worldwide basis to users authorized by the U.S.

The GPS consists of three major segments: space, control and user segment (U.S. Naval Observatory, 2004). The space segment is a set of satellites providing known locations for resection, the ground segment is a set of ground control stations that communicate with the satellites and determine their locations and the user segment includes all military and civilian users of the system. The segments work together to implement the positioning procedure: the control stations locate the satellites precisely in space, each satellite generates radio signals that allow a receiver (user)

2. The main reference for this Section is Jekeli, 2001, Chapter 9.
to estimate the satellite location and the distance between the satellite and the receiver; then the receiver uses those measurements to calculate where on the Earth the user is located. The space segment consists of 24 operational satellites in six orbital planes (four satellites in each plane). The orbits are circular with a radius of 20,200 km, an inclination angle of 55° and a period of 12 hours. The position is therefore the same at the same sidereal time each day, i.e. the satellites appear 4 minutes earlier each day.

The control segment consists of five Monitor Stations (Hawaii, Kwajalein, Ascension Island, Diego Garcia, Colorado Springs), three Ground Antennas (Ascension Island, Diego Garcia, Kwajalein) and a Master Control Station (MCS) located at Schriever AFB in Colorado. The monitor stations passively track all satellites in view, accumulating ranging data. This information is processed at the MCS to determine satellite orbits and to update each satellite’s navigation message. Updated information is transmitted to each satellite via the Ground Antennas.

The user segment consists of antennas and receivers processors that provide positioning, velocity and precise timing to the user. The receivers contain an antenna that captures signals from visible satellites, a clock that internally generates signals to synchronize with the incoming satellite signal and a hardware and software system that process the signals and calculate the receiver’s location. The receivers characteristics that can impact the accuracy are: the frequency (single vs. dual), the number of channels available to track satellites (i.e. how many satellites can be tracked simultaneously), whether they are differential-ready and whether they use carrier signals in some fashion. Other receivers characteristics that may influence the choice of a system with respect to another one include: the size, the cost, the battery life and the interoperability with other systems like personal computers.

3.1.2.1 GPS signal

The signal transmitted by the GPS satellites is a carrier wave (sinusoidal) modulated in phase by binary codes. Mathematically, the signal $S(t)$ (or one component of it) may be represented by

$$ S(t) = AC(t)D(t)\cos(2\pi ft) $$

where $A$ and $f$ are the amplitude and the frequency of the signal, $C(t)$ is the code sequence, a step function having values (1, -1), also known as chips or bits. $D(t)$ represents a data message.

The total GPS signal includes two microwave carrier signals (L1 and L2), two code sequences (C/A and P) and the data message $D(t)$. L1 and L2 have frequencies $f_1 = 1575.42$ MHz and $f_2 = 1227.6$ MHz. L1 carries the navigation message and the SPS code signals, while L2 is used to measure the ionospheric delay by PPS equipped receivers.

The two codes that are applied on the microwave carrier signals are (Dana, 2004):

- the C/A Code (Coarse Acquisition). It is a repeating 1 MHz Pseudo Random Noise (PRN) Code that modulates the L1 carrier signal, “spreading” the spectrum over a 1 MHz bandwidth. There is a different C/A code PRN for each station vehicle

- the P-Code (Precise), that modulates both the L1 and L2 carrier phases. This code is a very long (seven days), 10 MHz PRN. In the Anti-Spoofing (AS) mode of operation, the P-Code is encrypted into the Y-Code and requires cryptographic keys for use.

Finally, the Navigation Message ($D(t)$) modulates the L1-C/A code signal. The Navigation Message is a 50 Hz signal consisting of data bits that describe the GPS satellite orbits, clock corrections and other system parameters.

The total signal transmitted by a GPS satellite $p$ results

$$ S^p(t) = A_pP^p(t)W^p(t)D^p(t)\cos(2\pi f_1 t) + A_cC^p(t)D^p(t)\sin(2\pi f_1 t) + B_pP^p(t)W^p(t)D^p(t)\cos(2\pi f_2 t) $$

55
Chapter 3. DIRECT GEOREFERENCING

\( C(t) \) and \( P(t) \) represent the C/A and P codes, \( A_P, A_C \), and \( B_p \) are their amplitudes, \( D(t) \) is the data message and \( W \) represents a special code which is used to decrypt a military code (Jekeli, 2001, p.263). Due to the spread spectrum characteristic of the signals, the system provides a large margin of resistance to interference. Each satellite transmits a navigation message containing its orbital elements, clock behavior, system time and status messages. In addition, an almanac is also provided which gives the approximate data for each active satellite. This allows the user set to find all satellites once the first has been acquired (U.S. Naval Observatory, 2004).

3.1.2.2 GPS observables

At the user segment level, the antenna receives the signal coming from the satellites, recognizes the satellite (through C/A code) and generates a signal copy. The correlation between the codes of the incoming and outcoming signals is used for the analysis. The delay of the incoming satellite codes with respect to the identical codes generated by the receiver represents the time on transit of the satellite codes from the satellite to the receiver. Multiplied by the speed of the light, the resulting distance is not the true range between receiver and satellite, but the pseudorange, because it includes the time lapses due to clock errors, the propagation medium effects, the multipath and receiver electronic delays. Disregarding these errors, the observed code delay is the range between the satellite at the point in its orbit when it transmits the signal and the receiver at the point on the rotating Earth when it receives the signal. The pseudorange is time-tagged by the receiver clock.

The other type of observable available on all geodetic receivers is the difference between the phase of the receiver-generated carrier signal at the time of reception and the phase of the satellite signal at the time of transmission (which arrives at the receiver unaltered except from the propagation effects that similarly corrupt the code measurement). Since the phases are created by the clocks, or frequency generators, of the receiver and satellite, the oscillator phase is equivalent to indicated (or tagged) time. As with the pseudoranges, the time interval of transit of the phases is fraught with errors due to the atmospheric refraction, the multipath, the equipment delays and the geometric offsets of the phase center from the geometric center of the receiver antenna and the offset of the satellite antenna from the center of mass.

The largest error is due to the receiver clock. The next significant error source is the medium where the signal travels: the Ionosphere (between 50 km and 1000 km), which has many free electrons, and the Troposphere (between the Earth surface and 40 km), which is a non-dispersive medium with mostly electrically neutral particles. Both effects can be described by suitable physical models. Other errors in GPS observables include the multipath error (the reflection of the GPS signal from nearby objects prior to entering the antenna), the equipment delays and biases, the antenna eccentricities (phase center variations) and the thermal noise of the receiver (Jekeli, 2001, p.270).

3.1.2.3 Position estimation

The basic principle for position estimation is the measurement of distance between the receiver and the satellites using a combination of pseudorange and carrier phase observations in order to remove the constant errors contained in the observations. Some of these errors do not change in time, such as clock biases and the phase ambiguity, other change more slowly and other have a long correlation time, such as tropospheric delays. In addition, there are some error terms common to different observations that correspond to different receiver-satellite combinations. Using simultaneous observations of pseudorange and carrier phases from several different satellites it is possible to solve for these and other unknown error terms using an optimal estimation technique, such as a least-squares adjustment. This procedure is known as absolute (point) positioning, since
the position vector of the observer is to be determined from GPS observations independent of any other point. A more accurate method uses differences between simultaneous observations from different receivers, thus cancelling the common mode terms and greatly reducing the effect of some slowly varying error terms. This procedure is known as relative positioning, or differential positioning, and yields only the difference in coordinates between two points. If the absolute coordinates of one point are known, then the relative positioning also yields subsequently the absolute coordinates of the other point. It is also important to distinguish between static positioning and kinematic positioning. As the name implies, static positioning involves placing the receiver at a fixed location on the Earth and determining the position of that point. Kinematic positioning, on the other hand, refers to determining the position of a vehicle or platform that is moving continually with respect to the Earth. This could be attempted either in real time or usually with higher accuracy in a post-mission mode. There is an intermediate mode of positioning, known as semi-kinematic positioning, whereby the moving receiver (or antenna) is temporarily brought to rest at those points to be positioned, before moving to the next point, at all times maintaining signal lock.

In our case, as the GPS antenna moves with the platform (aircraft or satellite), the processing used for the estimation of the position is a post-mission differential kinematic positioning, also indicated with the acronym DGPS (Differential GPS).

3.1.3 INS system

The Inertial Navigation System (INS) is an instrument for the measurement of linear rates and linear changes in rates (accelerations) along a given axis. The basic INS consists of an Inertial Measurement Unit (IMU) or Inertial Reference Unit (IRU), a navigation computer and a clock. The IMU contains a cluster of sensors (gyroscopes and accelerometers), that are mounted to a common base to maintain the same relative orientations.

Gyroscopes are instruments that sense angular rate and are used to give the orientation of an object (angles of roll, pitch and yaw). Rate gyroscopes measure rotation rates, while displacement gyroscopes (also called whole-angle gyroscopes) measure rotation angles.

Accelerometers sense a linear change in rate (acceleration) along a given axis. However, they cannot measure gravitational acceleration, that is an accelerometer in free fall or in orbit has no detectable input. The input axis of an inertial sensor defines which vector component it measures. The IMU uses a combination of gyroscopes and accelerometers to maintain an estimate of the position, velocity, attitude and attitude rates of the vehicle in or on which the INS is carried.

In a typical inertial navigation system, there are three mutually orthogonal gyro and three mutually orthogonal accelerometers. This configuration gives three orthogonal acceleration components which can be vectorially summed. Combining the gyro-sensed orientation information with the summed accelerometer outputs yields the IMU's total acceleration in 3D space. At each time-step of the system's clock, the navigation computer time integrates this quantity once to get the body's velocity vector. The velocity vector is then time integrated, yielding the position vector. These steps are continuously iterated throughout the navigation process.

The inertial navigation systems are classified into two main groups: the gimbaled and the strap-down systems (Figure 3.1). In a gimbaled system the accelerometer triad is rigidly mounted on the inner gimbal of three gyro's. The inner gimbal is isolated from the vehicle rotations and its
attitude remains constant in a desired orientation in space during the motion of the system. The gyroscopes on the stable platform are used to sense any rotation of the platform and their outputs are used in servo feedback loops with gimbal pivot torque actuators to control the gimbals such that the platform remains stable. These systems are very accurate, because the sensors can be designed for very precise measurements in a small measurement range.

A strapdown inertial navigation system uses orthogonal accelerometers and gyro triads rigidly fixed to the axes of the moving vehicle. The angular motion of the system is continuously measured using the rate sensors. The accelerometers do not remain stable in space, but follow the motion of the vehicle.

![Diagram of Strapdown and Gimbaled Systems](image)

Figure 3.1. Inertial measurement units: strapdown (a) and gimbaled (b) systems (Grewal et al., 2001, p.12).

As the accuracy concerns, both gyroscopes and accelerometers measurements may contain errors. The common error sources for gyroscopes are: the output bias, the input axis misalignments, the combined (clustered) three-gyroscopes compensation, the input/output non-linearity and the acceleration sensitivity. The main error sources for accelerometers are: the biases, the parameter instabilities (i.e. turn-on and drift), the centrifugal acceleration effects due to high rotation rates, the center of percussion and the angular accelerometer sensitivity.

Since there is no single, standard design for an INS, the system-level error sources vary very much. General error sources can be classified as:

- initialization errors, coming from initial estimates of position and velocity
- alignment errors, for the initial alignment of gimbals or attitude direction cosines (for strapdown systems) with respect to navigation axes
- sensor compensation errors, due to the change in the initial sensor calibration over the time
- gravity model errors, that is, the influence of the unknown gravity modeling errors on vehicle dynamics.

### 3.1.4 GPS/INS Integration

Table 3.1 summarizes the main characteristics of the data provided by GPS and INS systems. GPS offers the possibility to determine position and velocity information at a very high absolute

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5. The main reference for this Section is Skaloud, 1999, Chapter 2 and Jekeli, 2001, Chapter 10.3.
accuracy. The accuracy level is dependent on the processing approach (absolute, relative), the type of observable (pseudorange, doppler, phase measurements) and the actual satellite geometry. To obtain highest accuracy the differential phase observations are used. Solving the ambiguities correctly and assuming a reasonable satellite geometry, a positioning accuracy up to 10cm is possible for airborne kinematic environments with remote-master receiver separation below 30km. The typical accuracy for the velocity determination is at the level of a few cm/s (Cramer, 1999). In contrast to this, inertial systems provide very high relative accuracy for position, velocity and attitude information, but the absolute accuracy decreases dependent on runtime if the system is working in stand-alone mode and no external update measurements are available.

Table 3.1. Main characteristics of GPS and INS as precision positioning devices (Jekeli, 2001, p.308).

<table>
<thead>
<tr>
<th></th>
<th>GPS</th>
<th>INS</th>
</tr>
</thead>
<tbody>
<tr>
<td>measurement principle</td>
<td>distances from time delays</td>
<td>inertial accelerations</td>
</tr>
<tr>
<td>system operation</td>
<td>reliance on space segment</td>
<td>autonomous</td>
</tr>
<tr>
<td>output variables</td>
<td>positions, time</td>
<td>positions, orientation angles</td>
</tr>
<tr>
<td>long-wavelength errors</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td>short-wavelength errors</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>data rate</td>
<td>low (less than 1Hz)</td>
<td>high (larger than 25Hz)</td>
</tr>
<tr>
<td>instrument cost</td>
<td>low ($20,000, geodetic quality)</td>
<td>high ($100,000, med/high accuracy)</td>
</tr>
</tbody>
</table>

These contrasting characteristics make GPS and INS systems complementary, rather than competitive and motivate their integration for precise positioning applications. An optimal integration allows fully exterior orientation determination with improved overall accuracy and at higher reliability compared to stand-alone units (Cramer et al., 2000b). In fact INS provides directly the dynamics of the motion between GPS epoch at high temporal resolution, complements the discrete nature of GPS and aids the positioning solution in the events of cycle slips or losses in the signal. Table 3.2 summarizes the benefits of GPS/INS integration.

Table 3.2. Benefits of INS/GPS integration (Skaloud, 1999, p.32).

<table>
<thead>
<tr>
<th></th>
<th>GPS</th>
<th>INS</th>
<th>DGPS/INS</th>
</tr>
</thead>
<tbody>
<tr>
<td>high position velocity accuracy over the long term</td>
<td>high position velocity accuracy over the short term</td>
<td>high position and velocity accuracy</td>
<td></td>
</tr>
<tr>
<td>noisy attitude information (multiple antenna arrays)</td>
<td>accurate attitude information</td>
<td>precise attitude determination</td>
<td></td>
</tr>
<tr>
<td>uniform accuracy, independent of time</td>
<td>accuracy decreasing with time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>low measurement output rate</td>
<td>high measurement output rate</td>
<td>high data rate</td>
<td></td>
</tr>
<tr>
<td>non-autonomous</td>
<td>autonomous</td>
<td>navigational output during GPS signal outages</td>
<td></td>
</tr>
<tr>
<td>cycle slip and loss of lock</td>
<td>no signal outages</td>
<td>cycle slip detection and correction</td>
<td></td>
</tr>
<tr>
<td>not sensitive to gravity</td>
<td>affected by gravity</td>
<td>gravity vector determination</td>
<td></td>
</tr>
</tbody>
</table>
There are different strategies for the integration of GPS and INS measurements. A first distinction is between open and close loops, according as the estimated sensor errors are fed back to correct the measurements or not. Then the types of integration can be categorized in two ways:

1. by the extent to which the data from each component aid the other’s function (mechanization, architecture of the system). The mechanization is generally related to the concept of coupling, that is the degree to which software components/modules depend upon each other (no coupling implies no data feedback from either instrument to the other for the purpose of improving its performance). The degree to which components are linked defines whether they operate in a tightly coupled relationship or in a loosely coupled relationship. Tight coupling is a form of integration in which each component has knowledge of the other component. The resulting data are produced simultaneously and optimally and used to enhance the function of individual sensor components, where possible. Thereby a change in one object will affect the other object. In loose coupling, one component does not have knowledge of the other and thereby is insulated from changes in the other. The processed data from one instrument are fed back in an aiding capacity to improve the utility of the other instruments’ performance, but each instrument still has its own individual data processing algorithm (Hattori et al., 2000). In case of GPS/INS integration, the real-time feedback of INS velocities to the GPS receiver enables an accurate prediction of GPS pseudorange and phase at next epoch, thus allowing a smaller bandwidth of the receiver tracking loop in a high-dynamic environment with a subsequent increase in accuracy. Conversely, inertial navigation improves if the GPS solution functions as an update in a Kalman filter estimation of the systematic errors in the inertial sensors. Similarly, GPS positions and velocities may be used to aid the INS solution in a high-dynamic situation by providing a better reference for propagating error states based on the linear approximation.

2. by the method of combining or fusing the data to obtain position accuracy. The processing algorithms for the data combination or fusion may be classified as centralized and decentralized. Centralized processing are usually associated to tight coupling system integration, because the raw sensor data are combined optimally using one central processor (e.g. Kalman filter or smoother) to obtain a position solution. Decentralized processing is a sequential approach to processing, where processors of individual systems provide solutions that subsequently are combined with various degrees of optimality by a master processor. In principle, if the statistics of the errors are correctly propagated, the optimal decentralized and centralized methods should yield identical solutions. In some certain cases, such as system fault detection, isolation and correction capability, the relative computational simplicity makes the decentralized approach more favorable. As navigation and positioning applications concern, the centralized approach is considered to yield the best performance, especially since error statistics can be more rigorously modeled and propagated within the single Kalman filter (smoother).

Table 3.3 gives an overview of the advantages and disadvantages of four combined methods for GPS and INS integration (open loops, closed loops, decentralized loosely coupled and centralized tightly coupled).

If properly designed, the closed-loop implementation generally has better performance and is therefore the preferred implementation when using a strapdown INS. The loosely-coupled filtering approach has been highly popular due to its modularity and smaller filter size. Although the arguments for choosing either form of the implementation have been very balanced, the tightly-coupled approach is currently gaining more weight mainly due to the rapid increase in computational power.
Section 3.1. EXTERNAL ORIENTATION FROM GPS/INS

In conclusion, the performance of an integrated INS/DGPS is a complex process depending on a variety of parameters including the quality and type of inertial sensors, the baseline length, some operational aspects, the validity of error models and the estimation algorithm. The improvements in trajectory determination are usually sought in the development of better models and estimation algorithms. With the rapid increase of computational power, the trend of finding the most suitable error model for a specific system and specific conditions is being replaced by using a multi-model approach in conjunction with some type of adaptive estimation. Another limiting factor is the band frequency. In the lower frequencies, the INS/DGPS integration reduces the overall error and in the high frequencies, the overall error is not reduced.

<table>
<thead>
<tr>
<th>IMPLEMENTATION</th>
<th>ADVANTAGES</th>
<th>DISADVANTAGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open loop</td>
<td>• KF may be run external to INS, suitable for platform INS • used when only navigation solution from INS is available</td>
<td>• Non-linear error model due to large second-order effect • Extended KF needed</td>
</tr>
<tr>
<td>Closed loop</td>
<td>• Inertial system errors, line model is sufficient • Suitable for integration at software level</td>
<td>• More complex processing • Blunders in GPS may affect INS performance</td>
</tr>
<tr>
<td>Loosely coupled (decentralized)</td>
<td>• Flexible, modular combination • Small KF, faster processing • Suitable for parallel processing</td>
<td>• Sub-optimal performance • Unrealistic covariance • Four satellites needed for a stable solution • INS data not used for ambiguity estimation</td>
</tr>
<tr>
<td>Tightly coupled (centralized)</td>
<td>• One error state model • Optimal solution • GPS can be used with less than 4 satellites • Direct INS aiding throughout GPS outages • Faster ambiguity estimation</td>
<td>• Large size of error state model • More complex processing</td>
</tr>
</tbody>
</table>

3.1.5 Commercial systems

Nowadays different commercial systems are available for the acquisition and integration of GPS and INS data. They provide the time, position and attitude of the instruments at each time exposures. Among these systems, the POS/AV by Applanix and the AEROcontrol by IGI mbH (Ingenieur-Gesellschaft für Interfaces mbH) are the most used. The potentials of these systems for direct georeferencing have been also investigated during the OEEPE test “Integrated Sensor Orientation” (Heipke et al., 2002).

**Applanix.** Applanix is the company leader in this sector. Its POS/AV system is one of the most used positioning instrument for photogrammetric applications. According to the data provided in Applanix, 2004, the accuracy that can be reached with high bandwidth is 0.005° for pitch and roll, 0.008° in heading (POS/AV 510 - post-processed) and 5-10cm sensor positioning (post-processed) at 200Hz data rates. The system is compact, with a lightweight IMU and flexible (different post-processing operations can be done in real-time, like differential GPS, time alignment of airborne sensors and stabilized platforms). For more information, see Applanix, 2004.
AEROcontrol. This system consists of a fibre-optic gyro based IMU and a computer with an integrated 12-channel L1/L2 GPS receiver. Depending on GPS constellation and distance from GPS Base/Monitor Station, a positioning accuracy better than 10cm RMSE and attitude accuracy of 0.01° RMSE for heading and of 0.005° RMSE for roll and pitch can be reached in post-processing. The airborne computer of the AEROcontrol system is used for data recording of IMU raw data, i.e. angular and acceleration increments at 64Hz, 128Hz or 256Hz and GPS raw data, i.e. positions and velocities, at 1Hz or 2Hz. For more details, see IGI, 2004.

Figure 3.2. Two commercial systems for the direct measurement of the position and attitude with GPS and INS: Applanix POS/AV (left, source Applanix, 2004) and IGI mbH AEROcontrol (right, source IGI, 2004).

3.2 EXTERNAL ORIENTATION FROM EPHEMERIS

For the imagery acquired by pushbroom sensors carried on satellite, the sensor external orientation can be computed from the physical properties of the orbits, through the Keplerian elements, or from the state vectors contained in the ephemeris. In the following paragraphs the calculation of an approximative sensor external orientation according to two different approaches is described.

Before going into details, we introduce some reference systems that will be mentioned in the text: the orbital plane system, the orbit system, the ECI and the ECR.

The orbital plane system (Section B.9) is a two dimensional frame with origin in the focus of the orbit occupied by the Earth; x-axis lies on the semi-major axis and points towards the perigee, while the y-axis lies in the orbital plane and is perpendicular to x-axis (Figure 3.7).

The orbit system (Section B.8), indicated with O, is a right-hand coordinate system with its origin at the spacecraft’s center of mass. The z-axis is aligned with the spacecraft-to-Earth pointing vector. The x-axis points along the satellite trajectory, therefore in the direction of the spacecraft velocity vector. The y-axis is defined by the cross product of the z-axis and the x-axis (Figure 3.3).

The Earth Centered Inertial system (ECI, Section B.4, Figure 3.4) has the origin in the centre of gravity of the Earth. The Z-axis points toward the North Pole, the X-axis lies in the equatorial plane and is directed toward the vernal equinox (JR2000), while the Y-axis completes a right handed orthogonal system (Figure 3.6b).

The Earth Centered Reference system (ECR, Section B.5, Figure 3.5) is fixed with respect to the Earth. The origin is in the centre of gravity of the Earth, the Z-axis points toward the North Pole, the X-axis is the intersection of the plane defined by the prime meridian (Greenwich) and the equatorial plane and the Y-axis completes a right handed orthogonal system.
3.2.1 Orientation with Keplerian elements

As mentioned in Section 2.6.1.1, the satellites move along an orbit, whose shape can be described using the well-known Keplerian elements. According to Keplerian laws, satellites move in a plane describing an elliptic orbit which can be identified with a set of six orbital parameters, called snapshot. These six parameters are:

- $a$ (semi-major axis): distance between perigee (point where the satellite is nearest the Earth) and apogee (point where the satellite is furthest from the Earth)
- $i$ (inclination): the angle between the orbital plane and the equatorial plane. By convention, inclination is a number between 0° and 180°
- $\omega$ (argument of perigee): the angle between the nodal line and the semi-major axis, measured from the ascending node to the perigee. The nodal line is the intersection line between the orbital plane and the equatorial plane
- $e$ (eccentricity): a number between 0 and 1 describing the "shape" of the ellipse: when $e$ is equal to 0, the ellipse is a circle, when $e$ is very near 1, the ellipse is very long and skinny. It is calculated as the ratio between the focal distance and the major axis
- $F$ (true anomaly): angle measured in the centre of the ellipse between the perigee and the posi-
tion of the satellite at epoch T. It marches uniformly in time from 0° to 360° during one revolution. It is defined to be 0° at perigee, and therefore is 180° at apogee

- Ω (right ascension of ascending node): angle measured at the centre of the earth from the vernal equinox to the ascending node. It is in the range 0° to 360°.

Figure 3.6 gives a representation of the Keplerian parameters in the orbital plane and in the ECI system.

![Figure 3.6. Representation of Keplerian parameters in orbital plane (a) and ECI systems (b).](image)

The position and orientation of a satellite along its orbit in the ECI system can be calculated using the above-described Keplerian parameters. The assumption is that the satellite is subjected to the gravitational force only and no perturbations occur. Therefore the satellite moves on a plane.

We call P the point representing the satellite. According to Figure 3.7 and using the notation for Keplerian elements introduced above, the position of P in the orbit system is described by the vector r with components

\[
r = \begin{bmatrix} 0 \\ 0 \\ |r| \end{bmatrix}
\]

The module of r represents the radius

\[
|r| = a \frac{1 - e^2}{1 + e \cos F}
\]

As the satellite moves on the orbital plane, the third components of the vector r is null.

Referring to Figure 3.6b, the orbit system can be rotated into the ECI one through the rotation matrix \( R_o^{ECI} \) (Neto, 1992). The coordinates of P in the ECI system (vector \( x_{ECI} \)) are

\[
x_{ECI} = R_o^{ECI} r
\]

The rotation matrix \( R_o^{ECI} \) is the combination of rotations around Z, X and Z axis

\[
R_o^{ECI} = R_z\left(-\frac{\pi}{2}\right) R_x\left(-\frac{\pi}{2}\right) R_z(U) R_x(I) R_z(\Omega)
\]

The angle U is defined as
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\[ U = \omega + F \] (3.7)

The complete rotation matrix results

\[
R^E_{\text{eci}} = \begin{bmatrix}
-sinU \cdot cos\Omega - sin\Omega \cdot cosi \cdot cosU & -sin\Omega \cdot sini \cdot cosU \cdot cos\Omega + sin\Omega \cdot cosi \cdot sinU \\
-sin\Omega \cdot sinU + cosU \cdot cosi \cdot cos\Omega & sini \cdot cos\Omega \cdot sinU - sin\omega \cdot cosU - cos\Omega \cdot cosi \cdot sinU \\
sini \cdot cosU & -cosi & -sini \cdot sin\Omega \\
\end{bmatrix}
\] (3.8)

In reality the orbit deviates from the elliptic form due to disturbing non-central forces, that can be modelled as linear angular changes of \( F \) and \( \Omega \) with time. The principal component of these forces is the 2nd degree zonal component \( J_2 \) of the Earth gravitational potential. The first order perturbations caused by \( J_2 \) are given by (Kaula, 1966) and are described by

\[
\begin{align*}
\Omega &= -\frac{3}{2} \cdot \frac{J_2 \cdot n \cdot R_e^2}{a^2 \cdot (1 - e^2)} \cdot \cos(i) + v \\
\omega &= -\frac{3}{4} \cdot \frac{J_2 \cdot n \cdot R_e^2}{a^2 \cdot (1 - e^2)} \cdot [1 - 5 \cdot \cos(i)^2] \\
M' &= -\frac{3}{4} \cdot \frac{J_2 \cdot n \cdot R_e^2 \cdot (3 \cdot \cos(i)^2 - 1)}{a^2 \cdot (1 - e^2)^{3/2}}
\end{align*}
\] (3.9)

where \( R_e \) is the Earth’s semi-major axis, \( v \) is the Earth rotation, \( n \) is the mean motion of the satellite and \( M \) is the mean anomaly.

![Figure 3.7. Orbital plane system.](image)

**3.2.2 Orientation from state vectors**

The ephemeris contain information that varies from one space agency to the other. In general, a state vector is a set of position, velocity and attitude values for a particular time. The number of state vectors, the time interval between the observations and the reference systems used are also varying according to the space agency.

The position, velocity and attitude are usually measured with instruments carried on board. The star trackers, for example, take an image a region of the sky using a CCD-like optical camera, and compare successive images to determine how much the orientation of the satellite has drifted. This information is used by the spacecraft pointing system to determine the actual pointing direction of the satellite at any instant. In other satellites, this information is sent to an attitude control system which then corrects for the drift by using on-board thrusters or other motion-generating devices to maintain the correct satellite pointing (Image, 2004).
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The position and velocity vectors of the satellite contained in the ephemeris are used to calculate the orientation of the orbital system with respect to the ECI and ECR systems. The difference between the two frames is that ECI is an inertial system, therefore it does not rotate and is fixed with respect to the celestial frame. On the other hand, the ECR is fixed with respect to the Earth frame and is synchronized with the Earth’s rotation. In both systems the $X$- and $Y$-axes lay on the equatorial plane and $Z$ is directed along the Earth rotation axis, but in case of ECI system $X$ is directed toward the vernal equinox (fixed in the celestial frame), while in case of ECR system $X$ is directed toward the Greenwich meridian (solid for the Earth’s rotation). The transformation between ECI and ECR frames is the following rotation around the $Z$-axis

$$
\begin{bmatrix}
X' \\
Y' \\
Z_{ECR}
\end{bmatrix}
= R_z(\theta)
\begin{bmatrix}
X \\
Y \\
Z_{ECI}
\end{bmatrix}
$$

(3.10)

The rotation angle, called $\theta$, is the angle between the meridian of the point $P$ and the meridian passing by the vernal equinox, or the longitude of $P$ with respect to the vernal equinox. It is called local sidereal time.

Due to the terrestrial rotation, $\theta$ is time-dependent. According to Figure 3.8, the function $\theta(t)$ is equal to the sum of $\theta_G$ (longitude of Greenwich meridian with respect to the vernal equinox, or Greenwich sidereal time) and the latitude $\lambda_p$ of $P$. It results

$$\theta = \theta_G(t) + \lambda_p$$

(3.11)

$\lambda_p$ is a constant value, while $\theta_G(t)$ is a time-dependent function. $\theta_G$ at time $t$ is calculated adding the value of $\theta_G$ at $0^h$ (midnight) of the day of interest and the angular rotation of the Earth between $0^h$ and $t$ of the day of interest ($\Delta t$). This angular rotation is obtained by multiplying the Earth’s rotation rate $\omega_e = 7.29 \times 10^{-5}$ rad/sec with the time $\Delta t$ in UTC (Coordinated Universal Time) system. In formulas, it yields

$$\theta_G(t) = \theta_G(0^h) + \omega_e \Delta t$$

(3.12)

$\theta_G(0^h)$ is calculated as

$$\theta_G(0^h) = 24110.54841 + 8640184.812866 \cdot T_u + 0.093104 \cdot T_u^2 - 6.2 \times 10^{-6} \cdot T_u^3$$

(3.13)

where $T_u = d_u/36525$ and $d_u$ is the number of days of Universal Time elapsed since JD (Julian Date) 2451545.0, corresponding to 1st January 2000, 12h UT1 (JR2000).

After these transformations, the position of the satellite at time $t$ is known in ECR system.

![Figure 3.8. Rotation angles between ECR and ECI systems.](image)

The rotation matrix from the orbit system and the ECI system, indicated with $R_o^{ECI}$, is calculated
as (Jovanovic et al., 1999a)

\[ R_{O}^{ECL} = \begin{bmatrix} r_{x} \end{bmatrix} \begin{bmatrix} r_{y} \end{bmatrix} \begin{bmatrix} r_{z} \end{bmatrix} \]  

(3.14)

Calling \( x_{i} \) and \( v_{i} \) the position and velocity vectors of the satellite in ECI system (Figure 3.9a), the vectors \( r_{\phi} \), \( r_{\psi} \) and \( r_{\omega} \) are calculated with the cross-products of vectors \( x_{i} \) and \( v_{i} \) in this order:

\[ r_{\phi} = \frac{x_{i} \times v_{i}}{||x_{i} \times v_{i}||} \]

\[ r_{\psi} = \frac{r_{\phi} \times v_{i}}{||r_{\phi} \times v_{i}||} \]

\[ r_{\omega} = r_{\psi} \times r_{\phi} \]

(3.15)

The same procedure can be applied to calculate the rotation matrix \( R_{O}^{ECR} \) from the orbit system to the ECR one, using the position and velocity vectors in the ECR system \( (x_{G} \) and \( v_{G} \), Figure 3.9b). Equation 3.15 is modified in

\[ r_{\phi} = \frac{-x_{G}}{||x_{G}||} \]

\[ r_{\psi} = \frac{r_{\phi} \times v_{G}}{||r_{\phi} \times v_{G}||} \]

\[ r_{\omega} = r_{\psi} \times r_{\phi} \]

(3.16)

The angles \( \omega \), \( \phi \) and \( \psi \) that rotate the orbit system into the ECR system around \( X \), \( Y \) and \( Z \) can be calculated by imposing

\[ R_{O}^{ECR} = R_{z}(\psi) \cdot R_{y}(\phi) \cdot R_{x}(\omega) = \begin{bmatrix} \cos \psi \cos k & \cos \psi \sin k + \sin \omega \sin \phi \cos k & \sin \omega \sin k - \cos \omega \sin \phi \cos k \\ -\cos \phi \sin k & \cos \phi \cos k - \sin \omega \sin \phi \sin k & \sin \omega \cos k + \cos \omega \sin \phi \sin k \\ 0 & -\sin \omega \cos \phi & \cos \omega \cos \phi \end{bmatrix} \]

(3.17)

with the formulas

\[ \omega = \text{atan} \left( \frac{r_{23}}{r_{33}} \right) \]

\[ \phi = \text{asin} (r_{13}) \]

\[ \psi = \text{atan} \left( \frac{r_{12}}{r_{11}} \right) \]

(3.18)

where \( r_{ij} \) is the element of the rotation matrix \( R_{O}^{ECR} \) in row \( i \) and column \( j \) (Kraus, 1993).

### 3.2.3 Interpolation between reference lines

In the previous Section we have seen that from the data contained in the ephemeris the values for the sensor external orientation at particular instants of time can be calculated. The next step is to interpolate the position and attitude values for the time of acquisition of each line in order to get the complete set of external orientation parameters for the images. First of all the acquisition time of each image line is calculated, then the external orientation values are interpolated with cubic splines.
3.2.3.1 Determination of line time

In general, the time of acquisition $t_i$ of line $i$ is calculated with a linear interpolation through Equation 3.19 using the time of acquisition of a line of reference (indicated by the subscript $0$) and the integration time ($\Delta t_5$), that is, the time required by the optical system to scan one line on the ground. In formulas

$$t_i = t_0 + (u_i - u_0)\Delta t_5$$

where $u_i$ and $u_0$ stand for the row numbers of lines $i$ and $0$ in the image and $t_0$ is the time of acquisition of the reference line.

If the integration time $\Delta t_5$ is not available, it can be derived using the acquisition time $t_1$ and $t_2$ of two generic lines 1 and 2 in row position $u_1$ and $u_2$,

$$\Delta t_5 = \frac{u_2 - u_1}{t_2 - t_1}$$

3.2.3.2 Interpolation

For the interpolation of the position and attitude, cubic splines are used. The spline functions belong to the finite elements interpolation methods, which are local (they work step by step on a single part of the observed data) and very flexible (Crippa and Forlani, 1990). They are defined on the whole real axis, usually continuous with a suitable (small) number of derivatives, and are based on simple functions that fit the data points. In particular, in cubic splines a series of unique cubic polynomials are fitted between each of the data points, with the condition that the curve obtained is continuous and appear smooth (Figure 3.10). In our application, splines interpolate equally spaced data points, although a more robust form could encompass unequally spaced points.

The fundamental idea behind cubic spline interpolation is based on the engineer’s tool used to draw smooth curves through a number of points. It consists of weights attached to a flat surface at the points to be connected. A flexible strip is then bent across each of these weights, resulting in a pleasingly smooth curve. The mathematical spline which is used for the interpolation of the external orientation between reference lines is similar in principle. The points, in this case, are numerical data. The weights are the coefficients on the cubic polynomials used to interpolate the data. The coefficients “bend” the line so that it passes through each of the data points without any
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erratic behavior or breaks in continuity. The essential idea is to fit a piecewise function of the form

\[
S(x) = \begin{cases} 
  s_1(x) & \text{if } x_1 + x < x_2 \\
  s_2(x) & \text{if } x_2 + x < x_3 \\
  \vdots & \\
  s_n(x) & \text{if } x_{n-1} + x < x_n 
\end{cases}
\] (3.21)

where \( n \) is the number of numerical data to fit and \( s_i \) is a third degree polynomial defined by

\[
s_i(x) = a_i(x - x_i)^3 + b_i(x - x_i)^2 + c_i(x - x_i) + d_i
\] (3.22)

for \( i = 1, 2, \ldots, n-1 \). The first and second derivatives \( (s'_i \text{ and } s''_i) \) are

\[
s'_i = 3a_i(x - x_i)^2 + 2b_i(x - x_i) + c_i
\] (3.23)

\[
s''_i = 6a_i(x - x_i) + 2b_i
\]

for \( i = 1, 2, \ldots, n-1 \).

In order to estimate the coefficients \( a_i, b_i \) and \( c_i \), the cubic splines must conform to the following conditions:

1. the piecewise function \( S(x) \) interpolates all points
2. \( S(x) \) is continuous on the interval \((x_i, x_{n})\)
3. \( S'(x) \) is continuous on the interval \((x_i, x_{n})\)
4. \( S''(x) \) is continuous on the interval \((x_i, x_{n})\).

By imposing these conditions on \( n \) points and using the notation

\[
y_i = S(x_i) \\
M_i = s''(x_i)
\]

\[
h = x_i - x_{i-1} = \text{const}
\]

we obtain the matrix equation

\[
\begin{bmatrix}
1 & 4 & 1 & 0 & \cdots & 0 & 0 & 0 \\
0 & 1 & 4 & 1 & 0 & \cdots & 0 & 0 \\
0 & 0 & 1 & 4 & 0 & \cdots & 0 & 0 \\
\vdots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots \\
0 & 0 & 0 & 4 & 1 & 0 & \cdots & 0 \\
0 & 0 & 0 & 0 & 1 & 4 & 0 & \cdots \\
0 & 0 & 0 & 0 & 0 & 1 & 4 & 1
\end{bmatrix}
\begin{bmatrix}
M_1 \\
M_2 \\
M_3 \\
M_4 \\
\vdots \\
M_{n-3} \\
M_{n-2} \\
M_{n-1} \\
M_n
\end{bmatrix}
= \begin{bmatrix}
y_1 - 2y_2 + y_3 \\
y_2 - 2y_3 + y_4 \\
y_3 - 2y_4 + y_5 \\
\vdots \\
y_{n-4} - 2y_{n-3} + y_{n-2} \\
y_{n-3} - 2y_{n-2} + y_{n-1} \\
y_{n-2} - 2y_{n-1} + y_n
\end{bmatrix}
\]

\[
\frac{6}{h^2}
\] (3.25)

This system with dimension \((n-2, n)\) is under-determined. In order to generate a unique cubic spline, two other conditions must be imposed upon the system.

This leads to the definition of three main types of splines:

1. Natural Splines. The second derivative is set equal to zero at the endpoints: \( M_1 = M_n = 0 \)

2. Parabolic Runout Splines. The second derivative at the endpoints \( M_1 \) and \( M_n \), is imposed to be equal to \( M_2 \) and \( M_{n-1} \), respectively: \( M_1 = M_2 \) and \( M_n = M_{n-1} \).

3. Cubic Runout spline. This type of spline has the most extreme endpoint behavior. It assigns
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$M_i$ to be a combination of $M_2$ and $M_3$ and $M_n$ to be the same combination for $M_{n-1}$ and $M_{n-2}$: $M_i = 2M_2 - M_3$ and $M_n = 2M_{n-1} - M_{n-2}$. This causes the curve to degrade to a single cubic curve over the last two intervals, rather than two separate functions.

Once all the conditions have been set, the unique solution (polynomial coefficients) can be calculated. In all three forms, the cubic splines are especially practical, because the set of equations imposed not only are linear, but also tridiagonal. Each $M_i$ is coupled only to the nearest neighbors at $i$, therefore the equations can be solved in $O(N)$ operations (De Boor, 1978).

In our case the interpolation of the position and attitude vectors for all the acquisition times is carried out using natural splines.

![Figure 3.10. Interpolation with cubic splines (Crippa and Forlani, 1993)](image)

3.3 DIRECT GEOREFERENCING

Using the sensor external orientation estimated for each line and any internal orientation parameters available from laboratory calibration (Section 2.4), the image coordinates of homologous points can be transformed in the object system through a forward intersection (direct georeferencing). In frame photogrammetry each image is acquired from a separate perspective center and is therefore the result of a central perspective. On the other hand, in images acquired by pushbroom sensors, each image line is independently scanned while the sensor is moving along its trajectory. As a consequence, the perspective projection and the collinearity equations are not valid for the full image, but in each CCD line direction only.

Like in frame photogrammetry, the points are measured in the image and transformed in this order:
1. from image to camera system, through an affine transformation
2. from camera to object system, based on the collinearity equations.

In the second transformation the points must be observed in at least two images and their object coordinates are estimated with forward intersection in two steps. In the first one the approximation of the ground coordinates are calculated by forward intersection of the two most external images, because the base over height ratio is bigger and the stereoscopy is more favorable (Figure 3.11a). Once the approximate ground coordinates are known, they are refined with a least squares solution in the second step, using all the available lines (Figure 3.11b).

In the next sections, the mentioned reference systems and transformations are described.

3.3.1 From image to camera coordinates

The image system is a 2D system in image space with origin in the top upper-left image pixel and two orthogonal axis oriented along the image rows ($v$) and columns ($u$), as described in Section B.1 and Figure 3.12a. The image coordinates ($u, v$) are transformed into the scanline system (indicated with $S$). This system is defined for each image line and is centered in the mean pixel of the line, with $y_S$ axis parallel to the image line and $x_S$ axis perpendicular to $y_S$, close to the flight direction (Section B.2 and Figure 3.12b).

Assuming an ideal case without lens distortions and geometric errors of the CCD line in the focal
Figure 3.11.Steps of direct georeferencing algorithm for three-line sensors: a) intersection of two homologous rays and b) refinement with three rays.

plane, the coordinate $y_s$ can be calculated with the transformation

$$y_s = \left( v - \frac{N_p}{2}\right)p_y$$

(3.26)

where $p_y$ is the pixel dimension in $y_s$ direction and $N_p$ is the number of pixels in each line. The coordinate $x_s$ is fixed equal to zero.

If the pre-flight laboratory calibration results are available, the given exact position of each CCD line in the focal plane are used as $x_s$ and $y_s$ values.

The camera system (indicated with letter C) is a 3D system centered in the perspective center (PC) of each lens (Section B.3 and Figure 3.12c). The axis $x_c$ and $y_c$ are parallel to $x_s$ and $y_s$. The $z$-axis $z_c$ is upwards directed and completes a right-hand coordinate system. The value of $z_c$ is equal to the lens focal length. The transformation between scanline and camera systems is

$$
\begin{bmatrix}
    x_c \\
    y_c \\
    z_c \\
\end{bmatrix} =
\begin{bmatrix}
    x_s \\
    y_s \\
    -f \\
\end{bmatrix}
$$

(3.27)

Due to the characteristics of the imagery from linear scanners, we cannot define a single camera system for the full image but we need to suppose one camera system for each line.

Figure 3.12.(a) Image system; (b) Scanline system; (c) Camera system.
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3.3.2 From camera to ground coordinates

As each image line is acquired through a central perspective, the relationship between camera and ground (or object) coordinates can be described by the collinearity principle. This relationships is valid for each image line.

The object system used for the georeferencing are the local tangential system (Section B.7) for airborne sensors and the ECR systems (Section B.5) for spaceborne sensors.

For each point observed in the images, the general relationship between camera and ground coordinates is described by the following equation

\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} = \begin{bmatrix}
Xc \\
Yc \\
Zc
\end{bmatrix} + mR(\omega_c, \varphi_c, \kappa_c) \begin{bmatrix}
x - x_p \\
y - y_p \\
-f
\end{bmatrix}
\] (3.28)

where

\([X, Y, Z]\): point coordinates in the ground system
\([Xc, Yc, Zc]\): PC position in the ground system
\([xc, yc]\): point coordinates in the camera system
\([xP, yP]\): principal point coordinates in the camera system
\(f\): focal length;
\(m\): scale factor
\(R(\omega_c, \varphi_c, \kappa_c)\): rotation matrix from camera to ground system.

If the principal point correction is already included in the calibration values, the following equation is used

\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} = \begin{bmatrix}
Xc \\
Yc \\
Zc
\end{bmatrix} + R(\omega_c, \varphi_c, \kappa_c) \begin{bmatrix}
x_c \\
y_c \\
-f
\end{bmatrix}
\] (3.29)

Later or we consider the principal point not included in the calibration values. Equation 3.28 describes a rototranslation with a scale factor. As shown in Figure 3.14, the vector \([Xc, Yc, Zc]\) represents the translation from the origin of the ground system to the camera PC and \(R(\omega_c, \varphi_c, \kappa_c)\) rotates the camera system into a system parallel to the ground one. \(R(\omega_c, \varphi_c, \kappa_c)\) is obtained combining three rotations around \(X\), \(Y\) and \(Z\), with the attitude angles \((\omega_c, \varphi_c, \kappa_c)\). The rotation is described by

\[
R(\omega_c, \varphi_c, \kappa_c) = R_z(\kappa_c) \cdot R_y(\varphi_c) \cdot R_x(\omega_c) = \\
\begin{bmatrix}
\cos \varphi_c \cos \kappa_c & \cos \omega_c \sin \kappa_c + \sin \omega_c \sin \varphi_c \cos \kappa_c & \sin \omega_c \sin \kappa_c - \cos \omega_c \sin \varphi_c \cos \kappa_c \\
-\cos \varphi_c \sin \kappa_c & \cos \omega_c \cos \kappa_c - \sin \omega_c \sin \varphi_c \sin \kappa_c & \sin \omega_c \cos \kappa_c + \cos \omega_c \sin \varphi_c \sin \kappa_c \\
\sin \varphi_c & -\sin \omega_c \cos \varphi_c & \cos \omega_c \cos \varphi_c
\end{bmatrix}
\] (3.30)

The external orientation parameters \([Xc, Yc, Zc, \omega_c, \varphi_c, \kappa_c]\) are different for each image line and are calculated by GPS/INS measurements or from ephemeris, as described in Sections 3.1 and 3.2.

For sensors whose optical systems consist of more lenses, additional geometric parameters describing the relative position and attitude of each lens with respect to the nadir one are imported in the collinearity equations (Ebner et al., 1992). The parameters \(d_{ij}\) represent
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the relative position and $\alpha_j, \beta_j, \gamma_j$ the relative attitude of each lens $j$ with respect to the reference one (Figure 3.13).

Calling $x_{pj}$ and $y_{pj}$ the principal point position and $f_j$ the focal length of lens $j$, Equation 4.4 is extended to

$$
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} = 
\begin{bmatrix}
X_c \\
Y_c \\
Z_c
\end{bmatrix} + R(\omega_c, \varphi_c, \kappa_c) 
\begin{bmatrix}
d_{xj} \\
d_{yj}
\end{bmatrix} + kS(\omega_c, \varphi_c, \kappa_c, \alpha_j, \beta_j, \gamma_j) 
\begin{bmatrix}
x - x_{pj} \\
y - y_{pj} \\
f_j
\end{bmatrix}
$$

(3.31)

where

- $M(\alpha_j, \beta_j, \gamma_j)$: rotation from camera system of the off-nadir lens $j$ to camera system of the central lens
- $R(\omega_c, \varphi_c, \kappa_c)$: rotation from camera system of the central lens to ground frame.

If the relative orientation parameters are equal to zero (nadir case), Equation 3.28 is obtained from Equation 3.31.

The algorithms that will be presented have been developed both for one-lens and multi-lens CCD linear sensors. For simplicity, in this Chapter only the formulas for single-lens systems are reported.

Figure 3.13. Relative orientation parameters between central line and off-nadir line $i$.

Figure 3.14. Transformation from camera to ground systems.
3.3.3 Estimation of approximate ground coordinates

A linear forward intersection of two homologous rays is performed in order to estimate the ground coordinates that will be used as initial approximations for the least-squares refinement. It is assumed that the position and the attitude of the sensor projection center is known for each image line.

The mathematical model is based on Equation 3.28. Calling

\[
\begin{bmatrix}
  x_{cr} \\
  y_{cr} \\
  z_{cr}
\end{bmatrix} = R(\omega_C, \psi_C, \kappa_C)
\begin{bmatrix}
  x_c \\
  y_c \\
  z_c
\end{bmatrix}
\]

Equation 3.28 can be also written as

\[
\begin{bmatrix}
  X \\
  Y \\
  Z
\end{bmatrix} = \begin{bmatrix}
  X_c \\
  Y_c \\
  Z_c
\end{bmatrix} + m
\begin{bmatrix}
  x_{cr} \\
  y_{cr} \\
  z_{cr}
\end{bmatrix}
\]

If point P is measured in two stereo images, we can impose the intersection of the two homologous rays (Figure 3.15, yielding

\[
\begin{aligned}
X_1 + m_1 x_{cr1} = X_2 + m_2 x_{cr2} \\
Y_1 + m_1 y_{cr1} = Y_2 + m_2 y_{cr2} \\
Z_1 + m_1 z_{cr1} = Z_2 + m_2 z_{cr2}
\end{aligned}
\]

where \( m_1 \) and \( m_2 \) are the scale factors for the two images. It gives the system

\[
\begin{aligned}
X_{c1} + m_1 x_{cr1} = X_{c2} + m_2 x_{cr2} \\
Y_{c1} + m_1 y_{cr1} = Y_{c2} + m_2 y_{cr2} \\
Z_{c1} + m_1 z_{cr1} = Z_{c2} + m_2 z_{cr2}
\end{aligned}
\]

In matrix notation, we have

\[
\begin{bmatrix}
  x_{cr1} - x_{cr2} \\
  y_{cr1} - y_{cr2} \\
  z_{cr1} - z_{cr2}
\end{bmatrix} \begin{bmatrix}
  m_1 \\
  m_2
\end{bmatrix} = \begin{bmatrix}
  X_{c2} - X_{c1} \\
  Y_{c2} - Y_{c1} \\
  Z_{c2} - Z_{c1}
\end{bmatrix}
\]

that can be written as

\[
Am = b + e
\]

being \( e \) the observation error.

This linear system is solved with linear least squares, with unique solution

\[
m = (A^T A)^{-1} A^T b
\]

Substituting the two scale factors contained in vector \( m \) into Equation 3.33 for both images, two different points are identified in object space. The mean point is taken as approximation \((X^0, Y^0, Z^0)\) of the ground coordinates of point P.
3.3.4 Refinement

The ground coordinates \((X^0, Y^0, Z^0)\) are refined using all the available stereo images. The mathematical model is based on the collinearity equations

\[
x_c = -f \frac{r_{11}(X - X_c) + r_{21}(Y - Y_c) + r_{31}(Z - Z_c)}{r_{13}(X - X_c) + r_{23}(Y - Y_c) + r_{33}(Z - Z_c)} = -f \cdot \frac{N_z}{D}
\]

\[
y_c = -f \frac{r_{21}(X - X_c) + r_{22}(Y - Y_c) + r_{32}(Z - Z_c)}{r_{23}(X - X_c) + r_{23}(Y - Y_c) + r_{33}(Z - Z_c)} = -f \cdot \frac{N_y}{D}
\]

which are obtained solving Equation 3.29 with respect to \(m\). Assuming that point \(P\) is observed in \(n\) images, a system containing Equations 3.39 written for each image is formed. The resulting system contains \(2 \cdot n\) observation equations and three unknown parameters (ground coordinates of the observed point). The system, which is non-linear with respect to the unknown ground coordinates, is linearized according to first-order Taylor decomposition using the derivatives:

\[
\frac{\partial x_c}{\partial X} = \frac{-f}{D^2} (Dr_{11} - N_x r_{13}) \quad \frac{\partial y_c}{\partial X} = \frac{-f}{D^2} (Dr_{12} - N_y r_{13})
\]

\[
\frac{\partial x_c}{\partial Y} = \frac{-f}{D^2} (Dr_{21} - N_x r_{23}) \quad \frac{\partial y_c}{\partial Y} = \frac{-f}{D^2} (Dr_{22} - N_y r_{23})
\]

\[
\frac{\partial x_c}{\partial Z} = \frac{-f}{D^2} (Dr_{31} - N_x r_{33}) \quad \frac{\partial y_c}{\partial Z} = \frac{-f}{D^2} (Dr_{32} - N_y r_{33})
\]

In matrix notation, the linearized system is written as

\[
v = Ad - l
\]

where

\(A\): design matrix, containing the first derivatives of the collinearity functions with respect to
the ground coordinates, evaluated in the approximations \((X^0, Y^0, Z^0)\)

\(d\): unknown vector \((dX, dY, dZ)\)

\(v\): vector with residuals

\(l\): vector containing the differences between the observed coordinates and the same coordinates evaluated substituting the approximations in the collinearity equations.

The matrix \(A\) is structured as shown in Figure 3.16.

\[
A = \begin{bmatrix}
\text{image 1} & \text{image i} & \text{image n}
\end{bmatrix}
\text{2 rows} \begin{bmatrix}
\frac{\partial X}{\partial X} & \frac{\partial X}{\partial Y} & \frac{\partial X}{\partial Z}
\frac{\partial Y}{\partial X} & \frac{\partial Y}{\partial Y} & \frac{\partial Y}{\partial Z}
\frac{\partial Z}{\partial X} & \frac{\partial Z}{\partial Y} & \frac{\partial Z}{\partial Z}
\end{bmatrix}
\text{3 columns}
\]

(a) (b)

Figure 3.16. Structure of \(A\) matrix (a) and derivatives contained in each block (b).

Calling \(W\) the diagonal matrix containing the observation weights, the system is solved with the solution

\[
\hat{d} = (A^TWAI)^{-1}A^TWl
\]

The residuals are calculated as

\[
v = A\hat{d} - l
\]

and the a-posteriori sigma \((\delta_0)\) is equal to

\[
\delta_0 = \sqrt{\frac{v^TWv}{r}}
\]

where \(r\) is the redundancy of the system (difference between number of equations and the number of unknowns), equal to \(2n-3\).

The iterations are repeated until all components of vector \(d\) are smaller than a threshold, depending on the images ground resolution and the accuracy of the point measurement in the images.

### 3.4 SOME CONSIDERATIONS ON GPS/INS MEASUREMENTS

In case of direct georeferencing with airborne imagery, the ground system is a local tangential system (indicated with letter \(L\)), centered at a point \(O\) in the study area. In order to use Equation 3.28, the angles that rotates the camera system into the ground local system \(L\) are needed. Additionally the vector containing the camera position from GPS measurement (in ECR system, indicated with letter \(G\)) must be transformed into the local ground system \(L\). Using these systems, the transformation from the camera system \(c\) to the ground local system \(L\) is described by

\[
\begin{bmatrix}
X_L \\
Y_L \\
Z_L
\end{bmatrix} = \begin{bmatrix}
X_C \\
Y_C \\
Z_C
\end{bmatrix} + mR^L_c \begin{bmatrix}
x_c \\
y_c \\
-z_c
\end{bmatrix}
\]

The notation \(R^B_A\) represents the rotation matrix from system \(A\) to system \(B\). The vector \([X_O, Y_O, Z_O]\) is the camera position given by GPS and transformed in the local ground system \(L\). As the attitude concerns, the matrix that rotates the camera system in to the ground local one \(R^L_c\) is different for each line and cannot be directly computed. Taking into account that the measurements
provided by INS give the rotation angles from the camera system to a local tangential system (indicated with letter P) centered in the camera PC, $R_c^L$ is described as the combination of three rotations: 1. from the camera system $c$ to a local system $P$ ($R_c^P$), 2. from the local system $P$ to the ECR one ($R_P^G$) and 3. from the ECR to the ground local system ($R_G^L$), as shown in Figure 3.17.

![Figure 3.17. Representation of transformations: (a) from camera to ground local systems; (b) from camera to platform systems; (c) from platform to ECR system; (d) from ECR to ground local system.](image)

The matrices are combined in this way

$$R_c^L(t) = R_G^L \cdot R_P^G(t) \cdot R_c^P(t)$$

(3.46)

$R_c^P$ and $R_P^G$ are time-dependent, while $R_G^L$ is constant.

$R_c^P$ is obtained by the rotations of roll ($r$), pitch ($p$) and yaw ($j$) angles (given by INS) around $x_C$, $y_C$ and $z_C$

$$R_c^P = \begin{bmatrix} \cos r \cos j & -\cos p \sin j & \sin p \\ \cos r \sin j + \sin r \sin p \cos j & \cos r \cos j - \sin r \sin p \sin j & -\sin r \cos p \\ \sin r \sin j - \cos r \sin p \cos j & \cos r \sin j + \sin r \sin p \sin j & \cos r \cos p \end{bmatrix}$$

(3.47)

$R_G^L$ is calculated as

$$R_G^L = R_L(90 - \phi_L) \cdot R_L(90 - \lambda_L)$$

(3.48)

where $\phi_L$ and $\lambda_L$ are the longitude and latitude of the origin of $L$ system.
Finally, \( R_P^C \) is the transpose (or inverse) of \( R_P^C \), defined as

\[
R_P^C = R_P^C = R_x(90 - \phi) \cdot R_z(90 - \lambda)
\]  

(3.49)

where \( \phi \) and \( \lambda \) are the longitude and latitude of the platform, calculated from the GPS measurements.

This approach is valid if the GPS and INS measurements refer to the camera PC, that is, if the camera, the GPS and the INS systems are placed in the same position (theoretical case). In practice during the georeferencing process, the location of the camera, the GPS and the INS systems must be taken into account (Skaloud and Schwarz, 2000, Forlani and Pinto, 2002). Thus we introduce:

- the GPS local system: tangential local systems with origin in the GPS antenna
- the INS local system: tangential local systems with origin in the INS instrument.

Figure 3.18 shows the mentioned reference systems and their displacements. Using the same notation as in Equation 3.45, the transformation from camera to ground local coordinates that takes into account these additional systems, is described by

\[
\begin{bmatrix}
X_L \\
Y_L \\
Z_L \\
\end{bmatrix}
= \begin{bmatrix}
X_C \\
Y_C \\
Z_C \\
\end{bmatrix}
+ R^C_P R^C_P R^P_{\text{INS}}
\begin{bmatrix}
x_c \\
y_c \\
z_c \\
\end{bmatrix}
+ R^P_{\text{GPS}}
\begin{bmatrix}
\Delta X_{\text{GPS}} \\
\Delta Y_{\text{GPS}} \\
\Delta Z_{\text{GPS}} \\
\end{bmatrix}
\]  

(3.50)

where

- \([X_0, Y_0, Z_0]\): sensor position provided by GPS and transformed to ground local system \( L \)
- \([\Delta X_{\text{GPS}}, \Delta Y_{\text{GPS}}, \Delta Z_{\text{GPS}}]\): offset between GPS and camera system
- \( R^P_{\text{GPS}} \): rotation matrix from GPS to INS system
- \( R^P_{\text{INS}} \): rotation matrix from INS to local system \( P \).

\( R^P_{\text{INS}} \), that rotates the camera system into the INS system, is obtained by substituting the INS observations into Equation 3.50. The rotation \( R^P_{\text{INS}} \) is calculated according to the angular misalignments between the GPS and INS systems. The angular and position displacement between GPS, INS and camera systems should be measured with pre-flight surveying techniques.

Figure 3.18. Reference systems used in direct georeferencing with GPS and INS observations.
3.5 ACCURACY EVALUATION

For the evaluation of the accuracy of the method a sufficient number of Check Points (CPs) are required. The CPs are measured in the images and in the object space. After applying the direct georeferencing, the estimated ground coordinates \([X, Y, Z]\) of the CPs are compared to the correct ones \([X_{corr}, Y_{corr}, Z_{corr}]\) and the RMSE are calculated as

\[
\text{RMSE}_x = \frac{\sum_{i=1}^{N_{CP}} (\hat{X}_i - X_{corr_i})^2}{N_{CP}} \quad \text{RMSE}_y = \frac{\sum_{i=1}^{N_{CP}} (\hat{Y}_i - Y_{corr_i})^2}{N_{CP}} \quad \text{RMSE}_z = \frac{\sum_{i=1}^{N_{CP}} (\hat{Z}_i - Z_{corr_i})^2}{N_{CP}}
\]

where \(N_{CP}\) is the number of CPs.

3.6 CONCLUSIONS

In this Chapter the mathematical formulation of the direct model for the georeferencing of CCD linear array sensors has been described. The model is based on the forward intersection of two or more homologous rays. The sensor internal orientation must be known, for example from laboratory calibration. For the sensor external orientation, the position and attitude are calculated from the metadata files of the images and interpolated for each image line with cubic splines. The accuracy of the method is evaluated through the RMSE of the check points.

For the orientation of pushbroom imagery, the approach based on direct georeferencing is very powerful because in theory it allows the determination of the ground coordinates of the points measured in the images without the use of GCPs, with a considerable reduction of the processing time, costs and efforts. It is a very useful tool for the evaluation of the accuracy that can be achieved in the object space using only the information provided by laboratory calibration and positioning systems carried on the air- or spacecraft.

Other applications based on this approach have also been investigated. For example the algorithm presented in this Chapter has been used for the determination of the ground coordinates of points measured in Meteosat scenes (Seiz et al., 2004).

The results may not be satisfying if the interior orientation parameters, given by pre-flight laboratory calibration and the exterior orientation measurements are not enough accurate. Anyway, even when those data are available at very high degree of accuracy, additional factors must be taken into account. For example, if GPS and INS observations are used, the values of the misalignments and shifts between the positioning and imaging instruments must be known, which is not always the case. Then few GCPs are needed for the bias corrections, as shown in Poli, 2001.
4

INDIRECT GEOREFERENCING

In the previous Chapter we have seen that a possible method for the georeferencing of pushbroom imagery is to apply a forward intersection using as internal orientation the parameters estimated in the laboratory calibration and as external orientation the GPS/INS measurements or the values calculated from the ephemeris (satellite case). We have concluded that the results depend on the accuracy of the point measurements and of the available internal and external orientation. The alternative method, the indirect georeferencing approach, is used if the sensor internal and external orientations are not available or not accurate enough for high-precision photogrammetric mapping. According to this approach, the sensor external and internal orientation are estimated with suitable parameterized functions, together with the ground coordinates of Tie Points (TPs). The solution is calculated through a bundle adjustment using well distributed GCPs.

In this Chapter the indirect georeferencing model is presented. After the overview of the model (Section 4.1), the external orientation modelling (Section 4.3), the self-calibration (Section 4.4), the generation of the final observation system (Section 4.5), the solution estimation (Section 4.6) and the accuracy tests (Section 4.7) are explained in details.

4.1 ALGORITHM OVERVIEW

For the georeferencing of CCD linear array sensors the basic collinearity equations represent the relationship between camera and object systems through a central projection in each image line. In their standard definition, they are too coarse as mathematical models and cannot describe the complexity of the pushbroom acquisition geometry. Therefore refinements and extensions of the equations are required.

In order to improve the physical description of the process to be modelled, additional parameters are introduced in the equations and will be determined as part of the total adjustment. The choice of the additional parameters must fulfill some requirements. First of all the new parameters must
not depend on existing parameters to be estimated in the adjustment. Furthermore, if the functions introduced are polynomials, the degree of the polynomials themselves cannot be too high, in order to avoid the uncontrolled behavior of higher degree terms. Statistical methods are useful to judge how far the individual additional parameters contribute significantly to the modelling. Figure 4.1 shows the development of the proposed algorithm. After extending the collinearity equations to multi-lens sensors (Section 4.2), the external orientation modelling functions are introduced and any available GPS/INS information are taken into account (Section 4.3). The systematic errors due to the lens and CCD lines distortions are included in the model through a self-calibration (Section 4.4). Then the resulting system is solved with least-squares adjustment.

Figure 4.1. Scheme of algorithm development.

4.2 EXTENSION TO MULTI-LENS SENSORS

As seen in Chapter 3, for each observed point, the relationship between camera and ground coordinates (Figure 3.14) is described by

\[
\begin{align*}
    x - x_p &= -f \left( r_{11}(X - X_c) + r_{21}(Y - Y_c) + r_{31}(Z - Z_c) \right) \\
    y - y_p &= -f \left( r_{13}(X - X_c) + r_{23}(Y - Y_c) + r_{33}(Z - Z_c) \right)
\end{align*}
\]

(4.1)

where

- \([X, Y, Z]\): point coordinates in the ground system;
- \([X_c, Y_c, Z_c]\): PC position in the ground system;
- \([x, y]\): point coordinates in the camera system, where \(y\) is calculated by Equation 3.26 and \(x\) is equal to zero;
- \([x_p, y_p]\): principal point coordinates in the camera system;
- \(f\): focal length;
- \(R(\omega_c, \varphi_c, \kappa_c)\): rotation matrix from camera to ground system, with the attitude angles \(\omega_c, \varphi_c, \kappa_c\).
For sensors whose optical systems consist of more lenses, additional geometric parameters describing the relative position and attitude of each lens with respect to the nadir one are imported in the collinearity equations (Ebner et al., 1992). For each lens \( j \), \( d_{xj}, d_{yj}, d_{zj} \) represent the relative position and \( \alpha_j, \beta_j, \gamma_j \) the relative attitude with respect to the reference one (Figure 3.13). Calling \( x_{pj} \) and \( y_{pj} \) the principal point positions and \( f_j \) the focal length, Equation 4.1 is extended to

\[
x - x_{pj} = -f_j \left( \frac{s_{11}(X - X_C) + s_{21}(Y - Y_C) + s_{31}(Z - Z_C) - (m_{11}d_{xj} + m_{21}d_{yj} + m_{31}d_{zj})}{s_{11}(X - X_C) + s_{22}(Y - Y_C) + s_{33}(Z - Z_C) - (m_{13}d_{xj} + m_{23}d_{yj} + m_{33}d_{zj})} \right) + \Delta x_j
\]

\[
y - y_{pj} = -f_j \left( \frac{s_{21}(X - X_C) + s_{22}(Y - Y_C) + s_{32}(Z - Z_C) - (m_{12}d_{xj} + m_{22}d_{yj} + m_{32}d_{zj})}{s_{21}(X - X_C) + s_{22}(Y - Y_C) + s_{33}(Z - Z_C) - (m_{13}d_{xj} + m_{23}d_{yj} + m_{33}d_{zj})} \right) + \Delta y_j
\]

where \( M(\alpha_j, \beta_j, \gamma_j) \): rotation from camera system centred in the off-nadir lens \( j \) to camera system with origin in the central lens.

\( S(\omega_C, \phi_C, \kappa_C) \): rotation from camera system centred in the central lens to ground frame.

\( \mathbf{S} = R(\omega_C, \phi_C, \kappa_C) \cdot M(\alpha_j, \beta_j, \gamma_j) \): complete rotation from camera system centred in the off-nadir lens \( j \) to ground system.

The algorithms that will be presented have been developed both for one-lens and multi-lens CCD linear sensors. Taking into account the self-calibration, Equation 4.2 is written as

\[
x - x_{pj} = -f_j \left( \frac{s_{11}(X - X_C) + s_{21}(Y - Y_C) + s_{31}(Z - Z_C) - (m_{11}d_{xj} + m_{21}d_{yj} + m_{31}d_{zj})}{s_{11}(X - X_C) + s_{22}(Y - Y_C) + s_{33}(Z - Z_C) - (m_{13}d_{xj} + m_{23}d_{yj} + m_{33}d_{zj})} \right) + \Delta x_j
\]

\[
y - y_{pj} = -f_j \left( \frac{s_{21}(X - X_C) + s_{22}(Y - Y_C) + s_{32}(Z - Z_C) - (m_{12}d_{xj} + m_{22}d_{yj} + m_{32}d_{zj})}{s_{21}(X - X_C) + s_{22}(Y - Y_C) + s_{33}(Z - Z_C) - (m_{13}d_{xj} + m_{23}d_{yj} + m_{33}d_{zj})} \right) + \Delta y_j
\]

where \( \Delta x_j \) and \( \Delta y_j \) are the terms containing the parameters modelling the lens and CCD lines distortions. They will be described in Section 4.4.

The basic relationship between image and ground coordinates based on the collinearity equations for multi-sensors (Equation 4.3) can be written as

\[
x - x_{pj} = -f_j \cdot \frac{N_x}{D} + \Delta x_j
\]

\[
y - y_{pj} = -f_j \cdot \frac{N_y}{D} + \Delta y_j
\]

where

\[
N_x = s_{11}(X - X_C) + s_{21}(Y - Y_C) + s_{31}(Z - Z_C) - (m_{11}\Delta x_j + m_{21}\Delta y_j + m_{31}\Delta z_j)
\]

\[
N_y = s_{21}(X - X_C) + s_{22}(Y - Y_C) + s_{32}(Z - Z_C) - (m_{12}\Delta x_j + m_{22}\Delta y_j + m_{32}\Delta z_j)
\]

\[
D = r_{13}(X - X_C) + r_{23}(Y - Y_C) + r_{33}(Z - Z_C) - (m_{13}\Delta x_j + m_{23}\Delta y_j + m_{33}\Delta z_j)
\]

### 4.3 EXTERNAL ORIENTATION MODELLING

The sensor external orientation (EO) is modelled by Piecewise Polynomial Functions (PPM) depending on time. Due to the possibility of changing the number of segments and the poly-
Chapter 4. INDIRECT GEOREFERENCING

mial degree, this function results quite flexible and applicable to both satellite and airplanes trajectories, as shown in Kratky, 1989, Valadan Zoej and Foomani, 1999 and Grün and Zhang, 2002a. If one segment only is used, the PPM becomes a parabolic function (Figure 4.2).

The platform trajectory is divided into segments according to the number and distribution of available GCPs and TPs. For each segment $i$, with time extremes $t_{i_{\text{init}}}$ and $t_{i_{\text{fin}}}$, the variable $\bar{t}$ is defined as

$$\bar{t} = \frac{t-t_{i_{\text{init}}}}{t_{i_{\text{fin}}}-t_{i_{\text{init}}}}$$

where $t$ is the time of acquisition of a generic image line.

Then in each segment the sensor external orientation $[X_0, Y_0, Z_0, \omega_0, \varphi_0, \kappa_0]$ is modelled with second-order polynomials depending on $\bar{t}$

$$X_c(t) = X_0 + X_1 \bar{t} + X_2 \bar{t}^2$$

$$Y_c(t) = Y_0 + Y_1 \bar{t} + Y_2 \bar{t}^2$$

$$Z_c(t) = Z_0 + Z_1 \bar{t} + Z_2 \bar{t}^2$$

$$\omega_c(t) = \omega_0 + \omega_1 \bar{t} + \omega_2 \bar{t}^2$$

$$\varphi_c(t) = \varphi_0 + \varphi_1 \bar{t} + \varphi_2 \bar{t}^2$$

$$\kappa_c(t) = \kappa_0 + \kappa_1 \bar{t} + \kappa_2 \bar{t}^2$$

$[X_0, X_1, X_2, ..., \kappa_0, \kappa_1, \kappa_2]^T$ are the parameters modelling the external orientation in segment $i$. At the points of conjunction between adjacent segments, constraints on the zero, first and second order continuity are imposed on the trajectory functions: we force that the values of the functions and their first and second derivatives computed in two neighboring segments are equal at the segments boundaries (Section 4.3.2).

4.3.1 Integration of GPS/INS observations

In Chapter 4 we have seen that in case of pushbroom sensors carried on airplane the direct measurement of the sensor position and attitude with GPS and INS instruments is required, because the trajectory is not completely predictable.

We have also concluded that the observations provided by GPS and INS and filtered with Kalman filter may not be optimal for high-precision direct georeferencing. First of all the observations refer to the GPS antenna and the INS instrument, not to the sensor perspective center (as required in the collinearity conditions); the offsets and boresight angles between the GPS, INS and camera systems, if not known or not accurate enough, should be imported in the collinearity...
Section 4.3. EXTERNAL ORIENTATION MODELLING

equations, estimated and removed from the observations. Another important aspect to take into account is that the observations may contain residual systematic errors that were not eliminated in the filtering procedures. For these reasons the external orientation modelling must be extended in order to integrate and correct the GPS and INS observations. The PPM is suitable for this extension, as already proved in Grün and Zhang, 2002a. In fact the constant terms (parameters in Equation 4.9 indicated with subscript 0) can be used for the description of the constant misalignment and boresight angles between the GPS, INS and camera systems, while the first and second order terms (parameters in Equation 4.9 indicated with subscribes 1 and 2 respectively) may model other systematic errors occurring in the observations.

The trajectory is again divided into segments and for each segment \( i \), with time extremes \( t_{\text{ini}} \) and \( t_{\text{fin}} \), the variable \( \bar{t} \) is defined as

\[
\bar{t} = \frac{t - t_{\text{ini}}}{t_{\text{fin}} - t_{\text{ini}}} \tag{4.10}
\]

where \( t \) is the time of acquisition of each processed line. If the sensor position and attitude observations are provided for each line, the line number can be used instead of the time

\[
\bar{t} = \frac{l - l_{\text{ini}}}{l_{\text{fin}} - l_{\text{ini}}} \tag{4.11}
\]

where \( l_{\text{ini}} \) and \( l_{\text{fin}} \) are the line extremes of segment \( i \).

The sensor attitude and position of each image line \( l \) belonging to segment \( i \), indicated with \([X_c, Y_c, Z_c, \omega_c, \phi_c, \kappa_c]_l\), are modelled as the sum of the measured position and attitude data for that line \([X_{\text{instr}}, Y_{\text{instr}}, Z_{\text{instr}}, \omega_{\text{instr}}, \phi_{\text{instr}}, \kappa_{\text{instr}}]_l\) plus the second order polynomial functions depending on \( \bar{t} \), resulting in

\[
\begin{align*}
X_c(\bar{t}) &= X_{\text{instr}} + X_0^l + X_1^l \bar{t} + X_2^l \bar{t}^2 \\
Y_c(\bar{t}) &= Y_{\text{instr}} + Y_0^l + Y_1^l \bar{t} + Y_2^l \bar{t}^2 \\
Z_c(\bar{t}) &= Z_{\text{instr}} + Z_0^l + Z_1^l \bar{t} + Z_2^l \bar{t}^2 \\
\omega_c(\bar{t}) &= \omega_{\text{instr}} + \omega_0^l + \omega_1^l \bar{t} + \omega_2^l \bar{t}^2 \\
\phi_c(\bar{t}) &= \phi_{\text{instr}} + \phi_0^l + \phi_1^l \bar{t} + \phi_2^l \bar{t}^2 \\
\kappa_c(\bar{t}) &= \kappa_{\text{instr}} + \kappa_0^l + \kappa_1^l \bar{t} + \kappa_2^l \bar{t}^2
\end{align*}
\tag{4.12}
\]

\([X_0, X_1, X_2, ..., \kappa_0, \kappa_1, \kappa_2]^l\) are the 18 parameters modelling the misalignment and systematic errors contained in the observations in segment \( i \). The constant terms \([X_0, Y_0, Z_0, \omega_0, \phi_0, \kappa_0]^l\) compensate the shifts and angular drifts between the image system and the GPS and INS systems, while the linear and quadratic terms \([X_1, Y_1, Z_1, \omega_1, \phi_1, \kappa_1]^l\) and \([X_2, Y_2, Z_2, \omega_2, \phi_2, \kappa_2]^l\) model the additional systematic errors contained in the GPS and INS measurements.

At the points of conjunction between adjacent segments, constraints for the zero, first and second order continuity are imposed on the trajectory functions: we force that the values of the functions and their first and second derivatives computed in two neighboring segments are equal at the segments boundaries.
4.3.2 Function continuity

The continuity of the external orientation functions, together with their first and second order derivatives, are imposed at the points of junction between segments.

4.3.2.1 Zero-order continuity

At the point on the border between segment $i$ and $i+1$, $t = 1$ in segment $i$ and $t = 0$ in segment $i+1$. Applying the zero order continuity for $X_c$ function, we impose

$$X_c^i |_{t=1} = X_c^{i+1} |_{t=0} \quad (4.13)$$

According to Equation 4.9, we obtain

$$X_0^i + X_1^i + X_2^i = X_0^{i+1} + X_1^{i+1} + X_2^{i+1} \quad (4.14)$$

It yields to

$$X_0^i + X_1^i + X_2^i = X_0^{i+1} \quad (4.15)$$

For all the external orientation functions it results

$$X_0^i + X_1^i + X_2^i = X_0^{i+1}$$

$$Y_0^i + Y_1^i + Y_2^i = Z_0^{i+1}$$

$$Z_0^i + Z_1^i + Z_2^i = Z_0^{i+1}$$

$$\omega_0^i + \omega_1^i + \omega_2^i = \omega_0^{i+1}$$

$$\phi_0^i + \phi_1^i + \phi_2^i = \phi_0^{i+1}$$

$$\kappa_0^i + \kappa_1^i + \kappa_2^i = \kappa_0^{i+1} \quad (4.16)$$

In case of GPS/INS integration, according to Equation 4.12, we introduce $X_{in\text{str}}^f$ for $l_{fin}$ and $X_{in\text{str}}^\text{int}$ for $l_{int}$. Equation 4.15 becomes

$$X_{in\text{str}}^f + X_0^i + X_1^i + X_2^i = X_{in\text{str}}^{i+1} + X_0^{i+1} \quad (4.17)$$

As $X_{in\text{str}}^f = X_{in\text{str}}^\text{int}$, the two terms can be cancelled and Equation 4.16 can be used also in case of GPS/INS observations.

4.3.2.2 First order continuity

We impose that the value of the first derivative of each function at the end of segment $i$ ($t = 1$) is equal to the value of the first derivative of the same function at the beginning of segment $i+1$ ($t = 0$). In case of $X_c^i (\vec{t})$

$$\frac{\delta X_c^i}{\delta t} |_{t=1} = \frac{\delta X_c^{i+1}}{\delta t} |_{t=0} \quad (4.18)$$

that is
After substituting \( \vec{t} \), we obtain

\[
X_1^i + 2X_2^i = X_1^{i+1}
\]  
(4.20)

Extending to the other external orientation functions, it yields

\[
\begin{align*}
X_1^i + 2X_2^i &= X_1^{i+1} \\
Y_1^i + 2Y_2^i &= Y_1^{i+1} \\
Z_1^i + 2Z_2^i &= Z_1^{i+1} \\
o_1^i + 2o_2^i &= o_1^{i+1} \\
\phi_1^i + 2\phi_2^i &= \phi_1^{i+1} \\
\kappa_1^i + 2\kappa_2^i &= \kappa_1^{i+1}
\end{align*}
\]  
(4.21)

Equations 4.21 are also valid in case of GPS and INS integration, because the terms \([X_{\text{inst}}, Y_{\text{inst}}, Z_{\text{inst}}, o_{\text{inst}}, \phi_{\text{inst}}, \kappa_{\text{inst}}]_i\) are constant with null derivatives.

### 4.3.2.3 Second order continuity

The continuity of the second derivative between adjacent segments is imposed. For function \(X_C\), between segments \(i\) and \(i+1\) we have

\[
\left. \frac{\delta^2 X_C^i}{\delta \vec{t}^2} \right|_{\vec{t}=1} = \left. \frac{\delta^2 X_C^{i+1}}{\delta \vec{t}^2} \right|_{\vec{t}=0}
\]  
(4.22)

that is

\[
2X_1^i \bigg|_{\vec{t}=1} = 2X_1^{i+1} \bigg|_{\vec{t}=0}
\]  
(4.23)

After substituting \( \vec{t} \), we get

\[
X_2^i = X_2^{i+1}
\]  
(4.24)

Extending to the other external orientation functions, we obtain

\[
\begin{align*}
X_2^i &= X_2^{i+1} \\
Y_2^i &= Y_2^{i+1} \\
Z_2^i &= Z_2^{i+1} \\
o_2^i &= o_2^{i+1} \\
\phi_2^i &= \phi_2^{i+1} \\
\kappa_2^i &= \kappa_2^{i+1}
\end{align*}
\]  
(4.25)

Similar to the first order continuity constraints, Equations 4.25 are valid also in case of GPS and INS integration, because the constant terms \([X_{\text{inst}}, Y_{\text{inst}}, Z_{\text{inst}}, o_{\text{inst}}, \phi_{\text{inst}}, \kappa_{\text{inst}}]_i\) have null derivatives.
4.3.3 Reduction of polynomial order

The degree of the polynomial functions modelling the external orientation can be reduced. In fact all the PPM parameters can be fixed to suitable values. An interesting application is that by fixing the 2\textsuperscript{nd} order parameters to zero, the polynomial degree is reduced to 1 and linear functions, instead of quadratic functions, are obtained.

This option allows the modeling of the sensor position and/or attitude in the segments with 2\textsuperscript{nd} or 1\textsuperscript{st} order polynomials, according to the characteristics of the trajectory.

4.4 SELF-CALIBRATION

The self-calibration is used to correct the observations from systematic errors due to the imaging instrument. In Section 2.4 we have seen that various errors may occur in the geometry of the CCD arrays and in the optical system. The most significant errors are modelled with suitable functions depending on the so-called additional parameters (APs). Further investigation on the parameters’ determinability will indicate which parameters can be estimated. The APs are introduced in the basic collinearity equations (Equation 4.2) through the $\Delta x$ and $\Delta y$ terms (Equation 4.3).

For the mathematical description of $\Delta x$ and $\Delta y$ two cases are distinguished: single-lens optical systems and multi-lens optical systems.

**Single-lens optical systems.** We have one lens, one principal point with coordinates $(x_p, y_p)$ in the camera system, one focal plane and $N_{LINES}$ linear arrays placed on the focal plane. In this configuration we model the distortion of one lens and the displacement of $N_{LINES}$ linear arrays. The additional parameters introduced are:

- $\Delta x_C$ and $\Delta y_C$ (one set for each CCD line): the displacement of each line in the focal plane (Figures 2.16 and 2.17)
- $k_1, k_2$ and $p_1, p_2$: the symmetric radial and decentering lens distortions, which are modelled with Equations 2.15 and 2.16
- $s_y$: scale factor in $y$ direction, modelled with Equation 2.17
- $\theta$: angle (one for each CCD line): CCD line rotation in the focal plane (Figure 2.18). For small angles the effect in $y$ direction is neglectable and the one in $x$ direction is modelled with Equation 2.8.

The total number of additional parameters is equal to $5 + N_{LINES} \times 3$. The contribution of each additional parameter is summed. Finally for each line $j$, the equations that describe the internal errors are

$$\begin{align*}
\Delta x_j &= \Delta x_C - \frac{\Delta f}{f} \tilde{x}_p + (k_1 r^2 + k_2 r^4) \tilde{x}_p + p_1 (r^2 + 2 \tilde{x}_p^2) + 2 p_2 \tilde{x}_p \tilde{y}_p + \tilde{x}_p \sin \theta \\
\Delta y_j &= \Delta y_C - \frac{\Delta f}{f} \tilde{y}_p + (k_1 r^2 + k_2 r^4) \tilde{y}_p + 2 p_1 \tilde{x}_p \tilde{y}_p + p_2 (r^2 + 2 \tilde{y}_p^2) + s_y \tilde{y}_p
\end{align*}$$

(4.26)

where $\tilde{x}_p = x - x_p$, $\tilde{y}_p = y - y_p$ and $r^2 = \tilde{x}_p^2 + \tilde{y}_p^2$.

**Multi-lens optical systems.** We have $N_{LENS}$ lenses and one set of CCD line in each focal plane. In this configuration we model the distortions of $N_{LENS}$ lenses and the displacements of $N_{LINES}$ linear arrays. As we work with 8-bit images (one channel), we consider one CCD array in each focal plane, therefore $N_{LINES} = N_{LENS}$. Then the additional parameters modelling the internal errors are:
• \( \Delta x_P \) and \( \Delta y_P \) (one set for each lens): the displacement of the lens principal point. These parameters are perfectly correlated with the displacement of the CCD line in the focal plane (\( \Delta x_C \) and \( \Delta y_C \)) and include their effect

• \( k_1, k_2 \) and \( p_1, p_2 \) (one set for each lens): the symmetric radial and decentering lens distortion, which are modelled with Equations 2.15 and 2.16

• \( s_y \) (one for each lens): scale factor in \( y \) direction, modelled with Equation 2.17

• angle \( \theta \) (one for each CCD line): CCD line rotation in the focal plane (Figure 2.18). As for the single-lens case for small angles, the effect in \( y \) direction is neglectable and the one in \( x \) direction is modelled with Equation 2.8.

The total number of additional parameters is equal to \( N_{\text{LENS}} \times 8 \). By summing the contributions of the additional parameters, we obtain for each lens \( j \)

\[
\begin{align*}
\Delta x_j &= \Delta x_{pj} \frac{\Delta f}{f} \bar{x}_{pj} + (k_1 r_j^2 + k_2 r_j^4) x_{pj} + p_1 (r_j^2 + 2 \bar{x}_{pj}^2) + 2 p_2 \bar{x}_{pj} \bar{y}_{pj} + p_3 (r_j + 2 \bar{x}_{pj} \bar{y}_{pj}) + \bar{x}_{pj} \sin \theta \\
\Delta y_j &= \Delta y_{pj} \frac{\Delta f}{f} \bar{y}_{pj} + (k_1 r_j^2 + k_2 r_j^4) \bar{y}_{pj} + 2 p_1 \bar{x}_{pj} \bar{y}_{pj} + p_2 (r_j^2 + 2 \bar{y}_{pj}^2) + s_y \bar{y}_{pj}
\end{align*}
\]

where \( \bar{x}_{pj} = x - x_{pj}, \bar{y}_{pj} = y - y_{pj} \) and \( r^2 = \bar{x}_{pj}^2 + \bar{y}_{pj}^2 \).

4.5 OBSERVATION EQUATIONS

In this Section, the observation equations that will form the final system are listed and described. In the following Equations the observed quantities are overlined and the adjusted orientation values are not overlined.

4.5.1 Image coordinates

The coordinates of the GCPs and TPs are measured (=observed) in the images. Their observation equations are the collinearity equations (Equation 4.4), which describe the relationship between the observed image coordinates \( \bar{x} \) and \( \bar{y} \), together with their corrections \( v_x \) and \( v_y \), and the sensor external and internal orientation parameters and the ground coordinates of the points

\[
\begin{align*}
\bar{x} + v_x &= x = x_{pj} - f_j \cdot \frac{N_x}{D} + \Delta x \\
\bar{y} + v_y &= y = y_{pj} - f_j \cdot \frac{N_y}{D} + \Delta y
\end{align*}
\]

These equations are not linear. Their linearisation for the adjustment will be treated in Section 4.6.2. The weights given to these observation depend on the accuracy of the measurements, according to Equation 4.42.

4.5.2 External orientation parameters

Two groups of observations are written for the external orientation parameters. The first group contains the constraints on the continuity of the PPM functions. To the second group belong the weighted observations that fix the initial approximations of the PPM parameters to suitable (observed) quantities.
4.5.2.1 Continuity constraints

The constraints on the continuity of the PPM functions and their first and second derivatives, described in Section 4.5.2.1, are imported in the equation system as pseudo-observations with very high weight. As the functions continuity concerns, Equations 4.16, 4.21 and 4.25 become

\[
\begin{align*}
(X_i^0 + X_i^1 + X_i^2 - X_{i+1}^0) + v_{X_{c0}} &= X_i^0 + X_i^1 + X_i^2 - X_{i+1}^0 \\
(Y_i^0 + Y_i^1 + Y_i^2 - Y_{i+1}^0) + v_{Y_{c0}} &= Y_i^0 + Y_i^1 + Y_i^2 - Y_{i+1}^0 \\
(Z_i^0 + Z_i^1 + Z_i^2 - Z_{i+1}^0) + v_{Z_{c0}} &= Z_i^0 + Z_i^1 + Z_i^2 - Z_{i+1}^0 \\
(\omega_i^0 + \omega_i^1 + \omega_i^2 - \omega_{i+1}^0) + v_{\omega_{c0}} &= \omega_i^0 + \omega_i^1 + \omega_i^2 - \omega_{i+1}^0 \\
(\varphi_i^0 + \varphi_i^1 + \varphi_i^2 - \varphi_{i+1}^0) + v_{\varphi_{c0}} &= \varphi_i^0 + \varphi_i^1 + \varphi_i^2 - \varphi_{i+1}^0 \\
(\kappa_i^0 + \kappa_i^1 + \kappa_i^2 - \kappa_{i+1}^0) + v_{\kappa_{c0}} &= \kappa_i^0 + \kappa_i^1 + \kappa_i^2 - \kappa_{i+1}^0
\end{align*}
\]

For the first order continuity, we have

\[
\begin{align*}
(X_i^1 + 2X_i^2 - X_{i+1}^1) + v_{X_{c1}} &= X_i^1 + 2X_i^2 - X_{i+1}^1 \\
(Y_i^1 + 2Y_i^2 - Y_{i+1}^1) + v_{Y_{c1}} &= Y_i^1 + 2Y_i^2 - Y_{i+1}^1 \\
(Z_i^1 + 2Z_i^2 - Z_{i+1}^1) + v_{Z_{c1}} &= Z_i^1 + 2Z_i^2 - Z_{i+1}^1 \\
(\omega_i^1 + 2\omega_i^2 - \omega_{i+1}^1) + v_{\omega_{c1}} &= \omega_i^1 + 2\omega_i^2 - \omega_{i+1}^1 \\
(\varphi_i^1 + 2\varphi_i^2 - \varphi_{i+1}^1) + v_{\varphi_{c1}} &= \varphi_i^1 + 2\varphi_i^2 - \varphi_{i+1}^1 \\
(\kappa_i^1 + 2\kappa_i^2 - \kappa_{i+1}^1) + v_{\kappa_{c1}} &= \kappa_i^1 + 2\kappa_i^2 - \kappa_{i+1}^1
\end{align*}
\]

and for the second order derivative

\[
\begin{align*}
(X_i^2 - X_{i+1}^2) + v_{X_{c2}} &= X_i^2 - X_{i+1}^2 \\
(Y_i^2 - Y_{i+1}^2) + v_{Y_{c2}} &= Y_i^2 - Y_{i+1}^2 \\
(Z_i^2 - Z_{i+1}^2) + v_{Z_{c2}} &= Z_i^2 - Z_{i+1}^2 \\
(\omega_i^2 - \omega_{i+1}^2) + v_{\omega_{c2}} &= \omega_i^2 - \omega_{i+1}^2 \\
(\varphi_i^2 - \varphi_{i+1}^2) + v_{\varphi_{c2}} &= \varphi_i^2 - \varphi_{i+1}^2 \\
(\kappa_i^2 - \kappa_{i+1}^2) + v_{\kappa_{c2}} &= \kappa_i^2 - \kappa_{i+1}^2
\end{align*}
\]

The weights of the corresponding pseudo-observations are set at very high values (~10^{20}).

4.5.2.2 Observations for the external orientation parameters

The initial values of the PPM parameters are treated as pseudo-observations. In each segment the following equations are written for the external orientation parameters
4.5. OBSERVATION EQUATIONS

\[
\begin{align*}
\bar{X}_0 + v_{X_0} &= X_0 \\
\bar{Y}_0 + v_{Y_0} &= Y_0 \\
\bar{Z}_0 + v_{Z_0} &= Z_0 \\
\bar{X}_1 + v_{X_1} &= X_1 \\
\bar{Y}_1 + v_{Y_1} &= Y_1 \\
\bar{Z}_1 + v_{Z_1} &= Z_1 \\
\bar{X}_2 + v_{X_2} &= X_2 \\
\bar{Y}_2 + v_{Y_2} &= Y_2 \\
\bar{Z}_2 + v_{Z_2} &= Z_2 \\
\bar{\omega}_0 + v_{\omega_0} &= \omega_0 \\
\bar{\phi}_0 + v_{\phi_0} &= \phi_0 \\
\bar{\kappa}_0 + v_{\kappa_0} &= \kappa_0 \\
\bar{\omega}_1 + v_{\omega_1} &= \omega_1 \\
\bar{\phi}_1 + v_{\phi_1} &= \phi_1 \\
\bar{\kappa}_1 + v_{\kappa_1} &= \kappa_1 \\
\bar{\omega}_2 + v_{\omega_2} &= \omega_2 \\
\bar{\phi}_2 + v_{\phi_2} &= \phi_2 \\
\bar{\kappa}_2 + v_{\kappa_2} &= \kappa_2
\end{align*}
\]

(4.32)

If the degree of the polynomials of any external orientation functions is reduced to 1 or 0 (Section 4.3.3), the initial values of the corresponding 2nd and 1st order parameters are put equal to 0 and the weights of the corresponding pseudo-observations are set at very high values (~10^20).

4.5.3 Self-calibration parameters

In case the parameters modelling the internal orientation are known from laboratory calibration, the measurements can be treated as weighted observations.

For the lens/ the observation equations for the internal orientation parameters are

\[
\begin{align*}
\Delta x_p + v_{\Delta x_p} &= \Delta x_p \\
\Delta y_p + v_{\Delta y_p} &= \Delta y_p \\
\Delta f + v_{\Delta f} &= \Delta f \\
\bar{k}_1 + v_{\bar{k}_1} &= k_1 \\
\bar{k}_2 + v_{\bar{k}_2} &= k_2 \\
\bar{p}_1 + v_{\bar{p}_1} &= p_1 \\
\bar{p}_2 + v_{\bar{p}_2} &= p_2 \\
\bar{s}_y + v_{\bar{s}_y} &= s_y \\
\bar{\theta} + v_{\bar{\theta}} &= \theta
\end{align*}
\]

(4.34)

The weights are inversely proportional to the variances of the calibration results.

4.5.4 Ground control points

The ground coordinates of the GCPs are not treated as fixed parameters in a refined adjustment. As they are themselves derived from measurements, they have an accuracy quantified by a standard deviation and must be treated as observations. The observation equations for the ground coordinates of the GCPs results

\[
\begin{align*}
\bar{X} + v_X &= X \\
\bar{Y} + v_Y &= Y \\
\bar{Z} + v_z &= Z
\end{align*}
\]

(4.35)
4.6 LEAST SQUARES ADJUSTMENT

4.6.1 Theory of least squares adjustment

We consider the set of linear equations

\[ l_i = \sum_{j=0}^{n} a_{ij} x_j \quad (4.36) \]

where
- \( a_{ij} \): coefficients of design matrix \( A \)
- \( l_i \): observations
- \( x_j \): unknown parameter
- \( n \): number of observations
- \( u \): number of unknowns

If the number of observations and unknowns is the same, the solution of the system \( l = Ax \) is unique and can be calculated as \( x = A^{-1} l \). However, if there are more observations than unknowns, the solution will be estimated under the condition that the sum of the squares of the corrections \( v \) of the observations is a minimum. In this case the system \( l = Ax \) is rewritten in the form of observation equations

\[ v = A\hat{x} - l \quad (4.37) \]

The unknown vector \( \hat{x} \) can then be determined from the minimum condition

\[ v^T v = \min = (A\hat{x} - l)^T (A\hat{x} - l) \quad (4.38) \]

with solution

\[ \frac{\partial (v^T v)}{\partial \hat{x}} = 2\hat{x}^T A^T A - 2l^T A = 0 \quad (4.39) \]

\[ \hat{x} = (A^T A)^{-1} A^T l \]

where \((A^T A)\) is the normal equation matrix.

In case of a non-linear system of equations

\[ l_i = f(x_i) \quad (4.40) \]

the equations must be linearized: the non-linear equations are replaced by an approximation consisting in the first terms of a Taylor series expansion with the initial values \( x^0 \).

The unknown vector \( x \) now represents the corrections that must be applied to the initial values of the parameters \( x^0 \). The design matrix contains the partial derivatives of the system functions with respect to the unknown parameters and expressed numerically by substituting the approximations \( x^0 \). Now the vector \( l \) is the difference between the observation \( l \) and the value calculated from the non-linear equations using the approximations \( x^0 \)

\[ l = l - f(x^0) \quad (4.41) \]

For a correct solution of the system, two extensions of the method are required. The first extension regards the concept of groups of observations with different accuracies. The
accuracy is expressed by the standard deviations of an observation \( \sigma_i \), or by the variance \( \sigma_i^2 \). It is introduced into an adjustment in the form of \( p_i \) in a weight matrix \( P_u \). The weights \( p_i \) are calculated as

\[
p_i = \frac{\sigma_i^2}{\sigma_0^2}
\]  

(4.42)

where \( \sigma_0^2 \) is the a-priori variance of unit weight. In order to calculate suitable values for more groups of observations, the following rule has been followed. Considering two groups of observations A and B and calling \( \sigma_A \) and \( \sigma_B \) the standard deviations of the measurements and \( p_A \) and \( p_B \) the corresponding weights, the Equation

\[
\frac{p_A}{p_B} = \frac{\sigma_B^2}{\sigma_A^2}
\]

(4.43)

describes the relationship between \( \sigma_A, \sigma_B, p_A \), and \( p_B \).

Therefore, once the weight \( p_A \) is set, the weight of any other group of observations B can be calculated as

\[
p_B = \frac{p_A \cdot \sigma_B^2}{\sigma_A^2}
\]

(4.44)

We assume that the observations are independent; therefore \( P_u \) is a diagonal matrix. The minimum condition \( v^T v = \text{min} \) then becomes \( v^T P_l v = \text{min} \), which leads to the solution

\[
\hat{x} = (A^T P_u A)^{-1} A^T P_u l
\]

(4.45)

Introducing the normal matrix \( N \) and the vector \( z \), defined as

\[
N = A^T P_u A
\]

(4.46)

\[
z = A^T P_u l
\]

(4.47)

Equation 4.45 can now be seen as the linear system

\[
\hat{x} = N^{-1} z
\]

(4.48)

By inserting \( \hat{x} \) in Equation 4.37, the corrections \( v \) for all observations \( l \) are calculated. The estimated vector \( \hat{x} \) is used to update the vector containing the current parameters values \( X \). At iteration \( i \) the values of the parameters are the initial approximations (Section 4.6.2.2). For the iteration \( i \)

\[
X^{i+1} = X^i + x
\]

(4.49)

At iteration \( i+1 \), the design matrix \( A \) and the vector \( l \) are recomputed using the new values \( X^{i+1} \) from Equation 4.49 and a new solution is estimated. The iterative process stops when absolute tests on the values of vector \( x \) are satisfied. The thresholds are different for each group of unknowns and are decided by the operator, according to the single case study.
4.6.2 Linearization

The collinearity equations are not linear with respect to the unknowns and must be linearized. According to the Taylor decomposition until the first derivative, a non linear function

\[
f(x_1, \ldots, x_n) = f(x_1, \ldots, x_n)_0 + \frac{\delta f}{\delta x_1} \delta x_1 + \ldots + \frac{\delta f}{\delta x_n} \delta x_n
\]  

(4.50)

The same rule is followed for the linearization of the equations used in the model. In the next sections the computation of the derivatives are reported.

4.6.2.1 Derivatives of collinearity equations

Referring to Equation 4.3 for the collinearity equations and to Equation 4.9 and Equation 4.12 for the external orientation modelling, the derivatives of \( x \) with respect to the external orientation parameters are calculated in this way

\[
\begin{align*}
\frac{\delta x}{\delta X_0} &= \frac{\delta x}{\delta X_0} \frac{\delta X_C}{\delta X_0} \\
\frac{\delta x}{\delta Y_0} &= \frac{\delta x}{\delta Y_0} \frac{\delta Y_C}{\delta Y_0} \\
\frac{\delta x}{\delta Z_0} &= \frac{\delta x}{\delta Z_0} \frac{\delta Z_C}{\delta Z_0} \\
\frac{\delta x}{\delta \omega_0} &= \frac{\delta x}{\delta \omega_0} \frac{\delta \omega_C}{\delta \omega_0} \\
\frac{\delta x}{\delta \phi_0} &= \frac{\delta x}{\delta \phi_0} \frac{\delta \phi_C}{\delta \phi_0} \\
\frac{\delta x}{\delta \kappa_0} &= \frac{\delta x}{\delta \kappa_0} \frac{\delta \kappa_C}{\delta \kappa_0}
\end{align*}
\]  

(4.51)

and the same logic is followed for \( y \)

\[
\begin{align*}
\frac{\delta y}{\delta X_0} &= \frac{\delta y}{\delta X_0} \frac{\delta X_C}{\delta X_0} \\
\frac{\delta y}{\delta Y_0} &= \frac{\delta y}{\delta Y_0} \frac{\delta Y_C}{\delta Y_0} \\
\frac{\delta y}{\delta Z_0} &= \frac{\delta y}{\delta Z_0} \frac{\delta Z_C}{\delta Z_0} \\
\frac{\delta y}{\delta \omega_0} &= \frac{\delta y}{\delta \omega_0} \frac{\delta \omega_C}{\delta \omega_0} \\
\frac{\delta y}{\delta \phi_0} &= \frac{\delta y}{\delta \phi_0} \frac{\delta \phi_C}{\delta \phi_0} \\
\frac{\delta y}{\delta \kappa_0} &= \frac{\delta y}{\delta \kappa_0} \frac{\delta \kappa_C}{\delta \kappa_0}
\end{align*}
\]
Section 4.6. LEAST SQUARES ADJUSTMENT

\[
\begin{align*}
\frac{\delta y}{\delta \phi_0} &= \frac{\delta y}{\delta \phi_1} = \frac{\delta y}{\delta \phi_2} = \frac{\delta y}{\delta \phi_3} = \frac{\delta y}{\delta \phi_c}, \\
\frac{\delta y}{\delta \kappa_0} &= \frac{\delta y}{\delta \kappa_1} = \frac{\delta y}{\delta \kappa_2} = \frac{\delta y}{\delta \kappa_c} \\
\frac{\delta y}{\delta \kappa_c} &= \frac{\delta y}{\delta \phi_c} \\
\frac{\delta y}{\delta \phi_c} &= \frac{\delta y}{\delta \phi_c} \\
\frac{\delta y}{\delta \phi_c} &= \frac{\delta y}{\delta \phi_c} \\
\frac{\delta y}{\delta \phi_c} &= \frac{\delta y}{\delta \phi_c} \\
\frac{\delta y}{\delta \phi_c} &= \frac{\delta y}{\delta \phi_c} \\
\frac{\delta y}{\delta \phi_c} &= \frac{\delta y}{\delta \phi_c} \\
\frac{\delta y}{\delta \phi_c} &= \frac{\delta y}{\delta \phi_c} \\
\frac{\delta y}{\delta \phi_c} &= \frac{\delta y}{\delta \phi_c}
\end{align*}
\] (4.52)

The partial derivatives are

\[
\begin{align*}
\frac{\delta X_C}{\delta X_0} &= \frac{\delta Y_C}{\delta Y_0} = \frac{\delta Z_C}{\delta Z_0} = \frac{\delta \omega_C}{\delta \omega_0} = \frac{\delta \phi_C}{\delta \phi_0} = \frac{\delta \kappa_C}{\delta \kappa_0} = 1 \\
\frac{\delta X_C}{\delta X_1} &= \frac{\delta Y_C}{\delta Y_1} = \frac{\delta Z_C}{\delta Z_1} = \frac{\delta \omega_C}{\delta \omega_1} = \frac{\delta \phi_C}{\delta \phi_1} = \frac{\delta \kappa_C}{\delta \kappa_1} = t \\
\frac{\delta X_C}{\delta X_2} &= \frac{\delta Y_C}{\delta Y_2} = \frac{\delta Z_C}{\delta Z_2} = \frac{\delta \omega_C}{\delta \omega_2} = \frac{\delta \phi_C}{\delta \phi_2} = \frac{\delta \kappa_C}{\delta \kappa_2} = t^2
\end{align*}
\] (4.53)

The derivatives with respect the sensor position and attitude are

\[
\begin{align*}
\frac{\partial x}{\partial X_C} &= \frac{f}{D^2} (s_{13} N_x - s_{11} D) = a_{1,1} \\
\frac{\partial x}{\partial Y_C} &= \frac{f}{D^2} (s_{23} N_x - s_{21} D) = a_{1,2} \\
\frac{\partial x}{\partial Z_C} &= \frac{f}{D^2} (s_{33} N_x - s_{31} D) = a_{1,3} \\
\frac{\partial x}{\partial \omega_C} &= \frac{f}{D} \left[ (X - X_C) \frac{\delta s_{13}}{\delta \omega_C} + (Y - Y_C) \frac{\delta s_{23}}{\delta \omega_C} - (Z - Z_C) \frac{\delta s_{33}}{\delta \omega_C} \right] + \frac{N_x}{D} - (X - X_0) \frac{\delta s_{11}}{\delta \omega_C} - (Y - Y_0) \frac{\delta s_{21}}{\delta \omega_C} \\
&\quad - (Z - Z_0) \frac{\delta s_{31}}{\delta \omega_C} \\
\frac{\partial x}{\partial \phi_C} &= \frac{f}{D} \left[ (X - X_C) \frac{\delta s_{13}}{\delta \phi_C} + (Y - Y_C) \frac{\delta s_{23}}{\delta \phi_C} - (Z - Z_C) \frac{\delta s_{33}}{\delta \phi_C} \right] + \frac{N_x}{D} - (X - X_0) \frac{\delta s_{11}}{\delta \phi_C} - (Y - Y_0) \frac{\delta s_{21}}{\delta \phi_C} \\
&\quad - (Z - Z_0) \frac{\delta s_{31}}{\delta \phi_C} \\
\frac{\partial x}{\partial \kappa_C} &= \frac{f}{D} \left[ (X - X_C) \frac{\delta s_{13}}{\delta \kappa_C} + (Y - Y_C) \frac{\delta s_{23}}{\delta \kappa_C} - (Z - Z_C) \frac{\delta s_{33}}{\delta \kappa_C} \right] + \frac{N_x}{D} - (X - X_0) \frac{\delta s_{11}}{\delta \kappa_C} - (Y - Y_0) \frac{\delta s_{21}}{\delta \kappa_C} \\
&\quad - (Z - Z_0) \frac{\delta s_{31}}{\delta \kappa_C} \\
\frac{\partial y}{\partial X_C} &= \frac{f}{N^2} (r_{13} Z_y - r_{13} N) = a_{2,1} \\
\frac{\partial y}{\partial Y_C} &= \frac{f}{N^2} (r_{23} Z_y - r_{23} N) = a_{2,2} \\
\frac{\partial y}{\partial Z_C} &= \frac{f}{N^2} (r_{33} Z_y - r_{33} N) = a_{2,3}
\end{align*}
\]
\[
\frac{\partial y}{\partial \Omega_c} = \frac{f}{N}\left\{\left[(Y - Y_0)r_{33} - (Z - Z_0)r_{23}\right] \frac{Z_y}{N} - (Y - Y_0)r_{32} - (Z - Z_0)r_{22}\right\} = a_{2,1}
\]

\[
\frac{\partial y}{\partial \kappa_c} = \frac{f}{N}\left[\left((Z_x \cos \kappa) - (Z_y \sin \kappa)\right) \frac{Z_y}{N} + N \cos \kappa\right] = a_{2,2}
\]

\[
\frac{\partial y}{\partial \kappa} = \frac{f}{N}Z_y = a_{2,3}
\]

The coefficients \( a_{ij} \) refer to the position in the matrices \( A_{GCP} \) and \( A_{TP} \) (Section 4.6.3). The derivatives of Equation 4.3 with respect to the ground coordinates of the GCPs and TPs are

\[
\frac{\partial x}{\partial X} = \frac{f}{D} \left( Ds_{11} - N_x s_{13} \right) = b_{1,1}
\]

\[
\frac{\partial y}{\partial X} = \frac{f}{D^2} \left( Ds_{12} - N_y s_{13} \right) = b_{2,1}
\]

\[
\frac{\partial x}{\partial Y} = \frac{f}{D} \left( Ds_{21} - N_x s_{23} \right) = b_{1,2}
\]

\[
\frac{\partial y}{\partial Y} = \frac{f}{D^2} \left( Ds_{22} - N_y s_{23} \right) = b_{2,2}
\]

\[
\frac{\partial x}{\partial Z} = \frac{f}{D^2} \left( Ds_{31} - N_x s_{33} \right) = b_{1,3}
\]

\[
\frac{\partial y}{\partial Z} = \frac{f}{D^2} \left( Ds_{32} - N_y s_{33} \right) = b_{2,3}
\]

The coefficients \( b_{ij} \) refer to the position in the matrices \( B_{GCP} \) and \( B_{TP} \) (Section 4.6.3). Regarding the self-calibration unknowns, all the parameters except \( \theta \) are linear. For \( \theta \) the derivatives are calculated from Equation 4.27, resulting

\[
\frac{\partial x}{\partial \theta} = \bar{y}_p \cos \theta = s_{1,9}
\]

\[
\frac{\partial y}{\partial \theta} = 0 = s_{2,9}
\]

The coefficients \( s_{ij} \) refer to the position in the matrix \( S \) (Section 4.6.3). The values of \( s_{ij} \) for the parameters \( \Delta x_p, \Delta y_p, \Delta x_C, \Delta y_C, c, k_1, k_2, p_1, p_2, s_y \) are listed in Table 4.1.

Table 4.1. Coefficients of \( \Delta x_p, \Delta y_p, \Delta x_C, \Delta y_C, c, k_1, k_2, p_1, p_2, s_y \) for \( x \) and \( y \) and position in matrix \( S \).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( x )</th>
<th>( y )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta x_p )</td>
<td>1</td>
<td>( s_{1,1} )</td>
</tr>
<tr>
<td>( \Delta y_p )</td>
<td>0</td>
<td>( s_{1,2} )</td>
</tr>
<tr>
<td>( \Delta x_C )</td>
<td>1</td>
<td>( s_{1,1} )</td>
</tr>
<tr>
<td>( \Delta y_C )</td>
<td>0</td>
<td>( s_{1,2} )</td>
</tr>
<tr>
<td>( c )</td>
<td>( \frac{1}{c} \bar{x}_p )</td>
<td>( s_{1,3} )</td>
</tr>
<tr>
<td>( k_1 )</td>
<td>( r^2 \bar{x}_p )</td>
<td>( s_{1,4} )</td>
</tr>
<tr>
<td>( k_2 )</td>
<td>( r^4 \bar{x}_p )</td>
<td>( s_{1,5} )</td>
</tr>
<tr>
<td>( p_1 )</td>
<td>( 2 \bar{x}_p^2 + r^2 )</td>
<td>( s_{1,6} )</td>
</tr>
<tr>
<td>( p_2 )</td>
<td>( 2 \bar{x}_p \bar{y}_p )</td>
<td>( s_{1,7} )</td>
</tr>
<tr>
<td>( s_y )</td>
<td>0</td>
<td>( s_{1,8} )</td>
</tr>
</tbody>
</table>
4.6.2.2 Initial values

In order to calculate the derivatives and run the iterative bundle adjustment, the initial approximations for all the unknown parameters are required. The approximative values of the parameters modelling the sensor external orientation are calculated by additional information on the platform trajectory. In case of sensors carried on satellite, the sensor position and attitude in the ECR system are computed from the ephemeris, as described in Section 3.2. Then the initial approximations for the PPM parameters \([X_0, X_1, X_2, \ldots, \kappa_0, \kappa_1, \kappa_2]\) of each segment are calculated with discrete mathematics methods. Considering the segment \(i\) with time extremes \(t_{ini}\) and \(t_{fin}\) and the function \(X_C(t)\), the values of \(X_C\) are interpolated with cubic splines (Section 3.2.3) for time \(t_{ini}\), \(t_{mid} = \frac{t_{fin} - t_{ini}}{2}\), and \(t_{fin}\), then the first and second derivatives are computed as

\[
d_1 = \frac{X(t_{fin}) - X(t_{ini})}{t_{fin} - t_{ini}}
\]

\[
d_2 = \frac{2 \cdot X(t_{mid}) - X(t_{fin}) - X(t_{ini})}{(t_{fin} - t_{ini})^2}
\]

Taking into account that

\[
X_C = X_0 + X_1 t + X_2 t^2
\]

\[
\frac{\delta X_C}{\delta t} = X_1 + 2X_2 t
\]

\[
\frac{\delta^2 X_C}{\delta t^2} = 2X_2
\]

for \(i = 1\) and \(X_0 = X_{ini}\), we have

\[
X_{fin} = X_{ini} + X_1 + X_2
\]

\[
\frac{\delta X_C}{\delta t} = X_1 + 2X_2
\]

\[
\frac{\delta^2 X_C}{\delta t^2} = 2X_2
\]

Imposing

\[
d_1 = \frac{\delta X_C}{\delta t}
\]

\[
d_2 = \frac{\delta^2 X_C}{\delta t^2}
\]

for each segment we can compute \(X_2\) as

\[
X_2 = \frac{d_2}{X_0}
\]

and \(X_1\) as

\[
X_1 = d_1 - 2X_2
\]
The same calculations are used for the estimation of the initial approximations for the PPM parameters modelling $Y_C, Z_C, \omega_C, \phi_C$ and $\kappa_C$.

As sensors carried on aircraft are concerned, the initial (approximate) parameters modelling the sensor external orientation are set equal to zero, that is, in the first iteration the sensor external orientation of each line is equal to the corresponding GPS and INS observations.

The approximate ground coordinates of the TPs are estimated with forward intersection (described in Section 3.3), using as sensor external orientation the values calculated from the approximate parameters.

Finally, the initial parameters modeling the self-calibration are set equal to the laboratory calibration values, if available, otherwise to zero.

**4.6.3 Design matrix construction**

In this paragraph the blocks constituting the complete design matrix are described and their structure is visualized in simple drawings. The following symbols will be used for the blocks dimensions: $N_{GCP}$ for the number of GCPs, $N_{TP}$ for the number of TPs and $N_S$ for the number of PPM segments used in the adjustment, $N_{LINES}$ for the number of linear arrays and $N_{LENS}$ for the number of lenses.

**4.6.3.1 Collinearity equations for GCPs and TPs**

After the linearization, the design matrices for the GCPs and TPs are filled with the derivatives of the collinearity equations with respect to the unknown parameters, computed in the approximate values of the parameters themselves.

For the GCPs the generated matrices are:

- $A_{GCP}$ with the derivatives with respect to the external orientation unknowns (Equations 4.54)
- $B_{GCP}$ containing the derivatives with respect to the ground coordinates (Equations 4.55)
- $S_{GCP}$ containing the coefficients for the self-calibration parameters (Equations 4.56).

The TPs fill the following matrices:

- $A_{TP}$ with the derivatives with respect to the external orientation unknowns (Equations 4.54)
- $B_{TP}$ containing the derivatives with respect to ground coordinates (Equations 4.55)
- $S_{TP}$ containing the coefficients for the self-calibration parameters (Equations 4.56).

$A_{GCP}$ and $A_{TP}$ are block matrices (Figure 4.3), where each block has dimension (2,18) (Figure 4.4). $A_{GCP}$ has dimension $[2\times N_{LINES}\times N_{GCP}, 18\times N_S]$, while $A_{TP}$ has dimension $[2\times N_{LINES}\times N_{TP}, 18\times N_S]$.

```
A =
```

![Figure 4.3. Structure of matrix A for GCP and TP.](image)
Section 4.6. LEAST SQUARES ADJUSTMENT

$B_{\text{GCP}}$ and $B_{\text{TP}}$ are diagonal block matrices (Figures 4.5 and 4.6) with dimension $[3 \times N_{\text{GCP}}, 3 \times N_{\text{GCP}}]$ and $[3 \times N_{\text{TP}}, 3 \times N_{\text{TP}}]$ respectively.

The matrices $S_{\text{GCP}}$ and $S_{\text{TP}}$ have the same structure and are slightly different for one-lens and multi-lens optical systems, because the number of parameters is different (Section 4.4). For one-lens optical systems the dimensions of $S_{\text{GCP}}$ and $S_{\text{TP}}$ are $[2 \times N_{\text{LINES}} \times N_{\text{GCP}}, 5 + 3 \times N_{\text{LINES}}]$ and $[2 \times N_{\text{LINES}} \times N_{\text{TP}}, 5 + N_{\text{LINES}} \times 3]$, while for multi-lens optical systems they are $[2 \times N_{\text{LINES}} \times N_{\text{GCP}}, 8 \times N_{\text{LENS}}]$ and $[2 \times N_{\text{LINES}} \times N_{\text{TP}}, 8 \times N_{\text{LENS}}]$. In Figure 4.7 the schemes of $S_{\text{GCP}}$ for one-lens and multi-lens sensors are shown. The same applies for $S_{\text{TP}}$. In Figure 4.8 the components of each block are shown.

Figure 4.4. Elements in matrices $A_{\text{GCP}}$ and $A_{\text{TP}}$.

Figure 4.5. Structure of matrix $B$ for GCP and TP.

Figure 4.6. Elements in matrices $B_{\text{GCP}}$ and $B_{\text{TP}}$.

Figure 4.7. Scheme of design matrices $S_{\text{GCP}}$ for one-lens (left) and multi-lens (right) pushbroom sensors.

Figure 4.8. Components of each block for $S_{\text{TP}}$. 
4.6.3.2 External orientation constraints

The design matrices describing the constraints on the polynomials' continuity are called \( C_n \), with \( n=0, 1, 2 \), according to the degree of the derivatives. They are obtained from Equations 4.29, 4.30 and 4.31. The size of the matrices is \([6 \times (N_S-1), 18 \times N_S]\).

The structure of matrix \( C_0 \) that describes the constraint on the continuity of the functions is shown in Figures 4.9 and 4.10. The design matrix describing the first order constraint, called \( C_1 \), and the design matrix describing the second order constraint, called \( C_2 \), are shown in Figures 4.11, 4.12, 4.13 and 4.14.

4.6.3.3 Initial values of PPM parameters

The unknown PPM parameters are fixed to the initial values by means of pseudo-observations. The design matrix describing the pseudo-observations for the PPM parameters is called \( F \). According to the formulas introduced in Section 4.5.2.2, the matrix \( F \) is a unit diagonal matrix, with dimension equal to the number of PPM parameters \([18 \times N_S, 18 \times N_S]\).

4.6.3.4 Initial values of APs

The matrix that describes the pseudo-observations on the self-calibration parameters \((\Delta x_P, \Delta y_P, k_1, k_2, p_1, p_2, s_y \) and \( 0)\) is a unit diagonal matrix, called \( S \), with dimension \([\text{dim}_S, \text{dim}_S]\). As shown in Section 4.4, the dimension \( \text{dim}_S \) is: \( N_{_\text{LINES}} \times 8 \) (multi-lens case) and \( 5+3 \times N_{_\text{LINES}} \) (single-lens case).

4.6.3.5 Initial values of GCP coordinates

The ground coordinates of the GCPs are introduced in the model as pseudo-observations. The observation matrix, indicated with letter \( E \), is a diagonal matrix with dimension \([3 \times N_{_\text{GCP}}, 3 \times N_{_\text{GCP}}]\).

4.6.3.6 Final matrix

The single blocks are positioned into the final design matrix (indicated with letter \( A \)), taking into account the structure of the vector \( x \), containing the unknown parameters of the model. In details, vector \( x \) contains:
- \( x_{\text{PPM}} \): PPM parameters \((18 \times N_S)\)
- \( x_{\text{TP}} \): TP's ground coordinates \((3 \times N_{_\text{TP}})\)
- \( x_{\text{GCP}} \): GCP ground coordinates \((3 \times N_{_\text{GCP}})\)
- \( x_{\text{SC}} \): self-calibration parameters \((5+3 \times N_{_\text{LINES}}\) for single-lens optical systems and \( 8 \times N_{_\text{LINES}} \) for multi-lens optical systems).
Section 4.6. LEAST SQUARES ADJUSTMENT

\[ C_0 = \begin{bmatrix} \text{segment 1} & \text{segment 2} & \text{segment } i & \text{segment } N_B \end{bmatrix} \]

Figure 4.9. Structure of matrix \( C_0 \).

\[ \begin{bmatrix} 111 \\ 100 \end{bmatrix} \]

Figure 4.10. Single blocks in matrix \( C_0 \).

\[ C_1 = \begin{bmatrix} \text{segment 1} & \text{segment 2} & \text{segment } i & \text{segment } N_B \end{bmatrix} \]

Figure 4.11. Structure of matrix \( C_1 \).

\[ \begin{bmatrix} 012 \\ 010 \end{bmatrix} \]

Figure 4.12. Single blocks in matrix \( C_1 \).

\[ C_2 = \begin{bmatrix} \text{segment 1} & \text{segment 2} & \text{segment } i & \text{segment } N_B \end{bmatrix} \]

Figure 4.13. Structure of matrix \( C_2 \).

\[ \begin{bmatrix} 001 \\ 00-1 \end{bmatrix} \]

Figure 4.14. Single blocks in matrix \( C_2 \).

Equations 4.64 and 4.65 and Figure 4.15 show the components of vector \( x \) and design matrix \( A \).

\[ x = \begin{bmatrix} x_{EO} \\ x_{TP} \\ x_{GCP} \\ x_{SC} \end{bmatrix} \quad \text{(4.64)} \]

\[ A = \begin{bmatrix} A_{GCP} & S_{GCP} \\ A_{TP} & B_{TP} & S_{TP} \\ C_0 \\ C_1 \\ C_2 \\ F \\ E \\ S \end{bmatrix} \quad \text{(4.65)} \]
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The final observation system results

\[
\begin{align*}
\begin{bmatrix}
  v_{GCP} = & A_{GCP}x_{EO} + S_{GCP}x_{SC} - l_{TP} : P_{GCP} \\
  v_{TP} = & A_{TP}x_{EO} + B_{TP}x_{TP} + S_{GCP}x_{SC} - l_{C0} : P_{C0} \\
  v_{C0} = & C_{0}x_{EO} - l_{C1} : P_{C1} \\
  v_{C1} = & C_{1}x_{EO} - l_{C2} : P_{C2} \\
  v_{C2} = & C_{2}x_{EO} - l_{F} : P_{F} \\
  v_{E} = & Fx_{EO} - E_{GCP} : P_{E} \\
  v_{S} = & S - l_{S} : P_{S}
\end{bmatrix}
\]

(4.66)

The matrices \( P_{xx} \) are the weight matrices of the single observations groups. They form the complete weight matrix \( P_{n} \), a diagonal matrix with structure

\[
P_{n} = \begin{bmatrix} P_{GCP} & P_{TP} & P_{C0} & P_{C1} & P_{C2} & P_{EO} & P_{E} & P_{S} \end{bmatrix}
\]

(4.67)

Calling \( n \) the number of observations and \( u \) the number of unknowns, the dimensions of \( x, A \) and \( P_{n} \) are \([u, 1]\), \([n, u]\) and \([n,n]\) respectively.

The resulting normal matrix \( N \), obtained by Equation 4.46, has dimensions \([u, u]\), is symmetric and sparse.

Figure 4.15. Structure of design matrix (right) and unknown vector (left).
4.6.4 Solution of linear system

Now the system

\[ Nx = z \]  \hspace{1cm} (4.68)

must be solved with respect to \( x \).

The normal matrix \( N \) is composed by blocks with different design: diagonal, hyperdiagonal, null and sparse matrices. It is a complex structure with a variable number of submatrices, depending on the parameters to be modelled. Such a structure needs to be treated with suitable algorithms, in order to reduce the storage and the computing efforts. The success of the methods depends on the degree with which, in the reduction, the filling with non-zero elements can be limited, on the extend to which the zero elements can be kept out of the numerical process and on the use of simple and fast routines for the computation of the solution.

The main methods used for the solution of general least squares problems are based on LU factorization, Cholesky factorization and QR factorization. In all three methods a matrix is decomposed into the product of two matrices with specific characteristics that render the calculation of the solution more simple. In literature different publications can be found about the comparison of the three methods (Choi et al., 1994, Dongarra, 1995, Hairer and Wanner, 1996).

In our model the normal matrix is solved with the LU decomposition. According to this method, the normal matrix \( N \) is written as the product of two matrices

\[ N = LU \]  \hspace{1cm} (4.69)

where \( L \) is lower triangular (with elements \( \alpha_{ij} \) only on the diagonal and below) and \( U \) is upper triangular (with elements \( \beta_{ij} \) only on the diagonal and above). For the case of a \([n,n]\) matrix, Equation 4.69 becomes

\[
\begin{bmatrix}
\alpha_{11} & 0 & 0 & \cdots & 0 \\
0 & \alpha_{22} & 0 & \cdots & 0 \\
0 & 0 & \alpha_{33} & \cdots & 0 \\
\cdots & \cdots & \cdots & \cdots & \cdots \\
0 & 0 & 0 & \cdots & \alpha_{nn}
\end{bmatrix}
\begin{bmatrix}
\beta_{1n} \\
\beta_{2n} \\
\beta_{3n} \\
\vdots \\
\beta_{nn}
\end{bmatrix}
\]

(4.70)

Using this decomposition, the linear set

\[ Nx = (LU)x = L(Ux) = z \]  \hspace{1cm} (4.71)

is solved by first solving for the vector \( y \) such that

\[ Ly = z \]  \hspace{1cm} (4.72)

and then solving

\[ Ux = y \]  \hspace{1cm} (4.73)

The advantage of breaking up one linear set into two successive ones is that the solution of a triangular set of equations is quite trivial. Thus, Equation 4.72 can be solved by forward substitution as follows

\[ y_1 = \frac{z_1}{\alpha_{11}} \]

(4.74)

\[ y_i = \frac{1}{\alpha_{ii}} \left[ z_i - \sum_{j=1}^{i-1} \alpha_{ij} y_j \right] \]

(4.75)

\( i = 2, 3, ..., n \)

while Equation 4.73 can then be solved by back-substitution.
For the stability of the method, pivoting is essential. Pivoting consists of the selection of a advantageous pivot element for the divisions required during the processing. The pivot element is chosen as the largest element on the diagonal. Only partial pivoting (interchange of rows) can be implemented efficiently. However this is enough to make the method stable. This means, incidentally, that a row-wise permutation of \( N \), not actually \( N \), is decomposed into LU form.

Equations 4.74 and 4.75 total (for each right-hand side \( z \)) \( n^2 \) executions of an inner loop containing one multiply and one add. If we have \( n \) right-hand sides which are the unit column vectors (which is the case when we are inverting a matrix), then taking into account the leading zeros reduces the total execution count of Equation 4.74 from \( 1/2 \ n^3 \) to \( 1/6 \ n^3 \), while Equation 4.75 is unchanged at \( 1/2 \ n^3 \). Once the LU decomposition in applied on \( N \), all the desired right-hand sides can be solved, one at a time (Press et al., 1992, pp. 43-44).

4.7 ANALYSIS OF RESULTS

When the bundle adjustment is completed, the internal and external accuracy of the ground coordinates of the observed points are analyzed. The correlations between the unknown parameters are studied in order to remove any over-parameterization. A blunder detection is also performed. These topics are described in details in the following paragraphs.

4.7.1 Internal accuracy

Sigma naught (indicated with \( \delta_0 \)) is the a-posteriori standard deviation of unit weight. It is calculated using the vector \( \nu \), computed with Equation 4.37, and the system redundancy (difference between number of equations and number of unknown parameters)

\[
\delta_0 = \sqrt{\nu^T \nu / (n - u)}
\]  

(4.76)

Using the matrix \( Q_{xx} \) defined as

\[
Q_{xx} = N^{-1}
\]  

(4.77)

the covariance matrix \( K_{xx} \) is calculated as

\[
K_{xx} = \delta_0^2 Q_{xx}
\]  

(4.78)

\( K_{xx} \) is symmetric. The general diagonal element

\[
\delta_{kk} = \delta_0 \sqrt{q_{kk}}
\]  

(4.79)

represents the mean-square errors of the individual unknown \( x_k \). The non-diagonal elements occupying the position \((i,j)\) represent the covariances between the unknowns \( x_i \) and \( x_j \).

The planimetric and height precision of the ground coordinates of GCPs and TPs are calculated separately as follows
Section 4.7. ANALYSIS OF RESULTS

\[ \sigma_x^2 = \frac{tr(K_{xx})}{g} \quad \sigma_y^2 = \frac{tr(K_{yy})}{g} \quad \sigma_z^2 = \frac{tr(K_{zz})}{g} \quad (4.80) \]

where
\( \sigma_x, \sigma_y, \) and \( \sigma_z \): standard deviation in X, Y and Z coordinates
\( K_{xx}, K_{yy}, \) and \( K_{zz} \): parts of \( K \) corresponding to X, Y and Z coordinates of GCPs (or TPs)
\( g \): number of points.

4.7.2 RMSE calculations

The TPs with known ground coordinates are used as Check Points (CPs). The estimated ground coordinates \([\hat{X} \ \hat{Y} \ \hat{Z}]\) are compared to the correct ones \([X_{corr} \ Y_{corr} \ Z_{corr}]\) and the RMSE are calculated as

\[ \text{RMSE}_x^2 = \frac{\sum_{i=1}^{N_{CP}} (X - X_{corr})^2}{N_{CP}} \quad \text{RMSE}_y^2 = \frac{\sum_{i=1}^{N_{CP}} (Y - Y_{corr})^2}{N_{CP}} \quad \text{RMSE}_z^2 = \frac{\sum_{i=1}^{N_{CP}} (Z - Z_{corr})^2}{N_{CP}} \quad (4.81) \]

where \( N_{CP} \) is the number of CPs.

4.7.3 Correlations

An investigation of the determinability of the additional parameters is also required in order to avoid over-parameterization. For this task the correlations \( \rho_{ij} \) between the parameters are calculated as

\[ \rho_{ij} = \frac{q_{ij}}{\sqrt{q_{ii} \cdot q_{jj}}} \quad (4.82) \]

where \( q_{ij} \) are the elements of the matrix defined in Equation 4.77 in position \((i,j)\). Absolute values of \( \rho_{ij} \) close to 1 indicates high correlation between parameter \( x_i \) and \( x_j \). If highly correlated parameters are found, one of the two is manually fixed to constant values using pseudo-observations (Section 4.5.2 and Section 4.5.3).

4.7.4 Blunder detection

As the true errors \( \nu_x \) and \( \nu_y \) of the adjustment system (Equation 4.28) are not available, the image coordinates observations are tested for blunders using Grün’s approach for photogrammetric block adjustment proposed in (Grün, 1982). This approach is based on Baarda’s data snooping technique. According to the test, for each observation \( i \) the value \( w_i \)

\[ w_i = \frac{-\nu_i}{\delta_{vi}} \quad (4.83) \]

is computed, with \( \delta_{vi} = \delta_{vi} \sqrt{q_{ii}} \), where \( \sqrt{q_{ii}} \) is the \( i \)-th element of the matrix \( Q\nu\nu \) defined as

\[ Q_{\nu\nu} = P_{ii}^{-1} - A(A^T P_{ii} A)^{-1} A^T \quad (4.84) \]
Chapter 4. INDIRECT GEOREFERENCING

If the null-hypothesis

\[ H_0^v: E(v_i) = 0 \]  \hspace{1cm} (4.85)

is true, \( w_i \) is \( \tau \)-distributed. If the redundancy of the system is large enough, the \( \tau \) distribution can be replaced by the Student distribution, which is far easier to handle. The blunder detection is run at the end of the adjustment. The observations that are detected as blunders are manually removed and the adjustment is repeated.

4.8 FORWARD INTERSECTION

Once the parameters modelling the internal and external orientation are estimated, it is possible to calculate the ground coordinates of any point measured in the images. The algorithm for the forward intersection is based on the principles described in Section 3.3. For each lens \( j \), the point coordinates in the camera systems are projected into the ground system with

\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} = \begin{bmatrix}
X_c \\
Y_c \\
Z_c
\end{bmatrix} + \begin{bmatrix}
d_{xj} \\
d_{yj} \\
d_{zj}
\end{bmatrix} + k \begin{bmatrix}
\omega_c \\
\phi_c \\
\kappa_c \end{bmatrix} \begin{bmatrix}
\alpha_j \\
\beta_j \\
\gamma_j
\end{bmatrix} \begin{bmatrix}
x - x_{pj} + \Delta x_j \\
y - y_{pj} + \Delta y_j \\
\end{bmatrix}
\]  \hspace{1cm} (4.86)

where

- \([X, Y, Z]\): point coordinates in the ground system;
- \([X_c, Y_c, Z_c]\): PC position in the ground system
- \([x, y]\): point coordinates in the camera system
- \([x_{pj}, y_{pj}]\): principal point coordinates of lens \( j \) in the camera system
- \([\Delta x_j, \Delta y_j]\): terms containing self-calibration parameters for lens \( j \)
- \( f\): focal length
- \( k\): scale factor
- \( d_{xj}, d_{yj}, d_{zj}\): relative position of each lens \( j \) with respect to the central one
- \( \alpha_j, \beta_j, \gamma_j\): relative attitude of each lens \( j \) with respect to the central one
- \( R(\omega_c, \phi_c, \kappa_c)\): rotation from camera system of the central lens to ground frame
- \( \hat{R} = R(\omega_c, \phi_c, \kappa_c) \cdot M(\alpha_j, \beta_j, \gamma_j)\): complete rotation from camera system of the off-nadir lens \( j \) to ground system
- \( M(\alpha_j, \beta_j, \gamma_j)\): rotation from camera system of the off-nadir lens \( j \) to camera system of the central lens.

Imposing the intersection of two homologous rays, the ground coordinates of the points measured in two or more images can be estimated through a forward intersection. In Equation 4.86 the external orientation parameters are calculated introducing the estimated EO parameters in Equation 4.9 or Equation 4.12, if GPS and INS observations are used. In the same way \([\Delta x_j, \Delta y_j]\) are computed with Equation 4.26 (one-lens system) or Equation 4.27 (multi-lens systems). The solution is estimated in two steps, using the algorithm described in Section 3.3. This algorithm is used not only for the calculation of the ground coordinates of the check points, but also for the generation of DSM and DTM. In fact if a large number of points are matched in the images, using the forward intersection a 3D point cloud is automatically created in the ground system. By mean of suitable interpolation algorithms, a regular surface (DSM) is created.
4.9 SUMMARY AND COMMENTS

In this Chapter the mathematical formulation of the indirect model for the georeferencing of CCD linear array sensors has been described.

The model is based on the collinearity equations, which are extended in order to include the sensor internal and external orientation modelling. The internal orientation is improved by taking into account the lens distortions and the displacements and rotations of the CCD lines in the focal plane. The external orientation is modelled with second order piecewise polynomials (PPM) depending on time or image-line number. According to this approach, the trajectory is divided into a suitable number of segments and for each segment it is modelled with parabolic functions. Additionally, the GPS and INS measurements, which are indispensable for pushbroom sensors carried on airplane or helicopter, can be integrated in the adjustment and corrected from systematic errors (shifts and misalignments, first and second order errors). The number of segments is decided in each case study according to the trajectory length and smoothness. In general, for satellite orbits, 2 segments are sufficient, but for sensors carried on airplane or helicopter a larger number of segments is recommended, as the trajectory is less smooth. The system is solved with a least-squares adjustment, using a suitable number of ground control points. The weights for the observations (collinearity, pseudo-observations for the unknowns) are calculated according to the accuracy of the corresponding measurements.

As mentioned in the Introduction, nowadays many models with different complexity and rigor exist. Few of them include the self-calibration, which is recommended if the instrument’s laboratory calibration is not available. Concerning the sensor position and attitude modelling, Lagrange polynomials or second order polynomials are often used; in some cases linear functions are preferred for satellite trajectories. This option is also included in our model, because the second order parameters in the PPM can be fixed to zero using highly weighted pseudo-observations. Taking into account the rigorous models presented in literature, few of them can be used for any pushbroom sensor carried on satellite and even fewer can be used for airborne sensors too. Our model, on the other hand, has been designed in order to be as flexible as possible for the georeferencing of a wide class of pushbroom sensors. In fact it uses a quite flexible function for the external orientation modelling and takes into account systematic errors due to lens distortions and CCD lines displacements that may occur during the image acquisition. In the design phase, the main idea was to create a model that could describe the image acquisition of pushbroom sensors with different characteristics, and then, according to the specific case study, to estimate only the parameters of interest. For example, the number of segments is decided according to the platform (satellite, airplane or helicopter), the length of the trajectory and the distribution of ground control and tie points (at least one tie point in each segment). The estimation of only the parameters of interest is possible thanks to the use of pseudo-observations. In fact any parameter can be fixed to constant values using highly weighted pseudo-observations. This option may overcome the risk of over-parameterization. In order to select the parameters of interest, the analysis of the significance of each parameters and the correlation with the other unknowns are fundamental. In our software this selection is made manually.

Due to the fact that for each case study the number of parameters is different, the minimum number of ground control points required in the bundle adjustment is not unique. In general the number of unknowns depends on the number of segments in the PPM, the degree of the functions and which self-calibration parameters are estimated (Figure 4.15). Considering a simple case with two-line sensor carried on satellite, the trajectory modelled with two second order polynomials and no tie points, the number of unknowns is 36. As the constraints for the PPM continuity give 18 equations and each GCP give 4 observation equations, at least five GCPs are required for the solution of the system. In order to increase the redundancy, a minimum of six GCPs are recom-
mended. Of course the distribution of the GCPs may influence the number of GCPs required. Concerning the flexibility of the model, new cameras can be easily integrated. In fact the required sensor information (number of linear arrays, number of lenses, focal length, number of detector elements in each line, viewing angles) are accessible in literature as well as in the web. If no information on the sensor internal orientation is available, the model supposes that the CCD lines are parallel to each other in the focal plane and perpendicular to the flight direction and estimates the systematic errors through the self-calibration. Concerning the external orientation, in case of spaceborne sensors the satellite's position and velocity vectors, usually contained in the ephemeris, are required in order to compute the initial approximations for the PPM parameters. If this information is not available, the Keplerian elements can be used to estimate the nominal trajectory. For pushbroom scanners carried on airplane or helicopter the GPS and INS measurements are indispensable, due to the unpredictability of the trajectory.
Before applying the algorithms for the georeferencing of the images, some operations are required in order to prepare the input data. The pre-processing includes both the analysis of the metadata files for the extraction of the required information and the radiometric improvement of the images in order to facilitate the points measurement, which is usually performed with least-squares template matching.

5.1 METADATA FILES FORMATS

In order to extract the information regarding the sensor geometry, the image characteristics and the initial approximations of the external orientation, the metadata files must be analyzed. Due to the variety of formats, only the metadata files of the data used in this work will be taken into account. The information required for the image georeferencing with the developed sensor model are summarized in Table 5.1. Usually one metadata file is associated to each satellite scene. In case of MISR the same file contains the scenes and the image characteristics only. The information on the camera geometry are contained in the Camera Geometric Model (CGM) file, downloadable from NASA, while the ephemeris must be requested at the JPL NASA center in Pasadena, California, USA.

The metadata files are quite different from one satellite to the other. Apart of the file format (text, HDF -Hierarchical Data Format file-, XML -Extensible Markup Language-, ...), the kind of data contained and the reference systems used are not standard.

For ASTER the sensor position and velocity and the acquisition time are given for a defined number of so-called lattice points (Figure 5.1), whose number varies with the channels. In Table 5.2 the number of lattice points in the across and along track directions for each channel is given. The lattice grid covers an area which is larger than the scene in the along-track direction. The position of the scene area in the lattice grid in the along-track direction (segment called **off**-
Chapter 5. PREPROCESSING

The pointing vectors in SPOT-5/HRS metadata files are described by the two angles $\psi_y$ and $\psi_x$, defined in the orbit system, as shown in Figure 5.2.

Table 5.1. Main characteristics of metadata files used in this work. Abbreviations: RS = reference system; pos = position; vel = velocity; att = attitude.

<table>
<thead>
<tr>
<th>Data</th>
<th>EROS-A1</th>
<th>SPOT-5/HRS</th>
<th>ASTER</th>
<th>MOMS-P2</th>
<th>MISR</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of files</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>more</td>
</tr>
<tr>
<td>format</td>
<td>text (76 lines)</td>
<td>DIMAP</td>
<td>HDF</td>
<td>TEXT</td>
<td>HDF</td>
</tr>
<tr>
<td>acquisition time format</td>
<td>UTC</td>
<td>UTC</td>
<td>UTC</td>
<td>UTC</td>
<td>UTC</td>
</tr>
<tr>
<td>acquisition time density</td>
<td>first and last lines</td>
<td>center line</td>
<td>lattice points</td>
<td>first and last lines</td>
<td>every line</td>
</tr>
<tr>
<td>integration time</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>state vector format</td>
<td>time, position, velocity</td>
<td>time, position, velocity</td>
<td>time, position, velocity</td>
<td>time, position, velocity</td>
<td>time, position, velocity</td>
</tr>
<tr>
<td>state vector RS</td>
<td>ECI</td>
<td>ECR</td>
<td>ECR</td>
<td>ECR</td>
<td>ECI</td>
</tr>
<tr>
<td>state vector density</td>
<td>every 10 lines</td>
<td>every 30s (pos, vel), every second (att)</td>
<td>lattice points</td>
<td>every second (pos), every line (att)</td>
<td>every 1.024s</td>
</tr>
<tr>
<td>focal length</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>pixel size</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>calibration</td>
<td>no</td>
<td>yes, pointing vectors</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>viewing angles</td>
<td>yes (initial and final)</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
</tr>
</tbody>
</table>

Table 5.2. Number of lattice points for ASTER.

<table>
<thead>
<tr>
<th>BAND</th>
<th>n across</th>
<th>m along</th>
</tr>
</thead>
<tbody>
<tr>
<td>VNIR 1,2,3N</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>VNIR 3B</td>
<td>10</td>
<td>14</td>
</tr>
<tr>
<td>SWIR</td>
<td>103</td>
<td>105</td>
</tr>
<tr>
<td>TIR</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

Figure 5.1. Lattice points structure in ASTER scenes. $m$ and $n$ are lattice points counters.
5.2 INFORMATION EXTRACTION FROM METADATA FILES

The metadata files are indispensable to extract the information on:
- external orientation
- camera geometry
- acquisition time
- internal orientation

**External orientation.** For the dataset used in this work, two approaches have been used to calculate the sensor external orientation. In case of MOMS-P2, DLR provided the sensor position measured with GPS and the sensor attitude measured with INS. The data have been interpolated for each line using cubic splines (Section 3.2.3) and used to compute the initial approximation of the external orientation parameters, according to Equations 4.62 and 4.63.

In the other cases, the state vectors containing the platform position and velocity at some instants of time have been used to calculate the sensor attitude as described in Section 3.2.2. Again, the values have been interpolated for all the image lines.

As an example, the calculation of the external orientation in case of the MISR test is described. For simplicity, 10 state vectors of the original 256 are reported.

From the ephemeris for EOS-AMI where MISR is mounted, the position is extracted in ECI system (Section B.4)

### ECI System

<table>
<thead>
<tr>
<th>Time</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>272025550.435975015</td>
<td>-2803974.875</td>
<td>2758826.875</td>
<td>5879809.000</td>
</tr>
<tr>
<td>272025551.459975004</td>
<td>-2807005.250</td>
<td>2764557.625</td>
<td>5875679.250</td>
</tr>
<tr>
<td>272025552.483975053</td>
<td>-2810032.500</td>
<td>2770285.000</td>
<td>5871542.625</td>
</tr>
<tr>
<td>272025553.507975042</td>
<td>-2813056.375</td>
<td>2775009.125</td>
<td>5867399.125</td>
</tr>
<tr>
<td>272025554.531975031</td>
<td>-2816076.875</td>
<td>2781730.125</td>
<td>5863248.625</td>
</tr>
<tr>
<td>272025555.555975020</td>
<td>-2819094.125</td>
<td>2787447.750</td>
<td>5859091.250</td>
</tr>
<tr>
<td>272025556.579975009</td>
<td>-2822108.125</td>
<td>2793162.000</td>
<td>5854927.000</td>
</tr>
<tr>
<td>272025557.603974998</td>
<td>-2825118.750</td>
<td>2798873.125</td>
<td>5850755.750</td>
</tr>
<tr>
<td>272025558.627975047</td>
<td>-2828126.000</td>
<td>2804580.875</td>
<td>5846577.625</td>
</tr>
<tr>
<td>272025559.651975036</td>
<td>-2831130.000</td>
<td>2810285.375</td>
<td>5842392.625</td>
</tr>
</tbody>
</table>

During this transformation a rotation around Z-axis has been applied. The effect of the rotation is evident if the geographic coordinates (latitude and longitude in degrees, height in meters) are considered. In fact the longitude changes during the transformation, while the latitude and height remain stable:

### Geographic Coordinates

<table>
<thead>
<tr>
<th>ECI Position</th>
<th>ECR Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>3850830.658387</td>
<td>805468.538465</td>
</tr>
<tr>
<td>3857340.029129</td>
<td>804526.237219</td>
</tr>
<tr>
<td>3863844.738769</td>
<td>803582.237730</td>
</tr>
<tr>
<td>3870344.752453</td>
<td>802636.263701</td>
</tr>
<tr>
<td>3876840.173866</td>
<td>801688.246829</td>
</tr>
<tr>
<td>3883330.863947</td>
<td>800738.430798</td>
</tr>
<tr>
<td>3889816.822402</td>
<td>799786.816653</td>
</tr>
<tr>
<td>3896298.187611</td>
<td>79883.132750</td>
</tr>
<tr>
<td>3902774.751231</td>
<td>797877.608784</td>
</tr>
<tr>
<td>3909246.666285</td>
<td>796920.190498</td>
</tr>
</tbody>
</table>

During this transformation a rotation around Z-axis has been applied. The effect of the rotation is evident if the geographic coordinates (latitude and longitude in degrees, height in meters) are considered, In fact the longitude changes during the transformation, while the latitude and height remain stable:  

### Geographic Coordinates

<table>
<thead>
<tr>
<th>ECI Position</th>
<th>ECR Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>56.377077 135.465010</td>
<td>11.814085 710942.203262</td>
</tr>
<tr>
<td>56.317018 135.436511</td>
<td>11.781295 710929.184354</td>
</tr>
<tr>
<td>56.256951 135.408105</td>
<td>11.748597 710916.227333</td>
</tr>
<tr>
<td>56.196878 135.379786</td>
<td>11.715987 710903.281974</td>
</tr>
<tr>
<td>56.136798 135.331553</td>
<td>11.683463 710890.293368</td>
</tr>
<tr>
<td>56.076710 135.323410</td>
<td>11.651029 710877.317231</td>
</tr>
</tbody>
</table>
The attitude is calculated using the position and velocity vectors in ECR systems, according to Equations 3.16, 3.17 and 3.18, and results in

\[
\begin{array}{ccc}
-0.136150 & -0.575604 & -0.047969 \\
-0.136087 & -0.576701 & -0.048126 \\
-0.136024 & -0.577797 & -0.048283 \\
-0.135960 & -0.578894 & -0.048441 \\
-0.135897 & -0.579990 & -0.048599 \\
-0.135833 & -0.581087 & -0.048756 \\
-0.135769 & -0.582184 & -0.048914 \\
-0.135704 & -0.583280 & -0.049072 \\
-0.135640 & -0.584377 & -0.049230 \\
-0.135575 & -0.585473 & -0.049389 \\
\end{array}
\]

The same attitude in ECI system is

\[
\begin{array}{ccc}
-0.438708 & -0.407550 & -1.127126 \\
-0.439777 & -0.408016 & -1.127550 \\
-0.440847 & -0.408482 & -1.127974 \\
-0.441917 & -0.408947 & -1.128399 \\
-0.442987 & -0.409412 & -1.128824 \\
-0.444058 & -0.409877 & -1.129250 \\
-0.445129 & -0.410341 & -1.129677 \\
-0.446201 & -0.410805 & -1.130105 \\
-0.447273 & -0.411268 & -1.130533 \\
-0.448346 & -0.411731 & -1.130961 \\
\end{array}
\]

The external orientation values in ECI system are:

\[
\begin{array}{ccc}
X_e = 2803974.875 & Y_e = 2758827.875 & Z_e = 5879809.000 \\
\omega_x = 0.44 & \phi_x = 0.41 & \kappa_x = -1.13 \\
\end{array}
\]

and in ECR system they are:

\[
\begin{array}{ccc}
X_r = 3850830.658 & Y_r = 805468.538 & Z_r = 5879445.414 \\
\omega_x = 0.14 & \phi_x = 0.57 & \kappa_x = 0.05 \\
\end{array}
\]

**Camera data.** For the direct and indirect georeferencing models, the information about the instruments required are: number of lenses, number of linear arrays for each lens, number of detectors in each line, viewing angle and focal length of each lens. Usually these information are available in the metadata files. Otherwise they are found in literature or in the web sites of the corresponding space agencies or data distributors. For example, in case of SPOT-5/HRS the (nominal) focal length of the sensor (580mm) was found in (Gleyzes et al., 2003), while the viewing angle of each lens and the pixel size were calculated from the looking vectors (Figure 5.2), which have component \(|f_x, f_y|\). Calling \(\psi_x(i)\) and \(\psi_y(i)\) the values of \(\psi_x\) and \(\psi_y\) for the pixel in position \(i\), the off-nadir viewing angle of each lens (angle \(\beta\)) was calculated as the average of the along-track component of the looking vectors:

\[
\beta = \frac{\psi_x(12000) - \psi_x(1)}{12000} \tag{5.1}
\]

while the pixel size in across-track \((p_y)\) directions was calculated as

\[
p_y = f \cdot \frac{\psi_y(12000) - \psi_y(1)}{12000} \tag{5.2}
\]

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Acquisition time. Usually the acquisition time of the first line $t_0$ and the integration time $\Delta t_S$ are provided, therefore Equation 3.19 in Section 3.2.3 can be applied. This is the case of EROS-A1 and MOMS-P2. For MISR the exact acquisition time of each image line is already available in the metadata file and for SPOT-5/HRS the acquisition time of the central line (line 6001) is given together with the integration time $\Delta t_S$, therefore the acquisition time of any other line can be estimated with Equation 3.19 using the center line as reference.

In case of ASTER the acquisition time of each image line is interpolated from the values in correspondence of the lattice points. Taking into account the VNIR 3N and 3B images used in this work and later described in Section 6.4, the lattice grid covers an area of 4100x4800 pixels (image 3N) and 5000x5600 pixels (image 3B). The lattice point $n=0$ is located at line 263 and 204 for 3N and 3B respectively (offsets of 263 and 204 lines). The acquisition time of image lines 1 and 4200 (image 3N) and image lines 1 and 5400 (image 3B) are linearly interpolated as

$$t_1 = t_{263} + \frac{t_{263} + 4800 - t_{263}}{4800}(263 + 1)$$

(5.3)

for image 3N and

$$t_{4200} = t_{263} + \frac{t_{263} + 4800 - t_{263}}{4800}(263 + 4200)$$

for image 3B.

Additional parameters. These parameters include the sensor laboratory calibration. In case of MOMS-P2, a report contains the results obtained in the laboratory calibration as described in Section 2.4.3. In case of MISR, the parameters estimated in the on-flight calibration are reported in an extra file, called CGM (Camera Geometric Model). The procedure is explained in Jovanovic et al., 1999b. In case of SPOT-5/HRS the camera calibration consists of the pointing vectors of each pixel in the linear array (Figure 5.2).
5.3 RADIOMETRIC PREPROCESSING

In our processing chain 8-bit greyscale images are used. They are generated either from a single color channel (for example red channel in case of MISR, near infrared channel for ASTER) or from the panchromatic channels (as in case of EROS-A1, SPOT-5/HRS, MOMS-02). All the original images used in this work have the radiometric resolution of 8-bit (usually 8-bit and 11-bit images are supplied by the providers). If necessary, images with different radiometric resolutions may be reduced to 8-bit with a linear stretching between the minimum and maximum values.

The radiometric characteristics of the images are closely dependent on the acquisition aspects, like the sensor view angle, the sun angle and shadowing, the seasons, the atmospheric conditions and whether the scene is recorded in mono or stereo (Baltsavias et al. 2001). As there is limited opportunity for the user to dictate specific imaging dates, times and weather conditions, the radiometric quality may be improved by analyzing the initial histogram and applying algorithms for gamma correction, contrast enhancement, histogram equalization or a combination of them (Wallis filter). The resulting histograms, obtained with Adobe Photoshop (Adobe Photoshop, 2004) are shown in Figure 5.4.

5.3.1 Standard algorithms

**Gamma correction.** This is a nonlinear transformation that changes the brightness of an image in order to compensate for nonlinear responses in imaging sensors. The general form for gamma correction is

\[
img_{new}(x, y) = \frac{1}{\gamma} \cdot img(x, y)^\gamma
\]

If \(\gamma = 1.0\), the correction is null. If \(0 < \gamma < 1.0\), the correction creates exponential curves that darkens an image. If \(\gamma > 1.0\) the result is a logarithmic curve that brightens an image.

**Contrast enhancement.** The contrast enhancement increases the total contrast of an image by making the high grey values higher and the low grey values lower at the same time. It does this by setting all the components below a specified lower bound to zero, and all components above a specified upper bound to the maximum intensity (that is, 255). The radiometric values between the upper and lower bounds are set to a linear ramp of values between 0 and 255.

**Histogram equalization.** It is similar to the contrast enhancement, but the same number of pixels is approximately assigned to each output grey value. It is one of the most important part of the software for any image processing. The goal of histogram equalization is to obtain a uniform histogram, by redistributing the intensity distributions. If the histogram of any image has many peaks and valleys, it will still have peaks and valley after equalization, but peaks and valley will be shifted.

**Wallis filter.** The Wallis filter combines the radiometric equalization and the contrast enhancement in an optimal way (Wallis, 1976, Baltsavias, 1991, Valadan Zoej and Foomani, 1999). It is an adaptive, local filter, which has been extensively used at our Institute in image preprocessing for matching of satellite (e.g. Baltsavias and Stallmann, 1993, Baltsavias et al. 2001), airborne (Baltsavias et al., 1996a) and close range images (Grün et al., 2003a).

The filter is defined with the objective of forcing the mean and standard deviation of an image to given target values. The filtered image \(img_{new}\) is calculated from the original image \(img\) as

\[
img_{new}(x, y) = img(x, y) \cdot r_1 + r_0
\]
Section 5.3. RADIOMETRIC PREPROCESSING

where

\[
    r_1 = c \cdot \frac{s_f}{c s_g + (1-c) \cdot s_f} \\
    r_0 = b m_f + (1 - b - r_1) \cdot m_g
\]

(\(m_g, s_g\)) are the original mean and standard deviation of each block, (\(m_y, s_y\)) are the target mean and standard deviation for every block, \(b \) (\(0 \leq b \leq 1\)) is the brightness forcing constant and \(c \) (\(0 \leq c \leq 1\)) is the contrast expansion constant.

The filter works as follows. First the image is divided into rectangular blocks of given size and defined distance between the block centers. Then the parameters \(r_0\) and \(r_1\) are computed in each block. Finally each pixel of the original image is transformed with \(r'_0\) and \(r'_1\), which were bilinearly interpolated from the \(r_0\) and \(r_1\) values of the 4 neighboring block centers. In areas with the same grey values (e.g. saturated areas) the filter cannot create any texture, but in areas with weak texture patterns the filtering strongly enhances the texture so that the images are optimized for matching (Seiz, 2003). As example, the contrast enhancing effect of the Wallis filter on MOMS-P2 scenes is shown in Figure 5.3.

![Figure 5.3. Zoom in MOMS-P2 channel 7 before (a) and after (b) the radiometric equalization and contrast enhancement by Wallis filter. For more details about the scenes, see Section 6.2.](image)

5.3.2 Ad-hoc filters

In some cases special blurring effects require the implementation of specific filters to remove them. In the following, two examples of special filters applied on images used in this work are shown. In ASTER level 1A scenes, which are not radiometrically corrected, it is evident the presence of vertical stripes. For their correction the coefficients contained in the HDF files are used. These radiometric coefficients are generated in two steps. The first step is the off-line generation of radiometric coefficients at predefined reference temperature. These coefficients are effective for a long time, depending on the instrument stability, and available in radiometric correction data base files along with the temperature coefficients. Destriping parameters are generated from the image data analyzing the image data obtained during the initial checkout operation period. The second step is an on-line process executed during level 1 product generation to correct the radiometric coefficients for instrument conditions such as the detector temperature, which may

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change for every observation. Considering an image line, the radiometric value of each pixel is corrected with the following transformation (Abrams et al., 2002)

\[ I = \frac{v^2}{g} + d \]  (5.8)

where \( v \) and \( I \) are the input and output values, \( a \) is a linear coefficient, \( g \) is the gain and \( d \) an offset. These parameters are constant for all image lines. Figure 5.5 shows the positive effect of this filter, before and after applying the radiometric enhancement.

The second filter has been applied on MOMS-02 scenes in order to reduce the saturation in regions covered by clouds. In this case a template containing the standard saturation striping has been used to detect the saturated areas in the images through cross-correlation. Then a median filter was applied. The result in a zoomed region is shown in Figure 5.6.
Section 5.3. RADIOMETRIC PREPROCESSING

Figure 5.5. Radiometric correction in ASTER scenes.

Figure 5.6. Zoom in a saturated region before (a) and after (b) applying the median filter.
The sensor model presented in the previous Chapters has been used to orient images acquired by pushbroom sensors with different geometric characteristics. In order to demonstrate the flexibility of the model, images acquired with single- and multi-lens optical systems, synchronous and asynchronous acquisition modes and different resolutions have been used, as reported in Table 6.1. Among the pushbroom sensors used for photogrammetric applications (Chapter 2), the choice of the sensors to use for our tests depended exclusively on their availability. The MOMS-02 dataset was available at our Institute, the MISR and ASTER ones was downloaded for free (MISR) and at very low price (ASTER, $55 per scene) by NASA, while the EROS-A1 and SPOT-5/HRS images came from external scientific collaborations.

In this Chapter the workflow followed in the data processing is summarized in Section 6.1, then the results obtained with each dataset are described in the following Sections. For each dataset the instruments and the data are described and the results obtained by the image orientation are reported and commented. The results obtained using airborne sensors (SI-100) are described in Poli, 2002b. Before the application with real data, the model was also tested on simulated data. Part of these tests have been published in Poli, 2002a.

Table 6.1. Main characteristics of sensors analyzed in this Chapter.

<table>
<thead>
<tr>
<th>OPTICAL SYSTEM</th>
<th>SYNCHRONOUS</th>
<th>RESOLUTION</th>
<th>SENSOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>one</td>
<td>multi</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>EROS-A1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SPOT-5/HRS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ASTER/VNIR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MOMS-P2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MISR</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Chapter 6. APPLICATIONS

6.1 WORKFLOW

For each sensor the analysis and processing of the data has been carried out following these steps:

1. Analysis of metadata files for the extraction of the acquisition time of each image line, the sensor external and internal orientation (if available) and any additional information on the images. These operations have been described in Section 5.2.

2. Radiometric preprocessing of the images in order to improve the radiometric quality and facilitate the point measurement. This operation has been described in Section 5.3.

3. Measurement of object points. The image coordinates are usually estimated with template least-squares matching, while the ground coordinates are given by external providers (i.e. SPOT-5/HRS and EROS-A1 cases) or are measured in topographic maps (i.e. MOMS-P2, ASTER and MISR cases), or in rectified scenes from other sensors (i.e. Landsat).

4. Preparation of input files for direct georeferencing. The required files are: sensor characteristics (number of lenses, number of viewing directions, number of CCD lines, viewing angles, pixel size, focal length), image coordinates of tie points (row, columns) and external orientation (position and attitude at certain time intervals). If the external orientation is not provided for each image line but for a generic time interval (for example, the ephemeris observation time), then for each image the file containing the acquisition time of each image line is required. Thanks to this information, the external orientation for any line of interest is interpolated with cubic splines for the corresponding acquisition time. The reference systems for the external orientation accepted by the software are: the geocentric cartesian fixed system (ECR, Section B.5), the geographic system (Section B.6) and any local tangent systems (Section B.7). An additional facultative file is the calibration file for each sensor (position of each detector in the focal plane in the scanline system -Section B.2). More details about the format of the input files are in Appendix C.

5. Direct georeferencing of the images. The ground coordinates of the tie points measured in the images are estimated through a forward intersection using the available external and internal orientation, as described in Chapter 3. The process accuracy is analyzed through the residuals (RMSE) between the estimated and the correct ground coordinates of the points. In all the case studies reported in this Chapter a sub-pixel accuracy in the RMSE could not be achieved and the indirect georeferencing approach was used.

6. Preparation of input files for indirect georeferencing. The same input files used for the direct georeferencing are needed. In addition the file containing the ground coordinates of the control points is required. The reference systems accepted by the software are: the geocentric cartesian fixed system (ECR, Section B.5), the geographic system (Section B.6) and any local tangent systems (Section B.7).

7. Indirect georeferencing of the images. A bundle adjustment is performed in order to estimate the ground coordinates of the tie points, the piecewise polynomial model (PPM) parameters for the external orientation and the self-calibration parameters, as explained in Chapter 4. The program requires the number of ground control points (GCPs) and check points (CPs), the accuracy of the image and ground measurements, the number of segments for the PPM functions, the PPM degree for each function and for each segment, the accuracy of the available external orientation measurements, the self-calibration parameters to be estimated and the maximum number of iterations. Different tests are performed varying the number and distribution of GCPs, the PPM parameters (number of segments, degree) and the number of self-calibration parameters. In some cases the tests are limited by the small number of GCPs. The adjustment is evaluated through both the internal accuracy (standard deviation of unit weight a posteriori, standard deviation of estimated parameters) and the external accuracy (RMSE of...
CPs). In order to avoid over-parameterization, the correlation between the unknown parameters and the significance of the parameters are also analyzed. In addition, the Baarda test is performed to remove blunder observations.

8. In some cases, the DSM was generated and analyzed. The points have been matched in the images using the least-squares matching for pushbroom sensors developed at our Institute and contained in the SAT-PP software (Zhang and Grün, 2003). Then the 3D coordinates of the matched points are computed through a forward intersection, using the sensor internal and external orientation parameters estimated with the sensor model. From the resulting 3D irregular point cloud, a regular grid is generated using the software DTMZ developed at IGP. If a reference surface (i.e. from laser data) is available, the 2.5D and 3D differences between our point cloud and the reference surface are calculated with different commercial and IGP software.

9. Comparison with the accuracy achieved in the CPs and in the DSM (if available) by other models.

This workflow is graphically represented in Figure 6.1.

Figure 6.1. Workflow followed during the data processing.
6.2 MOMS-02

The indirect georeferencing model was used to orient a stereopair acquired by the German MOMS-02, mounted on the Russian MIR station during Priroda mission. The data were provided by DLR.

6.2.1 Sensor description

The Modular Optoelectronic Multispectral Stereo-scanner (MOMS-02) was developed by DLR during the 80’s. MOMS-02 is the first representative of a new along-track sensor generation, designed for the combined stereo-photogrammetric and thematic mapping of the Earth’s surface. The history of MOMS starts from the early 70’s, when the company Messerschmitt-Bölkow-Blohm (MBB), now Daimler Benz Aerospace (DASA), carried flight experiments with the Electro-Optical Scanner (EOS), built on the principle of the photo semiconductor sensors. Then the first two-channel space sensor MOMS-01 was developed by MBB and flown successfully on two Space Shuttle missions on the German “Shuttle Pallet Satellite” (SPAS, also developed by MBB) in 1983 and 1984. The further MOMS development was initiated and started under the supervision of the German Space Agency (DARA). MOMS-02 was first flown during the Second German Spacelab Mission D2 on Space Shuttle flight STS-55 and acquired data between the 26th April and the 6th May 1993 (Seige, 1995). From April 1996 till March 2003, the MOMS-02 instrument was operational on the Priroda module of the Russian Space Station MIR, with the name MOMS-2P (Seige et al., 1998). The station was flying along an orbit at a nominal height of 400km, with an inclination of 55° (Figure 6.2).

![Figure 6.2. MIR orbit and coverage during D2 and Priroda missions (Source MOMS-02, 2004).](image)

The major improvements of MOMS-2P compared with MOMS-02/D2 were: the long term observation capability (more than one year), the coverage of higher latitude (between 51.6°), a new high precision NAV (GPS and gyro) and a system multi-sensor approach in combination with other Priroda sensors.

The MOMS-2P optical system consisted of five lenses, three of which designated for the stereoscopic panchromatic images and the other two for the multispectral images (Figure 6.3 and Figure 6.4). The central lens (channel 5), with a focal length of 660mm, formed the core of the camera system. It allowed the high resolution imagery with a ground pixel size of 6x6m² (flight altitude 400km). In order to obtain a wide enough swath width in combination with this resolution, two linear sensors were optically combined in the focal plane. In connection with the use of
the high resolution lens, there were two additional lenses, each with a focal length of 237.2mm, a ground resolution of 18m and an offnadir angle of +21.4° (channel 7) and -21.4° (channel 6) respectively. In this configuration three-fold stereoscopic imagery was achieved (Figure 6.5). The focal length of these lenses was chosen in a way to achieve an integral relationship between the ground pixel sizes seen by the high resolution sense and the two inclined lenses by a ratio of 1:3. Two additional lenses, each with a focal length of 220 mm, enabled the multispectral imaging with a total of four channels (channels 1, 2, 3, 4). In order to simplify the image data analysis, the ratio of the ground pixel size of the high resolution channel with that of these multispectral channels was also selected to be 1:3. The detectors' size is 10μm x 10μm.

Figure 6.3. MOMS-02 sensor on its orbit (Source MOMS-02, 2004).

Figure 6.4. MOMS-02 lenses (Source MOMS-02, 2004).

Figure 6.5. MOMS-P2 acquisition geometry (Source MOMS-02, 2004).

The swath width for the high resolution channel is about 50km, depending on the recording mode, and for the other channels, up to 105km. These values are relative to a nominal orbit altitude of 400km. The three viewing angles allow to image a strip on the Earth's surface, at three different times and with the three different viewing angles (Figure 6.5). The fact that the three images are recorded within only about 40 seconds makes it easy to correlate them, because of their radiometric similarity.
MOMS-2P was designed for multispectral data acquisition in the visible and near infrared range (four channels) and for along-track stereo recording using a panchromatic channel for one nadir and two off-nadir looking modules. Table 6.3 gives basic information about the seven channels and the acquisition mode.

<table>
<thead>
<tr>
<th>Channel</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>Swath width (km)</th>
<th>Scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode A</td>
<td>8304</td>
<td>2976</td>
<td>2976</td>
<td>50/54</td>
<td>6</td>
<td>5</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mode B</td>
<td>5800</td>
<td>5800</td>
<td>5800</td>
<td>5800</td>
<td>105</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mode C</td>
<td>3220</td>
<td>3220</td>
<td>3220</td>
<td>6000</td>
<td>58/36</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mode D</td>
<td>5800</td>
<td>5800</td>
<td>5800</td>
<td>5800</td>
<td>105</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IFOV [urad]</td>
<td>45.45</td>
<td>45.45</td>
<td>45.45</td>
<td>45.45</td>
<td>15.15</td>
<td>42.16</td>
<td>42.16</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The center wavelength and width of the multispectral bands were optimized for vegetation related purposes. The center wavelength of the panchromatic bands was designed to minimize the atmospheric attenuation in the blue region and to get a maximum contrast between vegetated and non vegetated surfaces by including the steep increase of vegetation’s reflection at the beginning of the NIR wavelength region.

By combining the multispectral and panchromatic channels, the MOMS-2P camera is capable of 4 operational modes, as summarized in Table 6.2:
1. mode A: full-stereo with high resolution (channels 5-6-7), for DEM generation;
2. mode B: full-multispectral (channels 1-2-3-4) for thematic analysis and classification of ground objects;
3. mode C: multispectral and high resolution (channels 2-3-4-5) for thematic analysis and classification of ground objects;
4. mode D: multispectral and stereo (channels 1-4-6-7) for DEM generation and thematic analysis.

### 6.2.2 Data description

The images used in this work were acquired over South Germany on 14th March 1997, around 9:00 a.m., during the Priroda mission (data take: T083C) from a mean height of 388km. The two stereo scenes were taken in mode A, therefore from channel 6 and channel 7, with a time delay of 40 seconds and a ground resolution of 18m. The nadir image (channel 5) could not be used because the high resolution lens on Priroda was defocused. Each image has a dimension of 2976 pixels across-track and 5736 pixels along-track and consists of a combination of two overlapping scenes (scenes 25-26) in the flight direction. The images cover a hilly area in South Bavaria, partially with clouds (Figure 6.6).
Table 6.3. Characteristics of MOMS-02 channels in D2 and Priroda missions (nominal flight altitude of 400km, MS = multispectral, HR = high resolution); the swath width is depending on the operation mode

<table>
<thead>
<tr>
<th>Channel</th>
<th>Mode</th>
<th>Orientation</th>
<th>Band-Width (nm)</th>
<th>Ground Pixel (m) in D2/Priroda</th>
<th>Swath Width (km) in D2/Priroda</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>MS</td>
<td>Nadir</td>
<td>440 - 505</td>
<td>13.5 18</td>
<td>78/43 105</td>
</tr>
<tr>
<td>2</td>
<td>MS</td>
<td>Nadir</td>
<td>530 - 575</td>
<td>13.5 18</td>
<td>78/43 105/58</td>
</tr>
<tr>
<td>3</td>
<td>MS</td>
<td>Nadir</td>
<td>645 - 680</td>
<td>13.5 18</td>
<td>78/43 105/58</td>
</tr>
<tr>
<td>4</td>
<td>MS</td>
<td>Nadir</td>
<td>770 - 810</td>
<td>13.5 18</td>
<td>78/43 105/58</td>
</tr>
<tr>
<td>5</td>
<td>HR</td>
<td>Nadir</td>
<td>520 - 760</td>
<td>4.5 6</td>
<td>37/27 50/36</td>
</tr>
<tr>
<td>6</td>
<td>Stereo</td>
<td>+21.4</td>
<td>520 - 760</td>
<td>13.5 18</td>
<td>78/43 105/54</td>
</tr>
<tr>
<td>7</td>
<td>Stereo</td>
<td>-21.4</td>
<td>520 - 760</td>
<td>13.5 18</td>
<td>78/43 105/54</td>
</tr>
</tbody>
</table>

6.2.3 Preprocessing

The images from channels 6 and 7 were radiometrically improved with Wallis filter (Section 5.3.1). The initial approximations for the external orientation modelling were calculated using the ephemeris kindly provided by DLR. The data contained the MIR position in ECR system measured by GPS and the three Eulerian rotation angles measured by gyro instruments. The time interval between the observations was 1sec for the position and 2.4msec for the attitude. As the scanning integration time was 2.4msec, the cubic spline functions were used to interpolate the position data and obtain the position and attitude for the times of interest. The output data were then used to calculate the initial approximations for the external orientation, according to Equations 4.62 and 4.63.

29 object points in regions free from clouds were identified in the images and in a 1:50,000 digital topographic map in Gauss-Krüger coordinate system (CDROM Top 50 of Bavaria from Bayerische Vermessungsverwaltung, 2004). The accuracy of the ground coordinates measurements was about 10m. For the image coordinates measurement, the points were manually selected in the left image and transferred to the other one with semi-automatic template least squares matching developed at IGP (Baltsavias, 1991), as shown in Figure 6.7.

![Figure 6.7](image)

Figure 6.7. Measurement of GCPs in channels 6 (a) and 7 (b) and identification in the map (c).

The distribution of the 29 object points and the spacecraft trajectory are represented in Figure 6.8. The ground coordinates of the object points and the spacecraft position were transformed into the geocentric Cartesian system (ECR). The accuracy of the ground coordinates measurement was about 9m in planimetry and 12m in height.
Figure 6.6. Stereo images from MOMS-P2 from channel 6 (a) and channel 7 (b).

Figure 6.8. Distribution of GCPs in the original scene from channel 6 (a) and together with the MIR trajectory from ephemeris, in a local ground system (b).
6.2.4 Image orientation

The indirect georeferencing model was applied in order to estimate the parameters modelling the sensor internal and external orientation and the ground coordinates of the TPs measured in the stereo images. As two lenses acquired the stereopair, the extensions for multi-lens sensors (Section 4.2) was used. The values of the additional parameters describing the relative orientation between the lenses were available from the MOMS-2P calibration report (Kornus, 1996), kindly provided by DLR.

From the available 29 object points, some of them were used as GCPs and the others as CPs. The estimated ground coordinates of the CPs were compared to the correct ones and used for the external accuracy control through their RMSE (Section 4.7.2). The parameters used to control the internal accuracy of the adjustment are: the sigma naught a posteriori and the sigma of the Check Points (CPs) (Section 4.7.1).

The reference system used in the adjustment was the ECR. The tests were set as follows:
1. external orientation modeling with quadratic functions, varying the number of segments and GCPs, no self-calibration;
2. external orientation modeling with linear and quadratic functions, varying the number of segments and GCPs, no self-calibration;
3. self-calibration with best external orientation modeling configuration.

The sigma naught, sigma and RMSE of CPs obtained by the tests are summarized in Table 6.4.

Table 6.4. Results obtained using different GCPs and CPs configuration and external orientation modeling options. NS = number of segments in PPM, SC = self-calibration (Y = yes, N = no), DEG = degree of position (= pos) and attitude (= att) polynomials (Q = quadratic, L = linear).

<table>
<thead>
<tr>
<th>NS</th>
<th>DEG</th>
<th>SC</th>
<th>GCP</th>
<th>CP</th>
<th>$\delta_0$ (μm)</th>
<th>RMSE CPs (m)</th>
<th>σ CPs (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pos</td>
<td>att</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>Y</td>
</tr>
<tr>
<td>2</td>
<td>Q</td>
<td>Q</td>
<td>N</td>
<td>6</td>
<td>21</td>
<td>2.7</td>
<td>13.2</td>
</tr>
<tr>
<td>2</td>
<td>Q</td>
<td>Q</td>
<td>N</td>
<td>10</td>
<td>17</td>
<td>2.7</td>
<td>7.4</td>
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<tr>
<td>4</td>
<td>Q</td>
<td>Q</td>
<td>N</td>
<td>6</td>
<td>21</td>
<td>1.5</td>
<td>10.9</td>
</tr>
<tr>
<td>4</td>
<td>Q</td>
<td>Q</td>
<td>N</td>
<td>10</td>
<td>17</td>
<td>1.6</td>
<td>7.0</td>
</tr>
<tr>
<td>2</td>
<td>Q</td>
<td>L</td>
<td>N</td>
<td>6</td>
<td>21</td>
<td>3.0</td>
<td>10.9</td>
</tr>
<tr>
<td>2</td>
<td>Q</td>
<td>L</td>
<td>N</td>
<td>10</td>
<td>17</td>
<td>2.9</td>
<td>7.7</td>
</tr>
<tr>
<td>4</td>
<td>Q</td>
<td>L</td>
<td>N</td>
<td>6</td>
<td>21</td>
<td>1.8</td>
<td>11.7</td>
</tr>
<tr>
<td>4</td>
<td>Q</td>
<td>L</td>
<td>N</td>
<td>10</td>
<td>17</td>
<td>1.9</td>
<td>7.2</td>
</tr>
<tr>
<td>2</td>
<td>L</td>
<td>L</td>
<td>N</td>
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<td>4.1</td>
<td>19.6</td>
</tr>
<tr>
<td>2</td>
<td>L</td>
<td>L</td>
<td>N</td>
<td>10</td>
<td>17</td>
<td>4.4</td>
<td>14.5</td>
</tr>
<tr>
<td>4</td>
<td>L</td>
<td>L</td>
<td>N</td>
<td>6</td>
<td>21</td>
<td>2.8</td>
<td>16.2</td>
</tr>
<tr>
<td>4</td>
<td>L</td>
<td>L</td>
<td>N</td>
<td>10</td>
<td>17</td>
<td>3.1</td>
<td>11.0</td>
</tr>
<tr>
<td>2</td>
<td>Q</td>
<td>Q</td>
<td>Y</td>
<td>10</td>
<td>17</td>
<td>1.6</td>
<td>6.9</td>
</tr>
<tr>
<td>4</td>
<td>Q</td>
<td>Q</td>
<td>Y</td>
<td>10</td>
<td>17</td>
<td>1.2</td>
<td>6.8</td>
</tr>
</tbody>
</table>
As test 1 concerns, the spacecraft trajectory was divided into 2 and 4 segments (NS=2 and NS=4) of the same length, 6 and 10 points were used as GCPs. The corresponding results are reported in the first four rows in Table 6.4.

We can observe that:

- in all cases RMSE and sigma of CPs are smaller than 1 pixel. The best RMSE in the CPs, achieved with 10 GCP and 4 segments, correspond to 0.4, 0.4 and 0.5 pixels in X, Y and Z respectively
- by increasing the number of segments, the external orientation functions can better fit the real trajectory, improving the adjustment performance. This is demonstrated by the decrease of the sigma naught a posteriori and the sigma of CPs. The difference in the CPs RMSE between 2 segments and 4 segments configurations is less than 0.5m, corresponding to 3% of the ground pixel size
- by increasing the number of GCPs, sigma naught a posteriori remains approximately constant and the sigma of the CPs decreases, because the system is more stable
- the distribution of the residuals in the GCPs and CPs in Figure 6.9 (a and b) shows that all the systematic errors are removed.

Test 2 was performed in order to establish if the polynomial degree of the position or attitude functions could be reduced. The indirect georeferencing model was run using again 6 and 10 GCPs and 2 and 4 segments for the PPM. For the external orientation modelling, quadratic functions for the position and linear functions for the attitude (pos = Q, att = L, second group of rows in Table 6.4) and linear functions for both position and attitude (pos = L, att = L, third group of rows in Table 6.4) were tested. The comparison between the results achieved with quadratic and linear functions show that the sigma naught a posteriori, the sigma and RMSE of CPs increase, demonstrating that, at least with this particular dataset, quadratic functions for both position and attitude are recommended, because they fit better the true trajectory and produce the best results.

Finally a self-calibration was applied using the configuration with 10 GCPs and 17CPs, 2 and 4 trajectory segments and quadratic external orientation functions (pos = Q, att = Q). The flexibility of the software allows the user to fix any unknown parameters to the wished values with pseudo-observations (Section 4.5.2.2). Due to the very high correlation between the internal and external orientation, for each test with self-calibration the external orientation parameters were fixed to the values estimated in the same configuration without self-calibration and only the self-calibration parameters were estimated. In order to determine only the additional parameters (APs) of interest, the tests were repeated with different self-calibration configurations. In the first run all the self-calibration parameters were let free and their mean values, sigma and correlations were analyzed. The unpredictable or correlated parameters were fixed to constant values. The estimated APs were: θ for each line, \( p_i, p_2, k_1 \) and \( k_2 \) for both lenses. Among them, θ and \( k_2 \) resulted insignificant. The maximum effect of the other parameters for both lenses are computed for the pixels on the border (\( u = 1488 \)) according to the Equations in Section 4.4. The maximum values are:

- for \( p_i \): \( \Delta x = 0.010 \text{mm} \) (1 pixel)
- for \( p_2 \): \( \Delta y = 0.010 \text{mm} \) (1 pixel)
- for \( k_i \): \( \Delta y = 0.020 \text{mm} \) (2 pixels)

Comparing the values in Table 6.4 corresponding to NS = 2 and NS = 4, pos = Q, att = Q, GCP=10, CP = 17, without (SC = N) and with self-calibration (SC = Y), it can be observed that using self-calibration the system converges easier to the solution: the sigma a posteriori of the full adjustment reduces considerably together with the sigma of the CPs. The RMSE differs few
centimeters, with smaller values in $X$ and $Y$ and larger values in $Z$ (maximum 40cm). Considering the ground pixel size of 18.0m, these RMSE differences are not significant. The final RMSE distribution with self-calibration is shown in Figure 6.9 (e and d).

Apart of the tests where both the position and attitude are modelled with quadratic functions, the differences between the RMSE and the standard deviation of the CPs vary between 0.5m and 4m. Even if these values represent a small fraction of the pixel size (0.45 of the pixel size), they show that the theoretical (expected) accuracy is slightly better than the achieved one. This fact can be explained with a wrong weight assignment to the image and ground coordinates of the object points. In fact in our software the same weight is used for all the points. If a point is measured with a different accuracy, it may negatively affect the adjustment process.

![Residuals distributions in XY and Z](image)

**Figure 6.9.** Residuals distributions in XY (on the left side) and Z (on the right side) using quadratic function for position and attitude ($pos = Q$, $att = Q$), $NS = 2$, 10 GCPs (marked with triangles) and 17 CPs (marked with circles), before (top) and after (bottom) self-calibration.
6.2.5 Summary and conclusions

In this Section the processing of a MOMS-P2 stereopair has been presented. The work included the data preparation (radiometric preprocessing, point measurement, external orientation analysis) and the orientation with our rigorous sensor model. As the accuracy of the external orientation was not accurate enough for high precision mapping, the indirect georeferencing model was used in order to estimate the sensor orientation parameters and the ground coordinates of the tie points (GCPs and TPs). The model was run in the ECR system. Different GCPs distributions and PPM configurations (number of segments, polynomial degree) have been tested with and without self-calibration. The correct parameters for the focal length and principal points displacement were available from the laboratory calibration report (Kornus, 1996).

The results obtained in the internal and external accuracy, summarized in Table 6.4, show that using quadratic functions for the position and attitude modelling and a minimum of 6 GCPs sub-pixel accuracy in the CPs can be achieved. By increasing the number of GCPs to 10, residuals of 7.0m in X, 7.1m in Y and 9.6m in Z, corresponding to 0.4, 0.4 and 0.5 pixels respectively, can be achieved in the CPs. Using self-calibration, the RMS values do not change significantly and the standard deviations of the CP ground coordinates reduce of about 1.5m. We can conclude that for this dataset if the focal length and principal point displacement values available from the laboratory calibration are used, the self-calibration does not give a significant improvement of the final results.

In order to evaluate the performance of our model, the same stereopair has been oriented using Spotcheck+ software by Kratky Consulting (Kratky, 1989). According to Kratky's approach, the satellite position is derived from known nominal orbit relations, while the attitude variations are modelled by a simple polynomial model (linear or quadratic). For self-calibration two additional parameters are added: the focal length and the principal point correction. The exterior orientation and the additional parameters are determined in a general formulation by least-squares adjustment. This model has been used for the orientation of SPOT (Baltsavias and Stallmann, 1992), MOMS-02/D2 (Baltsavias and Stallmann, 1996b), Landsat TM and JERS-1/OPS and was also investigated and extended in Fritsch and Stallmann, 2000. Using 10 GCPs (the same points used in our tests) and modelling the attitude with quadratic functions, the sigma naught a posteriori was 2.2µm and the residuals achieved in 19 CPs were 5.2m in East, 4.4m in North and 11.1m in height in the Gauss-Krüger coordinate system (Foli et al., 2000). The corresponding values achieved with our model in Gauss-Krüger system are 5.5m, 4.3m and 11.3m for East, North and height. The results obtained by the two models are very similar; taking into account the ground resolution (18m), the differences are not significant. In both cases the modelling of the attitude with quadratic functions gave better results and the correction of the internal orientation parameters (in particular the focal length and principal point position) using the laboratory calibration or the self-calibration, is recommended.

At the Institute for Photogrammetry (IFP) of the University of Stuttgart, Spotcheck+ was used for the orientation of other MOMS-P2 scenes acquired again on 14\textsuperscript{th} March 1997 along the track T083C few seconds after our scenes (scenes 27-30). Using 10 GCPs, RMS values of 11.2m, 11.4m and 13.7m were achieved in X, Y and Z for 24 CPs. The points were measured in 1:25,000 scale digital topographic maps with an accuracy of 0.5 pixels in image space and 8.5m in object space. Compared to these results, the accuracy achieved with our model is satisfying.

In conclusion, we have shown that with sub-pixel accuracy can be achieved in the orientation of MOMS-P2 with our rigorous model, in accordance with the performance of other commercial software.
6.3 SPOT-5/HRS

In 2003 the Institute of Geodesy and Photogrammetry (IGP), ETH Zurich, joined the HRS Scientific Assessment Program (HRS-SAP), organized by CNES and ISPRS. This initiative, announced in Denver in 2002 at the ISPRS Commission I Symposium and concluded in Istanbul at the XX ISPRS Congress, had the aim to investigate the potential of SPOT-5/HRS sensor for DEM generation. The aim was to help CNES to improve its future Earth Observation systems and all users to better know and trust the accuracy and quality of the HRS instrument and the derived DEM. IGP joined the Initiative as Co-Investigator, that is, it processed the data provided by one of the Principal Investigators, generated two DEMs with two different orientation methods, compared them to the reference DEMs and produced a quality report. The dataset given to IGP for the processing was the number 9, over the Chiemsee Lake, in Germany. For more information about the Initiative see Baudoin et al., 2004.

SPOT-5 is the latest satellite of SPOT (Satellite pour l'Observation de la Terre) constellation of CNES, France. The SPOT system has been operational since 1986 when SPOT-1 was launched. SPOT-2 was placed in orbit in January 1990, followed by SPOT-3 in September 1993, SPOT-4 in March 1998 and SPOT-5 in May 2002. At present three satellites are in orbit: SPOT-2, SPOT-4 and SPOT-5, operated by SpotImage. The SPOT system is designed to achieve optimum image quality in terms of resolution and solar illumination and to respond quickly to the user requests. The satellites fly over the Earth at an altitude of 822 km at the Equator. The orbit is circular and near polar to maintain a constant resolution of any point on the globe and is phased, so that a satellite passes over the same point every 26 days. The satellites thus repeat the same ground tracks with the maximum distance at the Equator of 108 km. The instruments carried onboard the satellites acquire images at different resolution and spectral coverage and provide the users with a large variety of products. The spectral bands and resolutions of the sensors carried on SPOT satellites are summarized in Table 6.5.

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Sensor</th>
<th>Electromagnetic spectrum</th>
<th>Pixel size (m)</th>
<th>Spectral bands (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPOT-5</td>
<td>HRS</td>
<td>Panchromatic</td>
<td>10 (5)*</td>
<td>0.49 - 0.69</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Panchromatic</td>
<td>5 (2.5)*</td>
<td>0.48 - 0.71</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B1: green</td>
<td>10</td>
<td>0.50 - 0.59</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B2: red</td>
<td>10</td>
<td>0.61 - 0.68</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B3: near infrared</td>
<td>10</td>
<td>0.78 - 0.89</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B4: mid infrared (MIR)</td>
<td>20</td>
<td>1.58 - 1.75</td>
</tr>
<tr>
<td>SPOT-4</td>
<td>HRVIR</td>
<td>Panchromatic</td>
<td>10</td>
<td>0.61 - 0.68</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B1: green</td>
<td>20</td>
<td>0.50 - 0.59</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B2: red</td>
<td>20</td>
<td>0.61 - 0.68</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B3: near infrared</td>
<td>20</td>
<td>0.78 - 0.89</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B4: mid infrared (MIR)</td>
<td>20</td>
<td>1.58 - 1.75</td>
</tr>
<tr>
<td>SPOT-1</td>
<td>HRV</td>
<td>Panchromatic</td>
<td>10</td>
<td>0.51 - 0.73</td>
</tr>
<tr>
<td>SPOT-2</td>
<td>HRV</td>
<td>B1: green</td>
<td>20</td>
<td>0.50 - 0.59</td>
</tr>
<tr>
<td>SPOT-3</td>
<td>HRV</td>
<td>B2: red</td>
<td>20</td>
<td>0.61 - 0.68</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B3: near infrared</td>
<td>20</td>
<td>0.78 - 0.89</td>
</tr>
</tbody>
</table>

Table 6.5 SPOT satellite spectral bands and resolutions.

a.after resampling
6.3.1 Sensor description

Within the SPOT constellation, SPOT-5 is the most innovative satellite. The new HRG (High Resolution Geometry) instrument, derived from the HRVIR instrument on SPOT-4, offers up to 2.5m resolution in panchromatic mode in across-track direction. Moreover, the new HRS (High Resolution Sensor), used in this work, allows the acquisition of stereo images in along-track directions, using two instruments pointing about 20° forward and backward the flight direction (Figure 6.10). Each scene acquired by HRS has a field of view of 120km, with a ground resolution of 10m across and 5m along the flight direction. The 5m resolution is achieved after resampling. The technical data of the HRS instrument are summarized in Table 6.6.

<table>
<thead>
<tr>
<th>Table 6.6 HRS technical data.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mass</strong></td>
</tr>
<tr>
<td><strong>Power</strong></td>
</tr>
<tr>
<td><strong>Dimensions</strong></td>
</tr>
<tr>
<td><strong>Field of view</strong></td>
</tr>
<tr>
<td><strong>Focal length</strong></td>
</tr>
<tr>
<td><strong>Detectors per line</strong></td>
</tr>
<tr>
<td><strong>Detector size</strong></td>
</tr>
<tr>
<td><strong>Integration time per line</strong></td>
</tr>
<tr>
<td><strong>Forward/aft viewing angle relative to vertical</strong></td>
</tr>
<tr>
<td><strong>Spectral range (PAN)</strong></td>
</tr>
<tr>
<td><strong>Ground sample distance:</strong></td>
</tr>
<tr>
<td>- across track</td>
</tr>
<tr>
<td>- along track</td>
</tr>
<tr>
<td><strong>Signal-to-noise ratio</strong></td>
</tr>
</tbody>
</table>

\(^a\) after resampling

Figure 6.10 Acquisition of SPOT-5 HRS.

6.3.2 Data description

The dataset number 9 provided during the ISPRS-CNES Initiative covered partly South of Germany and partly Austria. The following data have been received from CNES and DLR Berlin:

- Stereo images from SPOT-5/HRS acquired on 1st October 2002 in the morning over an area of approximately 120km x 60km
- Metadata file for each scene. The files contain the time acquisition and image location, the sensor position and velocity measured by DORIS system every 30 seconds, the attitude and angular speeds from star trackers and gyros at 12.5 seconds interval, with respect to the local orbital coordinate frame, the sensor geometric (detectors looking angles) and radiometric calibration
- Description of exact position of 81 object points in Germany, measured with surveying methods. The coordinates were given in Gauss-Krüger system
- 4 DEMs in Southern Bavaria (Prien, Gars, Peterskirchen, Taching) created from laser scanner data with a pixel spacing of 5m and an overall size of about 5km x 5km. The height accuracy is
better then 0.5m

- 2 DEMs in the area of Inzell (total: 10km x 10km, 25m spacing). The first one, called 5-1, was derived from laser scanner data (northern part, height accuracy better then 0.5m) and the other one, called 5-2, was derived from contour-lines 1:10,000 (southern part, height accuracy of about 5m)

- A large coarse DEM (area of Vilsbiburg, 50km x 30km) with 50m spacing and height accuracy of about 2 meters, derived by conventional photogrammetric and geodetic methods; only a small part of this DEM is covered in the scenes.

An overview of the characteristics of the reference DEMs and their location in the image area are given in Table 6.7 and Figure 6.11.

The SPOT stereo scenes had a size of 12,000 pixels across the flight direction and 12,000 pixels along the flight direction, with a ground resolution of 10m (across-track) x 5m (along-track). The time difference between their acquisition was 90s. The scenes were a level 1A product, with radiometric correction of the distortions due to differences in sensitivity of the elementary detectors of the viewing instruments. In the next paragraphs the work applied on the SPOT scenes is described. After the scene orientation, a DEM was generated and compared to the reference data.

<table>
<thead>
<tr>
<th>DEM</th>
<th>Location</th>
<th>DEM Spacing</th>
<th>Source</th>
<th>DEM Size</th>
<th>Height Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Prien</td>
<td>5m x 5m</td>
<td>Laser Scanner</td>
<td>5km x 5km</td>
<td>0.5m</td>
</tr>
<tr>
<td>2</td>
<td>Gars</td>
<td>5m x 5m</td>
<td>Laser Scanner</td>
<td>5km x 5km</td>
<td>0.5m</td>
</tr>
<tr>
<td>3</td>
<td>Peterskirchen</td>
<td>5m x 5m</td>
<td>Laser Scanner</td>
<td>5km x 5km</td>
<td>0.5m</td>
</tr>
<tr>
<td>4</td>
<td>Taching</td>
<td>5m x 5m</td>
<td>Laser Scanner</td>
<td>5km x 5km</td>
<td>0.5m</td>
</tr>
<tr>
<td>5-1</td>
<td>Inzell-North</td>
<td>25m x 25m</td>
<td>Laser Scanner</td>
<td>10km x 1.3km</td>
<td>0.5m</td>
</tr>
<tr>
<td>5-2</td>
<td>Inzell-South</td>
<td>25m x 25m</td>
<td>Contour lines</td>
<td>10km x 7.7km</td>
<td>5.0m</td>
</tr>
<tr>
<td>6</td>
<td>Vilsbiburg</td>
<td>50m x 50m</td>
<td>Photogrammetry</td>
<td>50km x 30km</td>
<td>2.0m</td>
</tr>
</tbody>
</table>

### 6.3.3 Preprocessing

The images have been radiometrically enhanced with Wallis filter (Section 5.3.1). For each scene the acquisition time of each image line was calculated from the acquisition time of the central line and the scanning interval time contained in the metadata files, according to Equation 3.19. The ground control points were measured in the images using the description files provided by DLR. From the 81 points, only 41 have been measured in the images. The other points were not visible in the images or could not be recognized due to the resolution of the images. Figure 6.12 shows the point distribution in one of the two scenes. A digital map at 1:50,000 scale by Topo50 (Bayerische Vermessungsverwaltung, 2004) was used to recognize the main ground features (streets, rivers, lakes, forests, ...) and locate the points. The accuracy of the object coordinates was within few centimeters, as they were measured with topographic methods.

The exact image coordinates have been measured with sub-pixel accuracy with unconstrained Multiphotograph Least Squares Matching available at IGP (Baltsavias, 1991). We supposed a measurement accuracy of 0.5 pixels. Figure 6.13 shows an example of point measurement with matching.
Figure 6.11. Top: SPOT-5 image after resampling (pixel size 10m x 5m); bottom: SPOT-5 image at original pixel size (10m x 10m) and location of reference DEMs.

Figure 6.12. Point distribution in one of the SPOT5-HRS original images (pixel size: 10m x 5m).
6.3.4 Image orientation

The direct georeferencing approach was used in order to test if the camera calibration and the ephemeris available in the metadata files were accurate enough for high precision mapping. The information on the internal orientation was given through the viewing angles of each detector expressed within the sensor coordinate frame. From these data the position of each detector in the focal plane was computed as explained in Section 5.2. The position and velocity vectors were used for the estimation of the sensor attitude in the ECR system (Equation 3.16). Then the position and attitude were interpolated with cubic splines for the acquisition times of the image lines. A forward intersection was applied to calculate the ground coordinates of the object points. The resulting coordinates were compared to the correct values and the RMSE were evaluated. The results showed a large systematic error both in planimetry (2-3 pixels) and in height (~3 pixels). Therefore the indirect georeferencing model was required for the internal and external orientation refinement.

The object coordinates were transformed into the ECR system, which was used as reference system for the geometric processing. From the available 41 points, a group of them was used as GCPs and the remaining as CPs. The GCPs were chosen in order to have a good distribution. The a priori standard deviation of the GCPs was 3m. The tests have been carried out with different input configurations, in this order:

1. external orientation modeling with quadratic functions, varying the number of segments and GCPs configurations, no self-calibration
2. external orientation modeling with linear and quadratic functions, best GCPs configuration and best trajectory segments, no self-calibration
3. self-calibration with best external orientation modeling configuration.

As already encountered with MOMS-02, the PPM gave better results with quadratic functions, than with linear ones. Using linear functions, the RMS and standard deviation values were close to 1 pixel. The RMSE and the sigma of the CPs and the sigma naught of the adjustment obtained with quadratic functions without and with self-calibration are reported in Table 6.8.
Table 6.8. Results obtained using different GCPs and CPs configuration and external orientation modeling options. X, Y, and Z refer to ECR system. NS = number of segments in PPM, SC = self-calibration (Y = yes, N = no).

<table>
<thead>
<tr>
<th>NS</th>
<th>SC</th>
<th>GCP</th>
<th>CP</th>
<th>( \delta_0 ) (( \mu )m)</th>
<th>RMSE CPs (m)</th>
<th>( \sigma ) CPs (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( \mu )m</td>
<td>X</td>
<td>Y</td>
</tr>
<tr>
<td>2</td>
<td>N</td>
<td>6</td>
<td>35</td>
<td>2.7</td>
<td>5.6</td>
<td>8.7</td>
</tr>
<tr>
<td>2</td>
<td>N</td>
<td>12</td>
<td>29</td>
<td>2.9</td>
<td>5.5</td>
<td>7.2</td>
</tr>
<tr>
<td>4</td>
<td>N</td>
<td>6</td>
<td>35</td>
<td>2.6</td>
<td>5.5</td>
<td>8.5</td>
</tr>
<tr>
<td>4</td>
<td>N</td>
<td>12</td>
<td>29</td>
<td>2.8</td>
<td>5.4</td>
<td>7.1</td>
</tr>
<tr>
<td>2</td>
<td>Y</td>
<td>6</td>
<td>35</td>
<td>1.1</td>
<td>3.8</td>
<td>6.9</td>
</tr>
<tr>
<td>2</td>
<td>Y</td>
<td>12</td>
<td>29</td>
<td>1.2</td>
<td>3.7</td>
<td>6.1</td>
</tr>
<tr>
<td>4</td>
<td>Y</td>
<td>6</td>
<td>35</td>
<td>0.8</td>
<td>3.9</td>
<td>6.8</td>
</tr>
<tr>
<td>4</td>
<td>Y</td>
<td>12</td>
<td>29</td>
<td>0.9</td>
<td>3.7</td>
<td>6.0</td>
</tr>
</tbody>
</table>

Taking into account the results achieved without self-calibration (first 4 rows of Table 6.8), it can be seen that increasing the number of PPM segments the adjustment converges better (smaller \( \delta_0 \) and \( \sigma \) of the CPs) and the RMS values remain quite constant. As expected, the use of more GCPs gives better solutions, in terms of internal and external accuracy. The RMSE sizes and distributions in the object space evidence that if only the external orientation is modeled, the systematic errors are not completely removed. In the top of Figure 6.14 an example of RMSE distribution (12 GCPs and 29 CPs) is shown.

In the next step the self-calibrating bundle adjustment was used. Each adjustment with self-calibration was run with the external orientation parameters fixed to their values estimated without self-calibration. The results are reported in the last 4 rows of Table 6.8 (SC = Y). By a visual analysis, Figure 6.14 shows the reduction of the systematic behavior in the RMSE distribution. Also, the quantitative comparison between the RMSE and \( \sigma \) values of the CPs and the \( \delta_0 \) before and after the self-calibration confirms an improvement both in the internal and external accuracy of the adjustment. The significant self-calibration parameters were the symmetric radial distortion (through \( k_i \)) and the scale in y direction (\( s_y \)), with the focal length fixed. These parameters were different for each lens and their effect could not be compensated during the estimation of the external orientation parameters only, which is unique for the entire system. The maximum effects of the estimated parameters for each lens are calculated for the pixels on the image borders \( (u = 6,000) \) with Equation 2.15 for \( k_i \) and Equation 2.17 for \( s_y \). They are reported in Table 6.9.

Table 6.9. Maximum errors in lenses 1 (forward) and 2 (backward) caused by lens distortion. The errors are expressed in mm and in pixels.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lens 1</th>
<th>Lens 2</th>
<th>( \Delta y_1 ) (mm)</th>
<th>( \Delta y_2 ) (mm)</th>
<th>( \Delta y_1 ) (pixels)</th>
<th>( \Delta y_2 ) (pixels)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( k_i )</td>
<td>(-5.7 \times 10^{-7})</td>
<td>(-7.7 \times 10^{-7})</td>
<td>0.020</td>
<td>0.030</td>
<td>3.6</td>
<td>5.3</td>
</tr>
<tr>
<td>( s_y )</td>
<td>(-5.1 \times 10^{-4})</td>
<td>(-4.8 \times 10^{-4})</td>
<td>0.020</td>
<td>0.020</td>
<td>3.6</td>
<td>3.6</td>
</tr>
</tbody>
</table>
6.3.5 DEM generation

For the matching and DEM generation, algorithms and software packages developed in our group for airborne or spaceborne linear array sensors (Grün et al., 2004, Zhang and Grün, 2003, Grün and Zhang, 2002a) have been used. The approach takes into account the characteristics of the linear array image data for matching and automatic DEM extraction.

6.3.5.1 Image matching

The image matching used in this case study was implemented in SAT-PP software (Zhang and Grün, 2003). The algorithm, based on the Multi-Photo Geometrically Constraint (MPGC) matching (see Grün, 1985, Grün and Baltsavias, 1988, Baltsavias, 1991), is a combination of feature point, edge and grid point matching and can achieve sub-pixel accuracy for all the matched features. Figure 6.15 shows the matching process scheme.
Chapter 6. APPLICATIONS

Images and Orientation Data

Image Pre-processing & Image Pyramid Generation

Feature Point Matching
Edge Matching
Grid Point Matching

Geometrically Constrained Candidate Search, Adaptive Matching Parameter Determination

DSM (intermediate) Combination of feature points, grid points and edges

Modified Multi-Image Geometrically Constrained Matching (MPGC)

Final DSM

Figure 6.15. Workflow of the image matching procedure (Zhang and Grün, 2003).

After the pre-processing of the imagery and production of the pyramids, the matches of three kinds of features, i.e. feature points, grid points and edges, are found progressively in all pyramid levels starting from the low-density features on the images with the lowest resolution. A Triangular Irregular Network (TIN) based DEM is constructed from the matched features on each level of the pyramid and is used in turn in the subsequent pyramid level as approximation for the adaptive computation of the matching parameters. Finally the modified MPGC matching is used to achieve more precise results for all the matched features on the original resolution level (level 0) and to identify some inaccurate and possible false matches. The raster DEMs are interpolated from the original matching results using DTMZ software.

The main characteristics of the matching procedure are:

- It is a combination of feature point, edge and grid point matching. The grid point matching procedure uses relaxation-based relational matching algorithm and can bridge-over the non- and little-texture areas through the local smoothness constraints. The matched edges are introduced to control the smoothness constraints and preserve the surface discontinuities.

- The adaptive determination of the matching parameters results in higher successful rate and less false matches. These parameters include: the size of the matching window, the searching distance and the threshold values for cross-correlation and MPGC (Least Squares matching). For instance, the procedure uses a smaller matching window, larger search distance and a smaller threshold value in rough terrain area and vice versa. The roughness of the terrain can be computed from the approximate DEM on higher levels of image pyramid.

- Object edges are important for preserving the surface discontinuities. A robust edge-matching algorithm, which uses the adaptive matching window determination through the analysis of the image contents and local smoothness constraints along the edges, is combined into the procedure.

- Together with matched point features, edges (in 3D) are introduced as break-lines when a TIN-based DEM is constructed. It provides a good approximate for matching on the next pyramid
level. The computation of the approximated DEM for the highest-level image pyramid uses a matching algorithm based on “region-growing” strategy (Otto and Chau, 1989), in which the already measured GCPs and tie points can be used as “seed” points.

- Thanks to the quality control procedure, which can be the local smoothness and consistence analysis of the intermediate DEM on each image pyramid, the analysis of the difference between the intermediate DEMs and the analysis of the MPGC results, blunders can be detected and deleted.

- For each matched feature, a reliability indicator is assigned based on the analysis of the matching results (cross-correlation and MPGC). It results in different weights when a grid based DEM is generated.

In particular, considering the features of the SPOT-5/HRS image data, some small modifications were made in the matching procedure:

- The HRS imagery has 10 meters resolution in across-track direction and 5 meters in along-track direction (parallax direction). This configuration may result in a better accuracy for point determination and DEM generation, but it makes (area-based) matching more difficult. In order to solve the problem, the images have been resampled from 10m × 5m to 10m × 10m and processed with the matching procedure (except the MPGC part). Then the MPGC (Least Squares matching) was run on the original images (10m × 5m) in order to recover the original matching accuracy. This two-step method allowed the reduction of the search distance between corresponding points, which is equivalent to the reduction of the possibility of false matching and processing time.

- In some difficult areas, like small and steep geomorphologic features (an example is shown in Figure 6.16), some manually measured points can be introduced as “seed points”. This operation brings better approximations for the matching.

As the test area included a mountainous area (rolling and strongly inclined alpine area) on the lower part and some hill areas (rough/smooth and weakly inclined areas) on the upper part, the image matching software generated both a large number of mass points (feature points and grid points) and linear features. The TIN based DEM was generated from the matched mass points and the edges (as break-lines). As a result, more than 8.4 millions points were matched and 80% of them were marked as “reliable” points. Some areas as lakes and rivers could be manually set as “dead areas” with a user-friendly interface.
6.3.5.2 DEM generation

The ground coordinates of the 8.4 millions points measured in the images were estimated using a forward intersection algorithm (Section 4.8). The resulting coordinates, in the ECR Geocentric system, were transformed into Gauss-Krüger system in order to be compared to the reference DEMs. The 3D point cloud was transformed into a regular grid with 20m x 20m grid space with DTMZ software. In Figure 6.17 the generated DEM is shown.

6.3.6 Comparison

The generated DEM has been compared to the reference DEMs provided by the HRS-SAP. The main characteristics (location, spacing, source, size and height accuracy) of the reference data are shown in Table 6.7. The coordinate system used for the comparison is the Gauss-Krüger system Zone 4 with Bessel-ellipsoid and Potsdam datum.

Two accuracy tests have been performed, in 2.5D and 3D respectively. In the first test the differences between the heights of the reference DEMs and the corresponding height interpolated from our DEMs have been computed (2.5D). The limit of this approach is that it is highly influenced by the errors of the surface-modelling algorithm. Figure 6.18 illustrates the concept with a step profile: even if the measurements (point P) are accurate, the modeled profile cannot follow the true one. Consequently if the terrain height is compared, in presence of the step, a large difference ($\Delta h$) may be measured. For that reason the computation of the 3D orthogonal distance between the surfaces (distance $d$ in Figure 6.18) is theoretically more correct. Therefore the second accuracy test is based on the evaluation of the normal distance (3D) between our measurements (3D point cloud) and the reference DEMs. This test is fundamental in this case study where steep mountains (like Alps) are present. The results of the two tests are reported in Tables 6.10 and 6.12.

![Figure 6.18. Modelling problems. The true profile is the full black line, the modelled profile is the dashed line.](image)

6.3.6.1 Accuracy tests on the terrain height (2.5D)

This analysis has been carried out using different tools developed at IGP. The results obtained comparing all the points are reported in Table 6.10 (3rd to 6th column). It can be observed that the accuracy of the measured DEM is more or less on 1-2 pixels level, depending on the terrain type. As expected, a better accuracy is achieved in smooth and flat areas, while in the mountainous area (DEM 5-1 and 5-2) the RMSE are larger. In all datasets some blunders which failed to be detected are still present. In the reference datasets 5-1 and 5-2 some blunders are even above 100m, with a bias up to 1.0 pixels. Apart from the results of reference DEM 6, all the biases are negative, indicating that the generated DEM is higher than the reference ones. For further analysis, the frequency distribution of the height differences is shown in the second column of Table 6.11 (DEM 6 is missing because only a small portion was covered by the scenes). In the frequency distribution of the height differences two peaks occur, one located around value 0.0 and
Figure 6.17. DEM generated from 8.4 millions points with a forward intersection using the estimated internal and external orientations. The black holes represent "dead areas".
the other one around a negative value (ca. 8m). The relative frequency values could be correlated to the percentage of presence of trees. In fact from a qualitative analysis of the error distribution, we noticed that the negative height difference (the green areas) have the same clustering of the areas covered by trees, while the open areas have small height difference values. Then the bias located at -8m could be mainly caused by the trees. This is a main problem for extracting a DEM by using the optical imaging systems, as the light cannot penetrate the vegetation. In fact the generated digital model does not represent the terrain (DEM or DTM), but the surface (DSM) visible by an optical instrument, including houses, trees, bushes and so on. In order to verify that our results where affected by the influence of the trees, the areas covered by trees have been manually removed from the images and the accuracy tests have been repeated. The percentage of removed points is 25, 26, 17, 28, 75 and 71 for DEM 1, 2, 3, 4, 5-1, 5-2 and 6 respectively. The results obtained by the new accuracy tests are shown in Table 6.10 (last 4 columns). As expected, the negative bias was reduced. This is also graphically confirmed by the new frequency distribution reported in the third column of Table 6.11. The analysis of the frequency distributions shows that in steep mountain areas (DEMs 5-1 and 5-2) there are positive height-difference values. They are probably caused by the presence of blunders or by the local smoothness constraints used in the matching algorithm. In fact these constraints smooth out some steep and small features of the mountain areas under the condition that there are not enough extracted and matched linear features.

Table 6.10.2.5D comparison between reference and generated DEMs, with and without trees. For each comparison, the maximum, minimum and mean difference and the RMSE are reported.

<table>
<thead>
<tr>
<th>DEM Name</th>
<th>N. of Matched Points</th>
<th>Max (m)</th>
<th>Min (m)</th>
<th>Mean (m)</th>
<th>RMSE (m)</th>
<th>Max (m)</th>
<th>Min (m)</th>
<th>Mean (m)</th>
<th>RMSE (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
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</tr>
<tr>
<td>1</td>
<td>35448</td>
<td>22.1</td>
<td>-26.1</td>
<td>-4.0</td>
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<td>13.8</td>
<td>-23.6</td>
<td>-3.0</td>
<td>5.4</td>
</tr>
<tr>
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<td>32932</td>
<td>37.7</td>
<td>-37.1</td>
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<tr>
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<td>21.9</td>
<td>-14.6</td>
<td>-0.7</td>
<td>3.9</td>
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</tbody>
</table>

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Table 6.11. DEM accuracy analysis. First column: Name of reference dataset; second column: frequency distribution of the height-differences for all points; third column: frequency distribution of the height-differences for points after trees removal.

<table>
<thead>
<tr>
<th>DEM</th>
<th>Histogram for all points</th>
<th>Histogram without points on trees</th>
</tr>
</thead>
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<td><img src="image2" alt="Histogram without points on trees" /></td>
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<td><img src="image5" alt="Histogram for all points" /></td>
<td><img src="image6" alt="Histogram without points on trees" /></td>
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<tr>
<td>4</td>
<td><img src="image7" alt="Histogram for all points" /></td>
<td><img src="image8" alt="Histogram without points on trees" /></td>
</tr>
<tr>
<td>5-1</td>
<td><img src="image9" alt="Histogram for all points" /></td>
<td><img src="image10" alt="Histogram without points on trees" /></td>
</tr>
<tr>
<td>5-2</td>
<td><img src="image11" alt="Histogram for all points" /></td>
<td><img src="image12" alt="Histogram without points on trees" /></td>
</tr>
</tbody>
</table>
6.3.6.2 Accuracy tests based on the orthogonal distances

This analysis has been carried out with the commercial software Geomagic Studio v.4.1 by Rain-drop Geomatic (Geomagic Studio, 2004). This software can compare a 3D surface (in our case generated from the reference DEMs) and a point cloud (in our case, our 3D point cloud). It calculates the normal distance between each triangle of a surface and the closest point of the cloud. As output, the software gives the number of points compared (n), the mean (μ) and absolute maximum distance and the standard deviation (σ). The sign of the mean values has been changed to be homogeneous with the 2.5D results previously shown. From these elements the RMSE is calculated as:

$$RMSE^2 = \frac{n-1}{n} \sigma^2 + \mu^2$$  \hspace{1cm} (6.1)

The results are reported in Table 6.12. Comparing these results with those obtained in the 2.5D comparison, it can be seen that both the mean distance and standard deviation are now reduced in all datasets. This demonstrates that part of the errors estimated with the 2.5D accuracy tests may be due to modelling errors or to the planimetric errors. Again, the larger errors have been found in mountainous areas (DEM 5-2), while in flat terrains the accuracy of the generated DEMs is very good. The mean values and RMSE obtained by the 2.5D and 3D tests are graphically summarized in Figure 6.19.

From both the 2.5D and 3D quality analysis the average error between the generated and the reference DEMs is around 1-2 pixels (2.5D analysis) and up to slightly more than 1 pixel (3D analysis), depending on the terrain type. The best results were achieved in smooth and flat areas, while in mountain areas some blunders even exceeded 100 meters. In conclusion, this investigation demonstrated the possibility to apply the developed model on HRS scenes and the high potential of the scenes themselves for DEM generation.

Table 6.12.3D comparison between generated and reference DSMs.

<table>
<thead>
<tr>
<th>DEM</th>
<th>Maximum Difference (m)</th>
<th>Mean Difference (m)</th>
<th>Standard deviation (m)</th>
<th>RMSE (m)</th>
</tr>
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<tr>
<td>1</td>
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<td>1.5</td>
<td>2.2</td>
</tr>
<tr>
<td>2</td>
<td>38.0</td>
<td>-1.8</td>
<td>1.8</td>
<td>2.6</td>
</tr>
<tr>
<td>3</td>
<td>22.3</td>
<td>-1.4</td>
<td>1.3</td>
<td>1.9</td>
</tr>
<tr>
<td>4</td>
<td>19.7</td>
<td>-1.5</td>
<td>1.4</td>
<td>2.1</td>
</tr>
<tr>
<td>5-1</td>
<td>26.2</td>
<td>-6.3</td>
<td>4.3</td>
<td>7.6</td>
</tr>
<tr>
<td>5-2</td>
<td>73.6</td>
<td>-6.8</td>
<td>5.8</td>
<td>8.9</td>
</tr>
</tbody>
</table>

6.3.7 Summary and conclusions

Within the ISPRS-CNES initiative for the investigation on the potentials of SPOT-5/HRS for DEM generation (HRS-SAP), our rigorous model was used for the orientation of two HRS scenes (dataset number 9) and for the generation of a 3D point cloud. The work also included the radiometric preprocessing of the images, the measurement of the object points and the analysis of the information on the camera system and on the sensor external orientation contained in the metadata file.
Section 6.3. SPOT-5/HRS

Comparison of mean values

<table>
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<tr>
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<th>3</th>
<th>4</th>
<th>5-1</th>
<th>5-2</th>
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<td>-4</td>
<td>-3</td>
<td>-1.9</td>
<td>-3.8</td>
<td>-6.7</td>
<td>-5.7</td>
</tr>
<tr>
<td>2.5D no trees</td>
<td>-3</td>
<td>-1.8</td>
<td>-2.3</td>
<td>-2.8</td>
<td>-3.4</td>
<td>-4</td>
</tr>
<tr>
<td>3D all points</td>
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<td>-1.8</td>
<td>-1.4</td>
<td>-1.5</td>
<td>-6.3</td>
<td>-6.8</td>
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</table>

Comparison of RMSE

<table>
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<th>4</th>
<th>5-1</th>
<th>5-2</th>
</tr>
</thead>
<tbody>
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<td>2.5D all points</td>
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<td>5.5</td>
<td>4</td>
<td>5.2</td>
<td>9.4</td>
<td>11.2</td>
</tr>
<tr>
<td>2.5D no trees</td>
<td>5.4</td>
<td>3.9</td>
<td>3.4</td>
<td>3.9</td>
<td>5.3</td>
<td>7.4</td>
</tr>
<tr>
<td>3D all points</td>
<td>2.2</td>
<td>2.6</td>
<td>1.9</td>
<td>2.1</td>
<td>7.6</td>
<td>8.9</td>
</tr>
</tbody>
</table>

At first the direct georeferencing algorithm was applied in order to calculate the 3D ground coordinates of the points measured in the images through a forward intersection without GCPs. The residuals in the CPs were not satisfying for high accurate mapping, therefore the images were oriented with the indirect georeferencing model; the sensor external and internal orientation were estimated using a minimum number of 6 GCPs. The self-calibration was useful for the compensation of systematic errors due to the lens distortion. The parameters estimated for the two lenses had significant differences and could not be compensated by the external orientation modelling, which is unique for the full system.

The orientation of SPOT-5/HRS stereo scenes has also been investigated in many other research institutes that were involved in the HRS-SAP. The results achieved for the dataset number 9 are reported and compared to the performances of our model.

At the Institute of Geodesy and Photogrammetry (IGP) another approach based on Rational Polynomial Coefficients (RPC) was used to orient the images. This algorithm is implemented in the SAT-PP software, developed at IGP (Grün et al., 2005). For each scene the strict image-to-ground transformation described in SPOT Satellite Geometry Handbook, 2002 was implemented and used to generate three point grids in the object space at three different pre-defined heights. For this operation the position and attitude data and the look direction table for the 12,000 pixels contained in the metadata files were used. Then a set of RPC was derived for each scene.

Figure 6.19. Comparison of mean values and RMSE using 2.5D analysis and 3D analysis.
coefficients describe the relationship between image (row, column) and object coordinates (usually in the geographic coordinate system) through the ratio of 3rd order polynomials. Once the two sets of RPC are generated (one set for each scene), a block adjustment is performed in order to estimate six parameters describing additional constant systematic errors (shifts and misalignment in the position and attitude, residual internal orientation errors, on-board drifts errors). The minimum number of GCPs required is 4. In case of SPOT-5/HRS the images were orientated with 4 GCPs, with residuals of 5.6m, 4.0m and 2.4m in East, North and height (Gauss-Krüger system). The RMSE obtained with our rigorous model in the Gauss-Krüger system are: 5.9m, 4.2m and 3.5m. The difference between the two methods are not very significant. Anyway it must be taken into account that in general the rigorous models are sensitive to the GCPs distribution in the images and in our case the GCPs were located in the left part of the image only. On the other hand, the RPC were derived from the strict model designed for the full scene and the use of a block adjustment could compensate additional systematic errors. The differences in the orientation performance are of course present in the DSMs too, with values in the order of 5% of the pixel size (Poli et al., 2004a).

Among the Investigators and Co-Investigators who oriented the SPOT-5/HRS scenes of the dataset number 9, the results achieved by DLR (Reinartz et al., 2004) demonstrated that a mean terrain height differences in the order of 5m to 9m can be achieved in the CPs without using GCPs, with standard deviation of about 2m to 4m for single points and 4m to 7m for the interpolated DEMs in comparison to the reference DEM. The object space coordinates were calculated with forward intersection using the external and internal orientation contained in the metadata files and the strict model described in the SPOT Satellite Geometry Handbook, 2002. The sensor position and attitude for each image line was calculated with Lagrange and linear interpolation respectively.

Using our direct georeferencing model the residuals in the height was between 2 and 3 pixels. This is probably due to the fact that we did not use all the information contained in the metadata file, but only the position and velocity information (in order to calculate the attitude) and the pixel looking vectors (transformed into the pixel positions in the focal plane). The other information referred to additional systems adopted for HRS that can not be transformed in our systems. As the strict model contained in the SPOT Satellite Geometry Handbook, 2002 is designed for SPOT-5/HRS, it allows the achievement of more accurate results.

In Reinartz et al., 2004 additional investigations on the orientation of the HRS scenes are reported. The bundle adjustment software CLIC, developed by IPI Hannover (Konecny et al., 1997) was used for the estimation of the focal length, the principal point position and the viewing angle of each lens and the CCD line rotations in the focal plane. Then the height differences between a variable number of CPs and the reference DEMs were computed. The mean values ranged from -8.4m to 6.0m with a standard deviation of 2.0m-4.8m.


In particular, the results obtained by the HRS-SAP Principal Investigators and the Co-Investigators over the test area number 9 were compared with the same strategy and reported in Rudowski, 2004. In this analysis the DEMs generated at IGP using our sensor model (PI) and the RPC model (P2) and by other two investigators (II and I2) have been evaluated through the 2.5D height difference with the reference terrain models. The maximal and minimal values, the mean and standard deviation for 98% of the compared points are reported in Table 6.13. The mean and sigma values are visually represented in Figure 6.20. The results achieved by I2 are obtained without GCPs (Reinartz et al., 2004), while the orientation procedure used by I2 was the
BLASPO software developed by IPI Hannover (Jacobsen, 2004). The comparison showed that the best mean and RMSE values have been achieved in about all the reference areas by P1 and P2. The differences between P1 and P2 have already been commented. The comparison confirms that for this dataset our sensor model can achieve an accuracy both in the CPs and in the interpolated points in the same order or even better than the one obtained using other software and approaches.

Table 6.13. DEM accuracy analysis for HRS-SAP (test area number 9). The shaded cells refer to the results achieved with our sensors model. The values are in meters (Rudowski, 2004).

<table>
<thead>
<tr>
<th>DEM</th>
<th>Investigator</th>
<th>min</th>
<th>max</th>
<th>mean</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
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<td>14</td>
<td>4.0</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>P2</td>
<td>-7</td>
<td>14</td>
<td>2.6</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td>I1</td>
<td>0</td>
<td>31</td>
<td>10.0</td>
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<tr>
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<td>I2</td>
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<td>41</td>
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<td>10</td>
<td>0.5</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td>I1</td>
<td>0</td>
<td>24</td>
<td>7.0</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td>I2</td>
<td>-15</td>
<td>27</td>
<td>3.1</td>
<td>6.6</td>
</tr>
<tr>
<td>4</td>
<td>P1</td>
<td>-4</td>
<td>14</td>
<td>4.1</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>P2</td>
<td>-5</td>
<td>14</td>
<td>2.8</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td>I1</td>
<td>-4</td>
<td>28</td>
<td>8.6</td>
<td>5.9</td>
</tr>
<tr>
<td></td>
<td>I2</td>
<td>-12</td>
<td>32</td>
<td>4.6</td>
<td>8.4</td>
</tr>
<tr>
<td>5-1</td>
<td>P1</td>
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<td>20</td>
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<td>5.7</td>
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<td>I1</td>
<td>-82</td>
<td>58</td>
<td>10.1</td>
<td>18.7</td>
</tr>
<tr>
<td></td>
<td>I2</td>
<td>-51</td>
<td>38</td>
<td>12.2</td>
<td>12.9</td>
</tr>
<tr>
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<td>P2</td>
<td>-20</td>
<td>28</td>
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<td>6.9</td>
</tr>
<tr>
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<td>I1</td>
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<td>58</td>
<td>8.5</td>
<td>24.4</td>
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<tr>
<td></td>
<td>I2</td>
<td>-109</td>
<td>44</td>
<td>8.8</td>
<td>15.1</td>
</tr>
</tbody>
</table>

Figure 6.20. Comparison of mean values (right) and sigma (left) between 4 investigators.
### 6.4 ASTER

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) is one of the instruments flying on TERRA, a satellite belonging to the NASA's Earth Observing System (EOS). The purpose of the mission is to study the ecology and climate of the Earth through the acquisition of systematic and global multi-angle imagery in reflected sunlight.

The Terra spacecraft was launched on 18\textsuperscript{th} December 1999 and is still in orbit. The baseline orbit is sun-synchronous, with an inclination of 98.2°. The orbit period of 5,933 sec (98.88 min) and procession rate of 0.986°/day imply a ground repeat cycle of the spacecraft nadir point of exactly 16 days. The orbit is 705 km high, although the altitude varies from a minimum of about 704 km to a maximum of 730 km. The equatorial crossing is at 10:33 a.m.

Together with ASTER, the instruments carried on EOS are: the Multi-Angle Imaging SpectroRadiometer (MISR), the Moderate-Resolution Imaging Spectroradiometer (MODIS), the Clouds and the Earth's Radiant Energy System (CERES) and the Measurements Of Pollution In The Troposphere (MOPITT).

ASTER is a cooperative effort between NASA and Japan's Ministry of Economy Trade and Industry (METI) formerly known as Ministry of International Trade and Industry (MITI), with the collaboration of scientific and industrial organizations in both countries.

ASTER covers a wide spectral region with 14 bands from the visible to the thermal infrared with different spatial, spectral and radiometric resolution. An additional backward looking near-infrared band provides stereo coverage.

The ASTER instrument consists of 3 downlooking sub-systems: the Visible and Near-infrared (VNIR), the ShortWave Infrared (SWIR) and the Thermal InfraRed (TIR). VNIR has three bands in the visual and near infrared range, covering the wavelength range 0.52-0.86\(\mu\)m, with a spatial resolution of 15 m; SWIR has 6 bands in the range 1.6-2.4\(\mu\)m, with a spatial resolution of 30 m; TIR has 5 bands in the range 8.1-11.3\(\mu\)m, with a ground resolution of 90 m. Each subsystem was built by a different Japanese company. The spatial and spectral resolution of each instrument are summarized in Table 6.14. The scenes can be bought at a very low price ($55 for a 60 km x 60 km area) and contain all the channels.


<table>
<thead>
<tr>
<th>Instrument</th>
<th>Channel</th>
<th>Wavelength ((\mu)m)</th>
<th>Spatial resolution (m)</th>
<th>Spectral resolution (bit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VNIR</td>
<td>1</td>
<td>0.52-0.60</td>
<td>15</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.63-0.69</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3N</td>
<td>0.78-0.86</td>
<td></td>
<td></td>
</tr>
<tr>
<td>telescope 1</td>
<td>3B</td>
<td>0.78-0.86</td>
<td></td>
<td></td>
</tr>
<tr>
<td>telescope 2</td>
<td>4</td>
<td>1.60-1.70</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>2.14-2.18</td>
<td>30</td>
<td>8</td>
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<tr>
<td></td>
<td>6</td>
<td>2.18-2.22</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>2.23-2.28</td>
<td></td>
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<td></td>
<td>8</td>
<td>2.29-2.36</td>
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<td></td>
<td>9</td>
<td>2.36-2.43</td>
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<tr>
<td>SWIR</td>
<td>10</td>
<td>8.12-8.47</td>
<td></td>
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<td></td>
<td>11</td>
<td>8.47-8.82</td>
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<td></td>
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<tr>
<td></td>
<td>12</td>
<td>8.92-9.27</td>
<td>90</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>10.25-10.95</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>10.95-11.65</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
6.4.1 Sensor description

The instrument used for our test is the VNIR, the only one of ASTER with stereo capability. It consists of two independent telescopes, one looking nadir and one backward, with an angle of 27.6°. The focal plane of the backward looking telescope contains only a single detector array (channel 3B) and uses an interference filter for wavelength discrimination. The focal plane of the nadir telescope contains 3 line arrays (channels 1, 2 and 3N) and uses a dichroic prism and interference filters for spectral separation allowing all three bands to view the same area simultaneously. Channels 3N and 3B acquire in the same spectral range.

The detectors for each band consist of 5,000 CCDs, but not all of them are used at any one time. As during the time lag between the acquisition of the backward image and the nadir image the Earth rotation displaces the image center, the VNIR subsystem automatically extracts the correct 4,100 pixels based on orbit position information supplied by the EOS platform. The size of the CCD is different in the two telescopes. In the nadir one the size is 7.0μm x 7.0μm, while in the backward one it is 6.1μm x 6.1μm.

The ASTER scenes are available at different processing levels, as described in Abrams et al., 2002. For our purposes, level 1A is used, because it is not georeferenced and represents the original acquisition geometry.

6.4.2 Data description

The scene used in our work was acquired on 25th June 1999 at about 10:40 a.m. over Switzerland (orbit 18714, path 195, row 27). The scene center is located at latitude 47°09'43"N and longitude 7°42'28"N. The images corresponding to 3N and 3B channels, originally in HDF format, have been extracted in IDL environment. They had a size of 4,100 x 4,200 pixels (3N) and 5,000 x 5,400 pixels (3B) and cover an area of 61.5km x 63km and 61.5km x 81km, with a spatial resolution of 15m (Figure 6.21).

In the images mountainous, hilly and flat terrains are visible, together with lakes, rivers and urban areas. The cloud cover in the overlapping areas is approximately 0% both in 3N and 3B images. The HDF file contained the spacecraft position and velocity in the ECR system and the acquisition time of the lattice points, as explained in Section 5.1. As reference data, the DEM at 25m grid space (called DHM25) of Swisstopo (Swisstopo, 2004) has been used. The height accuracy of this product is around 2m (3m in the Alps). For more details about DHM25, see the information available at Swisstopo-DHM25, 2004.

6.4.3 Preprocessing

The images have been radiometrically corrected using the coefficients contained in the HDF file (Section 5.3.2). Then a radiometric enhancement was applied to facilitate the point matching (Figure 5.5). 46 points have been measured in the images with least-squares template matching (Baltsavias, 1991), using the nadir channel for the template selection, and their object coordinates have been manually read on 1:25,000 scale maps. Their location is shown in Figure 6.22.

The acquisition time for each image line has been linearly interpolated with Equations 5.3 and 5.4, assuming a constant scanning time. Using the position and velocity vectors, the attitude in the ECR system has been computed according to Equation 3.16. Then the sensor position and attitude were interpolated for the lines of interest with cubic splines (Section 3.2.3) and the initial approximations for the PPM coefficients were calculated according to the formulas in Section 4.6.3.3.
Figure 6.21. ASTER images: 3N on the left, 3B on the right. The arrow indicates the flight direction.

Figure 6.22. Distribution of object points in the 3N image.
6.4.4 Images orientation

The stereopair formed by the 3N and 3B images has been oriented using the indirect georeferencing model. The software has been adapted in order to treat stereo images, like these ones, with different size and CCD detectors dimensions. The same procedure used for MOMS-P2 (Section 6.2.4) has been followed. From the available object points, a part of them was used as GCPs and the remaining as tie points for final check (CPs). The a priori standard deviation of the ground coordinates was 10m.

In the first tests the external orientation only was estimated, using different distributions of GCPs and CPs (8 and 12 GCPs) and 2 and 4 segments for the PPM. For each test the internal and external accuracy of the system have been analyzed through the sigma naught a posteriori, the standard deviation and the RMSE of the CPs.

Using the blunder detection included in the model (Section 4.7.4) with a threshold of 3.0 (critical value of the t-Student distribution with infinite redundancy and a confidence interval of 99.9%), 8 points have been identified as outliers and eliminated, because their w value was larger then the threshold in almost all configurations.

After the blunder removal, the indirect georeferencing model was re-applied with the same configurations above described. The RMSE of the CPs showed errors in the order of 1-2 pixels for almost all configurations, with theoretic values (sigma) of about 1 pixel and sigma naught a posteriori of 3.5-3.7\(\mu\)m. The bundle adjustment was repeated with self-calibration, fixing the external orientation to the values previously estimated without self-calibration and keeping the APs free. Different tests have been run to check the correlation between the APs and the ground coordinates of CPs and decide which parameters had to be estimated. From this analysis, the most significant parameters were: \(k_1, k_2, p_1, p_2\) and \(s_y\). The maximum combined effect of these parameters (evaluated at the extremes of the image lines) was about 14\(\mu\)m (2.0 pixels) for 3N and 13\(\mu\)m (2.1 pixels) for 3B. As expected, the connection of the internal orientation parameters improved the internal and external accuracy of the adjustment. The results obtained with 4 segments in the PPM, with 8 and 12 GCPs and with/without self-calibration are reported in Table 6.15. The distribution of the residuals is shown in Figure 6.23.

These results confirm that for this dataset the self-calibration was required in order to model more accurately the acquisition geometry of the ASTER scenes.

Table 6.15. Results obtained using different GCPs and PPM configurations. X, Y and Z refer to the ECR system. NS = number of segments in PPM, SC = self-calibration (Y = yes, N = no).

<table>
<thead>
<tr>
<th>NS</th>
<th>SC</th>
<th>GCP</th>
<th>CP</th>
<th>(\hat{\phi}_0) ((\mu)m)</th>
<th>RMSE CPs (m)</th>
<th>(\sigma) CPs (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X   Y   Z</td>
<td>X   Y   Z</td>
</tr>
<tr>
<td>4</td>
<td>N</td>
<td>8</td>
<td>30</td>
<td>3.7</td>
<td>27.6 30.1 22.3</td>
<td>15.2 10.4 14.6</td>
</tr>
<tr>
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<td>N</td>
<td>12</td>
<td>26</td>
<td>3.5</td>
<td>22.6 20.1 16.3</td>
<td>11.2 9.4 8.6</td>
</tr>
<tr>
<td>4</td>
<td>Y</td>
<td>8</td>
<td>30</td>
<td>1.1</td>
<td>13.6 14.8 14.4</td>
<td>7.0 3.5 5.8</td>
</tr>
<tr>
<td>4</td>
<td>Y</td>
<td>12</td>
<td>26</td>
<td>1.0</td>
<td>12.7 12.2 14.0</td>
<td>6.5 3.4 5.0</td>
</tr>
</tbody>
</table>

6.4.5 DEM generation

For image matching the algorithm described in Section 6.3.5 was used in unconstrained mode. About 1,800,000 points have been extracted without any external or internal orientation information. The 2D image coordinates of the homologous points have been transformed in a 3D point cloud in the ECR system by forward intersection, using the external and internal orientation parameters estimated with the indirect georeferencing model. The geocentric coordinates have
been transformed in the Swiss local system CH1903, for further analysis. Then a 50m regular grid DEM (later on called ASTER-DEM) has been generated using the software DTMZ. The DEM is shown in Figure 6.24.
6.4.6 Comparison with reference DEMs

The DHM25 product by Swisstopo has been used to evaluate the accuracy of the generated DEMs. 20 blocks were overlapping the area covered by the ASTER scene, as shown in Figure 6.25. Because of the great amount of data, among the 20 blocks, the 6 blocks called 1107, 1108, 1127, 1128, 1147 and 1148, whose location is shown in Figure 6.26, have been used, because they are fully covered by the images.

The ASTER-DEM has been analyzed with the commercial software Geomagic Studio v.4.1 by Raindrop Geomatic (Geomagic Studio, 2004) and ArcGIS 8.3 by ESRI, ArcGIS ESRI, 2004. The 3D comparison between the reference and measured DEMs has been made with Geomagic Studio, as describe in Section 6.3.6.2. From each DHM25 block, provided as GRID files, a surface has been generated and compared to the corresponding overlapping part of the ASTER point cloud. As output, the software gives the number of points compared (N), the minimum, maximum and mean distance (Min, Max, Mean) and the standard deviation (St.dev). From this data the RMSE is computed. The results obtained from the comparison of each block with the measured DEM are reported in Table 6.16 and the error distribution is visually represented in Figure 6.27.

For the six blocks the mean values are smaller than 1 pixel, while the RMSE and standard deviations are slightly larger than 1 pixel. As expected, the frequency of the height differences follows a Gaussian distribution, as shown in Figure 6.28. From the error distributions in Figure 6.27 it can be seen that, as expected, the larger errors occur in mountainous areas. The slopes, calculated in ArcGis environment, are up to 80°, as shown in Figure 6.30

It must also be taken into account that part of the errors may be caused by the presence of buildings and trees. In fact the reference DEMs are produced by digitalization of the contour lines of 1:25,000 scale maps and refer to the terrain surface. On the other hand, the generated 3D point cloud is produced by images acquired by optical sensors and represent the visible surface. If the buildings and forest areas are removed, we expect a reduction of the mean differences and a slight improvement in the standard deviations and RMSE, as already proved in Section 6.3.

In particular, in order to verify the influence of the trees in our results, the land use layer (vector data at 1:200,000 scale by Swisstopo) was overlapped on the ASTER-DEM in GIS environment. From Figure 6.29 it can be noticed that the areas classified as forest and the areas with positive differences between the two surfaces (i.e. ASTER-DEM higher than reference DEM) have the same clustering.
Table 6.16. 3D comparison between generated and reference DSMs.

<table>
<thead>
<tr>
<th>DHM25 Block</th>
<th>N</th>
<th>Minimum Difference (m)</th>
<th>Maximum Difference (m)</th>
<th>Mean Difference (m)</th>
<th>Standard deviation (m)</th>
<th>RMSE (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1107</td>
<td>111319</td>
<td>-84.5</td>
<td>67.9</td>
<td>7.6</td>
<td>16.7</td>
<td>18.3</td>
</tr>
<tr>
<td>1108</td>
<td>120536</td>
<td>-74.7</td>
<td>92.3</td>
<td>5.1</td>
<td>14.8</td>
<td>15.6</td>
</tr>
<tr>
<td>1127</td>
<td>133179</td>
<td>-53.3</td>
<td>81.6</td>
<td>5.7</td>
<td>14.6</td>
<td>15.7</td>
</tr>
<tr>
<td>1128</td>
<td>127228</td>
<td>-54.5</td>
<td>55.8</td>
<td>3.7</td>
<td>14.1</td>
<td>14.6</td>
</tr>
<tr>
<td>1147</td>
<td>136508</td>
<td>-66.5</td>
<td>60.8</td>
<td>10.4</td>
<td>15.3</td>
<td>18.5</td>
</tr>
<tr>
<td>1148</td>
<td>119499</td>
<td>-71.9</td>
<td>83.9</td>
<td>8.9</td>
<td>15.4</td>
<td>18.5</td>
</tr>
</tbody>
</table>

Figure 6.27. 3D error distribution (in 3D shaped mode) for the six reference areas.
The presence of trees in areas with positive errors is also confirmed by the visual and qualitative comparison with an orthophoto of the same area. The orthophotos were generated in 1998, with a spatial resolution of 0.5m. For this analysis the height profiles of the ASTER-DEM and the reference DEM along a section have been plotted and compared. Figure 6.31 shows the location of the section (orange line) in the orthoimage and the plot of the height profiles. It can be noticed that the section segments where the ASTER-DEM profile is higher than the reference one corresponds to areas covered by trees in the orthoimage. In the rest of the section the fitting is quite good.

As further work, the ASTER-DEM has been imported in the commercial package Erdas Imagine 8.7 (ERDAS Imagine, 2004) for 3D visualization. Erdas, and in particular Virtual GIS, allows the management and visualization of geographic data, for interactive fly-through of user-defined flight paths. For the photo-realistic visualization of the measured DEM, two products have been used: an ASTER orthoimage and the airborne orthophotos by Swisstopo (Swisstopo, 2004), with
Figure 6.29. 3D error distribution between ASTER-DEM and reference DEM and vegetation coverage (dashed areas) for areas 1107, 1108, 1127, 1128, 1147 and 1148.

an accuracy of 0.5m. The ASTER orthoimage has been generated with PCI Geomatica software (PCI Geomatics, 2004), using as reference DEM the measured one and as original image a combination of the bands 1, 2 and 3N of the VNIR instrument (corresponding to the green, red and near infrared channels). The resulting false color rectified image could be used for further landscape and vegetation analysis. In this work, it was used for texture mapping. The ASTER-DEM was imported in Erdas after the conversion in the internal file format (IMG). Afterwards, the airborne orthoimages and the ASTER orthoimage have been overlapped to create two different 3D texture model of the area (Figure 6.32 and Figure 6.33). In general, the fitting between the generated DEM and the other layers (vegetation, orthoimage) is quite good, confirming the correctness of the recovered DEM and its potential as terrain support for land cover analysis.
6.4.7 Summary and conclusions

The work described in this Section has demonstrated that using our sensor model it is possible to orient an ASTER stereopair (channels 3N and 3B) with a sub-pixel accuracy in the checkpoints. The images cover a variegated areas in Switzerland, with flat, hilly and mountainous terrains (slopes in Alpine region up to 80°), lakes, rivers and urban areas. The results achieved using 8 and 12 GCPs are slightly different, demonstrating the stability of the model. The use of self-calibration was fundamental. In fact the effects due to the radial and decentering lens distortions could reach the values of 2.0 pixels for channel 3N and 2.1 pixels for channel 3B in the image borders. After the orientation, a 3D point cloud has been produced using the estimated parameters for the sensor internal and external orientation and about 1,800,000 points matched with least-squares matching. The accuracy of the resulting point cloud has been evaluated comparing the 3D distance between each point of the measured point cloud and the surface generated from the DHM25 product by Swisstopo (1-3m accuracy). For the analyzed test sites (six blocks with size 17.5km x 12.0km) the mean values are smaller than 1 pixel, while the RMSE and standard deviations are slightly larger than 1 pixel. Anyway the effect of the trees, which was proved with further analysis, was not removed. A false color orthophoto was generated from the ASTER images and mapped onto the DEM for 3D visualization.

The results achieved in the image orientation and in the DEM accuracy are within the specifications of the absolute DEM product (5-15m for the RMSE of GCPs and 7-30m for the DEM, Hirano et al., 2003) and in accordance with the results obtained by other authors.

In Toutin and Cheng, 2001 an ASTER stereopair over Drum Mountains, US, was orientated.

Figure 6.31. Analysis of a section profile in area 1128. Top: location of the section in the orthoimage; bottom: height profiles for the ASTER-DEM (green) and for the reference DEM (orange).
Figure 6.32. 3D texture model with airborne orthophotos in two zoomed areas.
using PCI Geomatica OrthoEngine software and 8 GCPs. The residuals in 6 CPs were 15.8m, 10.5m and 7.9m. The corresponding DEM was generated and compared with an USGS 7.5-Minute DEM (30m grid spacing), with a 7.5m RMS error. The elevation difference had a minimum value of -109m, a maximum value of 155m, a mean value of 1.9m and a standard deviation of 11.5m with an 85% level of coincidence.

In Hirano et al., 2003 four ASTER stereoscenes located in different mountainous areas have been used for DEM generation with R-WEL DMS software, using from 5 to 12 GCPs. The RMSE in height in the CPs was between 7.3m and 26.3m.
6.5 MISR

Together with ASTER, the Multi-Angle SpectroRadiometer (MISR) is a part of the Earth Observing System (EOS) of NASA. The work on MISR scenes has been developed during the EU Cloudmap2 project (Proposal No EVK2-2000-00547).

6.5.1 Sensor description

The MISR instrument consists of nine pushbroom cameras. One camera points toward the nadir (designated An), one bank of four cameras points in the forward direction (designated Af, Bf, Cf, and Df in order of increasing off-nadir angle), and one bank of four cameras points in the afterward direction (using the same convention but designated Aa, Ba, Ca, and Da). Images are acquired with nominal viewing angles of 0°, 26.1°, 45.6°, 60.0° and 70.5° for An, Af/Aa, Bf/Ba, Cf/Ca, and Df/Da, respectively (Figure 6.34). Each camera uses four CCD line arrays in a single focal plane for the acquisition in four different spectral channels with special filters. The line arrays consist of 1504 detectors plus 8 light-shielded detectors per array, each with size 21μm x 18μm.

The spectral band shapes are nominally gaussian and centered at 446, 558, 672, and 866 nm. The zonal overlap swath width of the MISR imaging data (that is, the swath seen in common by all nine cameras) is 360km, which provides global multi-angle coverage of the entire Earth in 9 days at the Equator and 2 days near the Poles. The across-track IFOV and sample spacing of each pixel is 275m for all of the off-nadir cameras and 250m for the nadir camera. The along-track IFOV depends on the viewing angle, ranging from 214m in the nadir to 707m at the most oblique angle. Sample spacing in the along-track direction is 275m in all cameras.

MISR is capable of taking image data in two different spatial resolution modes. In Local Mode (LM), selected targets 300km long are observed at the maximum resolution of 275 meters (pixel to pixel) in all cameras (250 meters across-track for the nadir camera). However, the data trans-
mission rate would be excessive if the instrument worked continuously at this maximum resolution. Therefore, away from these selected targets (there will typically be only 6 of these each day) the instrument operates in what is termed Global Mode (GM), where Earth is observed continuously at lower resolutions. This is achieved by averaging the adjacent samples in both the across-track and along-track directions on the ground. This averaging can be either 4 x 4, 1 x 4, or 2 x 2 pixels, and can be individually selected for each camera and spectral band (MISR, 2004). For our purposes, GM is used.

Different operational data products are available from MISR. They are described in (Lewicki et al, 1999) and represented in the processing chain in Figure 6.35. In this tests MISR level 1B1 Radiometric Product is used. It contains the data numbers (DNs) radiometrically-scaled to radiances. Two types of processing are included in this product. Firstly, the Radiance Scaling operation converts the camera’s digital output to a measure of energy incident on the front optical surface. The measurement is expressed in units called radiance (energy per unit area, wavelength, and solid angle) as defined by an international scale. Secondly, Radiance Conditioning modifies the radiances to remove instrument-dependent effects. Specifically, image sharpening is provided and focal-plane scattering is removed. Additionally, all radiances are adjusted to remove slight spectral sensitivity differences among the 1504 detector elements of each spectral band and each camera. This product is not geometrically corrected and therefore it can be georeferenced with a rigorous sensor model.

6.5.2 Data description

The level1B1 strip corresponding to path 195 and orbit 8826, acquired on 15th August 2001, was downloaded for free from the NASA Langley Research Center (LARC, NASA Langley, 2004). Among all the available strips in the NASA archive, this one was chosen because it covers central Europe and no clouds are present in this segment. The strips acquired by each camera were contained in separate files (called granules) in HDF format. From the nine viewing directions, the An, Af and Ab lenses (central ones) were used for this work. Each file contained the radiometric values for blue, green, red and near infrared channels in a matrix form. A segment of 4804 lines over central Europe was cut in each of three red-channel strips and transformed in TIFF format in IDL environment. The resulting images, with dimensions 1504 x 4808 pixels, are represented in Figure 6.36. The acquisition time difference between An and Af and between An and Aa is about 45 sec.
6.5.3 Preprocessing

The ephemeris corresponding to path 195, orbit 8826 were kindly provided by LARC. They contained the position and velocity every second in ECI coordinate systems (Section B.4). The data were transformed in ECR system and the sensor attitude was calculated, as explained in Section 5.2. The value of the focal length of each lens and the detector sizes were contained in the Camera Geometric Model (CGM) file, that can be downloaded from LARC. The scenes were transformed from 11 to 8 bit with Adobe Photoshop (Adobe Photoshop, 2004). Then, in order to facilitate the matching, they were pre-processed with Wallis filter (Section 5.3.1).

6.5.3.1 GCPs measurement.

The identification of GCPs in the MISR scenes was quite problematic due to the low ground resolution of the images (275m).

At the NASA Jet Propulsion Laboratory (JPL) a MISR GCP database is available. It contains 120 individual points distributed across all latitudes, the majority of which are in the United States. About 50 points are equally distributed across Russian, African and South American regions.
The remaining points are located in the Australia and New Zealand region. The database construction involved two stages. First is the acquisition and production of terrain-corrected Landsat Thematic Mapper (TM) scenes over the desired ground locations. The second is the extraction of image chips from the TM imagery and update of the Global Change Program Office (GCPO) database. Once the Landsat TM scene is selected, the terrain-corrected imagery is then used as the input to a ray-casting simulation software. The software replicates MISR viewing geometry, producing nine images (corresponding to nine MISR cameras) which are then used for the extraction of smaller image chips. This warping of TM imagery is necessary in order to obtain image chips with the best possible chances to be identified in the corresponding MISR imagery (Jovanovic et al., 2002). A single MISR ground control point is a collection of nine geolocated image patches of a well-defined and easily identifiable ground feature. The corresponding geodetic coordinates define the location of a particular ground feature. The accuracy of associated ground coordinates is expected to be 30m.

As not a single of the 120 GCPs was in path 195, we had to follow other methods. At first we compared the images and the cartographic maps (1:25,000 or 1:50,000) of the corresponding areas in order to recognize some well-defined features, like rivers, see costs and lake borders (Figure 6.37), but this method was very time consuming and not very accurate.

Figure 6.37. Examples of points searching along natural features (rivers, lakes, see costs) in MISR scenes.

The main problem was the identification of the features themselves in the images. For this reason we searched for points using other images of the same area with higher resolution, following the strategy adopted at JPL. Requirements for the new images were a ground resolution smaller than 50m and low costs. The Landsat 7 orthoproduct available in the Web for free (ESDI, 2004) was
suitable for our tasks. The Landsat Project is a joint initiative of the U.S. Geological Survey (USGS) and NASA to gather Earth resource data using a series of satellites. NASA was responsible for developing and launching the spacecraft, while the USGS was responsible for flight operations, maintenance and management of all ground data reception, processing, archiving, product generation and distribution. The Landsat Program is the longest running enterprise for acquisition of imagery of the Earth from space. The first Landsat satellite was launched in 1972; the most recent, Landsat 7, was launched on 15th April 1999. The instruments on the Landsat satellites have acquired millions of images, which are archived in the United States and at Landsat receiving stations around the world and represent a unique resource for global change research and applications in agriculture, geology, forestry, regional planning, education and national security (Landsat, 2004). Today Landsat 4 (launched in 1982), Landsat 5 (launched in 1984) and Landsat 7 (launched in 1999) are operational. The product used in this work consists of orthoimages from Enhanced Thematic Mapper Plus (ETM+) carried on board of Landsat 7 (for details see Table 6.17). This product is georectified, with planimetric coordinates in both geographic \((\varphi, \lambda)\) and UTM systems \((E,N)\). The ETM+ is a multispectral scanning radiometer that provides image data from eight spectral bands. The spatial resolution is 30m for the visible and near-infrared (bands 1-5 and 7). Resolution for the panchromatic (band 8) is 15m, and the thermal infrared (band 6) is 60m (Table 6.18). The approximate scene size is 170km x 183km. Eight scenes from paths 195 and 196 covering our area of interest were downloaded and pre-processed with radiometric equalization and contrast enhancement, using Wallis filter. Then 3 level pyramid images (reduce factor of 2) were generated, so that the lowest level resolution (240m) was in the same range of the MISR scenes resolution (275m).

Common points were identified in Landsat 3rd level pyramid images and in Aa, An and Af MISR images and matched with template multi-photo least-squares matching (Balsavias, 1991). The coordinates of the points of interest in Landsat images were transformed from the 3rd level to the original one and the corresponding geographic coordinates \((\varphi, \lambda)\) were read in the Landsat original orthoimages in PCI environment (PCI Geomatics, 2004). Once the planimetric coordinates were known, the corresponding height was read in 1:25,000 and 1:50,000 scale topographic maps of the areas of interest. Then the ground coordinates of the matched points were transformed into the ECR system (Section B.5). A sufficient number of points were measured in two distinct areas in the scenes: the upper part (North of Germany) and the lower part (South of France), as indicated in Figure 6.36. In each of these areas 6 points have been measured. In addition, 20 tie points (10 for each area) have been identified with least-squares matching in the image space. The accuracy of associated ground coordinates was about 30m.

### Table 6.17. Characteristics of Landsat-7.

<table>
<thead>
<tr>
<th>Launch date</th>
<th>15th April 1999</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td>705 km</td>
</tr>
<tr>
<td>Repeat cycle</td>
<td>16 days</td>
</tr>
<tr>
<td>Swath Width</td>
<td>185 km</td>
</tr>
<tr>
<td>Inclination</td>
<td>Polar (98.2°)</td>
</tr>
<tr>
<td>Orbit</td>
<td>Sun-synchronous</td>
</tr>
</tbody>
</table>

### Table 6.18. Specification of ETM+ instrument on Landsat-7.

<table>
<thead>
<tr>
<th>Band</th>
<th>Spectral resolution ((\mu m))</th>
<th>Resolution (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.45 - 0.515</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>0.525 - 0.605</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>0.63 - 0.690</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>0.75 - 0.90</td>
<td>30</td>
</tr>
<tr>
<td>5</td>
<td>1.55 - 1.75</td>
<td>30</td>
</tr>
<tr>
<td>6</td>
<td>10.40 - 12.5</td>
<td>60</td>
</tr>
<tr>
<td>7</td>
<td>2.09 - 2.35</td>
<td>30</td>
</tr>
<tr>
<td>pan</td>
<td>0.52 - 0.90</td>
<td>15</td>
</tr>
</tbody>
</table>
6.5.4 Image orientation

The sensor model was separately applied on the two regions where the object points were measured. For each region the 6 object points were all used as GCPs and the additional points were used as TPs. Unfortunately, we could not use any point for final check (CPs). The position and the attitude derived by the ancillary data were used for the direct georeferencing. From the Camera Calibration File (Version 7), only the focal length and the pixel size could be extracted and used. The other parameters were referring to specific systems used at JPL for the geolocation of the MISR images and could not be converted in the systems adopted in our model. As a consequence, the influence of the systematic errors due to the distortions of the optical instruments (Section 2.4.1 and Section 2.4.2) could not be taken into account a-priori and the RMSE for the GCPs were larger than 1 pixel.

Therefore the indirect georeferencing model was used to improve the internal and external orientation. According to the tests performed on ASTER, which is carried on the same platform of MISR, the sensor external orientation was modeled with quadratic functions and three segments were used for the PPM. The a priori standard deviation of the GCPs was 50m. The first tests without self-calibration were not satisfying, both in the internal (sigma naught, sigma of TPs) and external accuracy (RMSE of GCPs). The presence of systematic errors that were not compensated in the external orientation modelling was evident. For this reason, the self-calibration was necessary. As initial values, the additional parameters were set equal to zero. Due to the small number of available GCPs, the self-calibrating adjustment was run fixing the external orientation parameters to the values estimated in the previous adjustment without self-calibration. In order to determine the APs that could be estimated, different tests were carried out varying the fixed and free parameters. The significance of the parameters was analyzed through their mean values, standard deviations and correlations with the other unknown parameters (Section 4.7). Due to the low number of available object points, only the internal accuracy of the bundle adjustment could be evaluated. The standard deviation of the TPs was 150.6m in X, 160.2m in Y and 210.6m in Z in the French site and 250.3m in X, 201.5m in Y, and 198.6m in Z for the German site. The values refer to X, Y and Z in the ECR system. In both cases, the sigma naught a posteriori was 2μm. For the GCPs, the residuals had maximum values in the order of half pixel.

Concerning the APs, significant values have been obtained for the principal point displacement (Δxc and Δyc), with similar values in the French and German datasets. The values for Δxc were around 1 pixel for the forward viewing lens and -1 pixel for the nadir and backward viewing lenses. The values of Δyc were slightly less than one pixel for all lenses.

6.5.5 Summary and conclusions

The MISR sensor continuously acquires systematic, global, multiangle and multispectral imagery in order to improve studies of the ecology and climate of the Earth. Within the EU-project Cloudmap2 we oriented three scenes over Europe (processing level 1B1) using our sensor model. For this dataset the Camera Geometric Model (CGM) file was available, together with the sensor position and velocity measured with the Tracking and Data Relay Satellite System (TDRSS). The accuracy of the position observations was about 50m. The specific calibration datasets contained in the CGM were estimated through an in-flight calibration, as described in Jovanovic et al., 2002.

In our case, the direct georeferencing algorithm did not give satisfying results, because the lens distortions and CCD line rotations in the focal planes were not taken into account. In fact, the camera calibration parameters contained in the CGM referred to specific coordinated systems used at JPL and the conversion to the reference system used in our model was not possible. Among the parameters contained in the CGM, only the focal length and the pixel size values
were used. Without the other camera calibration parameters (and therefore assuming that no distortions in the optical systems occur), the RMSE in the GCPs were larger than one pixel. On the other hand, using our indirect georeferencing model with 6 GCPs, the standard deviations of the tie points and the RMSE of the GCPs were smaller than one pixel. These results are promising, but further work is required for the measurement of a larger number of points to be used for checking. The accuracy of the point measurement should be improved. In fact, even if the accuracy of the ground coordinates was quite good (about 30m), the identification of the points in the images was quite difficult.

In general, although the lack of good object points limited the tests, this work was useful to get familiar with low resolution images and the difficulties in their processing (above all the object points identification) and to explore the benefits given by the combination of different resolutions images (in this case, Landsat and MISR). We have not found any publication about the accuracy that can be achieved with the combination of the MISR multi-view images for the 3D coordinate estimation.
6.6 EROS-A1

The work on EROS-A1 imagery was possible thanks to the collaboration with the Department of Georesources and Land (DIGET) at the Politecnico of Turin, Italy. Even if the results achieved in the tests are not so accurate as those obtained with the other sensors, we want to include this work because EROS-A1 has asynchronous acquisition mode and today few rigorous models have been successfully applied for its imagery orientation (Crespi et al., 2003, Baiocchi et al., 2004, Toutin, 2004).

The EROS (Earth Resources Observation System) program conducted by ImageSat International (ISI) intends to operate a constellation of eight commercial imaging satellites in LEO (Low Earth Orbit). The first satellite, EROS-A1, was successfully launched from the Russian START-1 payload on the 5th December 2000 and is presently (April 2005) successfully operating. The second satellite, EROS-B1, was planned to be launched in 2004 (Bar-Lev et al., 2001, Chien and Teo, 2002). The main characteristics of EROS-A1 and EROS-B1 satellites are summarized in Table 6.19.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>EROS-A1</th>
<th>EROS-B1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>250kg</td>
<td>350kg</td>
</tr>
<tr>
<td>Dimensions (Launch)</td>
<td>DIAM1210*2235mm</td>
<td>DIAM 1210*2255mm</td>
</tr>
<tr>
<td>Orbit altitude</td>
<td>480km</td>
<td>600km</td>
</tr>
<tr>
<td>Lifetime</td>
<td>over 6 years</td>
<td>over 10 years</td>
</tr>
<tr>
<td>Imaging sensor</td>
<td>CCD line, &gt;7000pixels</td>
<td>CCD TDI, 32 stages, &gt;15000pixels</td>
</tr>
<tr>
<td>Panchromatic Imaging</td>
<td>1.8m</td>
<td>0.87m (@600km)</td>
</tr>
<tr>
<td>GSD at Nadir</td>
<td>12km</td>
<td>13km</td>
</tr>
<tr>
<td>Swath</td>
<td>11bits</td>
<td>10bits</td>
</tr>
<tr>
<td>Multispectral Imaging</td>
<td>None</td>
<td>4 bands</td>
</tr>
<tr>
<td>GSD at Nadir</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swath</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Video Transmission Rate</td>
<td>70Mbit/sec</td>
<td>280Mbit/sec</td>
</tr>
</tbody>
</table>

6.6.1 Sensor description

EROS-A1 flies along a sun-synchronous near polar orbit at a height of 480km. The NA30 camera on EROS-A1 is a high-resolution pushbroom sensor with 4 CCD arrays resulting in 7490 CCD elements; the scanning mode is asynchronous, that is, the satellite ground speed is faster than its rate of imaging, as described in Section 2.5.2.2. In Standard Mode EROS-A1 produces panchromatic images in the band of 500nm - 900nm wavelength at 1.8m resolution, while the B1-B5 satellites will provide both panchromatic and multispectral imagery with better than 1m resolution. ISI provides 3 different levels of images: 0A (raw scene), 1A (radiometrically corrected scene) and 1B (radiometrically and geometrically corrected scene). For our purposes, level 1A was chosen, because it preserves the original geometry of the acquisition.
6.6.2 Data description and preprocessing

In this work the scene acquisition, preprocessing and object points measurements were done at DIGET. We received the image and ground coordinates of the object points and the scenes metadata files in order to orient the scenes.

The images used in this study are two stereo images acquired by the EROS-A1 satellite on the 3\textsuperscript{rd} February 2003. They cover the test site of Caselle airport (Figure 6.38), in the outskirts of the city of Turin in Piedmont region (Italy). The images are about 19km large and 12km wide, with central latitude of 45.20°N and central longitude of 7.66°E (Figure 6.40).

![Figure 6.38. Test site location.](image)

The scenes have been acquired in along-track stereo mode with non-constant symmetric viewing angle, varying from 43° to 24° (forward scene) and from -24° to -41° (backward scene). The two scenes have a size of 7940 x 4935 pixels, a ground resolution of about 2.6m and a time difference of about 30sec. Figure 6.39 shows a zoom in the two images.

![Figure 6.39. Zoom of EROS-A1 stereo images over Caselle airport.](image)

A 50m x 50m grid DEM of the Piedmont Region with an accuracy of 5m was available, together with a raster 1:5,000 scale Technical Provincial Map (CTP) in the Gauss-Boaga reference system. According to the expected scale mapping, the CTP was used as cartographic reference. The DEM and CTP were adopted to collect 14 points over the stereo images. The corresponding image coordinates were measured with manual matching (error of about 0.5 pixels). Unfortunately, due to the bad radiometric quality of the images in the corners due to saturation, the points could not be measured in an optimal configuration.
The metafile of each scene contained the following data of interest:

- the initial and final times of acquisition of the scene
- the integration time
- the satellite position and velocity in the ECI system at 6.8 sec time interval (state vectors)
- initial and final value of $\gamma$, defined as the angle between the camera Z-axis and the nadir.

The acquisition time of each image line was computed using the acquisition time of the first line and the integration time (6.8 msec for both scenes). The sensor position and velocity in the ECI system were transformed into the ECR system and the attitude was calculated as described in Section 3.2. Then the approximations for the PPM parameters were calculated (Section 4.6.2.2). The ground coordinates of the object points were transformed from the Gauss-Boaga to the ECR system.

For the off-nadir viewing angle, we assumed that the rate of change of $\gamma$ was constant. The initial and final values of $\gamma$ for each scene were used to calculate the values for each image line. These angles were introduced in the collinearity equations in place of $\beta$ (Section 4.2). In fact comparing the reference systems adopted in the metadata definitions and the systems used in our work, the $\gamma$ angle represents the relative orientation between the camera system of each lens and the camera system with z-axis pointing in the nadir direction.
The indirect georeferencing model, that was originally designed for fixed relative orientation angles ($\alpha$, $\beta$, $\gamma$), was adapted in order to read the relative orientation angles with linear variations.

### 6.6.3 Image orientation

The georeferencing was performed in the ECR system. A group of available points were used as GCPs and the remaining as control (CPs). As the total number of object points was 14, 8 points were used as GCPs and 6 points as CPs. The a-priori standard deviation of the GCPs was 1m. Different tests were performed in order to decide the distribution of GCPs, the number of trajectory segments and the polynomial degree for the PPM and the additional parameters in the self-calibration.

Each test consisted of a two-step processing. At first the external orientation only was estimated, then it was fixed to the estimated values and the adjustment was repeated with self-calibration, varying the free APs. About the external orientation modelling, there was not a considerable difference between using 2 or 4 segments for the piecewise functions, but the results were much worse if the polynomial degree was decreased from 2 to 1. Therefore the external orientation was modelled with 2 segments of 2nd order polynomials.

The correlation between the APs, the external orientation parameters and the ground coordinates of the CPs were analyzed in order to decide the APs that could be estimated. Finally the internal orientation parameter that mostly affected the results was the scale in $y$ direction, that is $s_y$. Using 8 GCPs and 6 CPs, the internal orientation accuracy (sigma of CPs) achieved was 3.3m in $X$, 2.6m in $Y$ and 5.7m in $Z$ (1.3, 1.0 and 2.2 pixels). Sigma naught a posteriori was 0.024mm (1.3 pixels). The RMSE of CPs were 4.8m in $X$, 2.7m in $Y$ and 5.9 in $Z$, corresponding to 1.8, 1.0 and 2.3 pixels. The differences between the RMSE and sigma values of the ground coordinates of the CPs can be due to the wrong weight assignment fo the image and ground coordinates of the GCPs and CPs or to the presence of additional errors that have not been compensated in the model. Even if the accuracy achieved is larger than 1 pixel, the results are promising.

The difficulties encountered with EROS imagery mostly related due to the understanding of all the attitude parameters contained in the metadata files and in the modelling of the asynchronous acquisition. For example, we took the values for the off-nadir angles $\gamma$ reported in the metadata.
file as the relative orientation angle $\beta$ for our system. Although this assumption was justified by the reference systems description in the users' EROS documentation, it may not be completely correct. Another aspect to take into account is that, due to the lack of detailed information on the acquisition geometry, we assumed that the rate of change of $\gamma$ was constant. This may also introduce additional errors. Concerning the bundle adjustment, the non-optimal distribution of the GCPs influenced its performance.

### 6.6.4 Summary and conclusions

Thanks to the collaboration with the Department of Georesources and Land of the Politecnico of Turin (DIGET), who provided the dataset, we oriented a stereo pair acquired by EROS-A1 with our sensor model. Due to the lack of information on the sensor internal and external orientation, the self-calibrating bundle adjustment contained in the indirect georeferencing model was used, with 6 GCPs and 8 CPs. The accuracy achieved in the CPs was 3.3m in $X$, 2.6m in $Y$ and 5.7m in $Z$ (1.3, 1.0 and 2.2 pixels) for the standard deviation and 4.8m in $X$, 2.7m in $Y$ and 5.9 in $Z$ (1.8, 1.0 and 2.3 pixels) for the RMSE. Sigma naught a posteriori was 0.024mm (1.3 pixels).

We have also concluded that if more knowledge on the sensor geometry will be available, then more correct parameters for the viewing angles could be calculated and the model performance improved.

The asynchronous acquisition of EROS-A1 causes some difficulties in the rigorous modelling of the images. Today few rigorous models have been applied for the georeferencing of EROS-A1 imagery and can be used for a validation of our results.

The SISAR rigorous model, developed at the University of Rome, has been used for the orthorectification of 4 EROS-A1 images with a ground resolution of 1.8m and acquired with different $\gamma$ angle (Baiocchi et al., 2004). Using a minimum of 9 GCPs, the RMSE achieved in at least 40 CPs were 3.7m in East and 2.1m in North. Using the rigorous model and the RPC model in PCI Geomatica similar results were obtained. In Toutin et al., 2002 the RMSE obtained with the rigorous model in PCI Geomatica and 10 GCPs was 3.9m in East and 3.5m in North (14 CPs, ground resolution of 2m).

Again with this commercial software, an EROS-A1 stereo pair acquired over Québec, Canada, was oriented using 18 GCPs. The RMSE in the 112 CPs were 4.2m in East, 4.2m in North and 5.9m in height (ground resolution of 1.8m).

From this analysis it can be concluded that the results achieved with our approach are close to those obtained with other rigorous models available in commercial software. Anyway, we think that the results can be improved if a deeper knowledge on the sensor geometry is available.
CONCLUSIONS AND OUTLOOK

7.1 CONCLUSIONS

In this thesis the geometric modelling of pushbroom sensors has been investigated and the rigorous model implemented for their orientation has been presented. The imagery acquired by this kind of sensors has very high potential for photogrammetric mapping at different scales from airborne and satellite platforms and its orientation is a fundamental step in the processing chain for the generation of orthoimages and Digital Elevation Models (DEMs).

As seen in the Introduction, today various models based on different approaches have been developed, but few of them are rigorous and can be used for a wide class of pushbroom sensors. On the other hand it has been demonstrated that the sensor model presented in this thesis can be applied for the orientation of linear array scanners with different camera designs.

In general a rigorous sensor model aims to describe the relationship between image and ground coordinates, according to the physical properties of the image acquisition. In order to develop such a model, the analysis of different aspects of pushbroom sensors (optical system, linear arrays geometry, acquisition mode) and their imagery (resolutions, processing levels) were investigated in Chapter 2.

The proposed model includes two different orientation approaches, described in Chapters 3 and 4. In the direct georeferencing model the ground coordinates of the homologous points measured in the images are estimated through a forward intersection, using as external orientation the data provided by geopositioning systems carried on board (GPS, INS, star trackers) or the trajectory calculated by mathematical formulas describing the sensor trajectory (only for satellite-based sensors). This approach does not require any ground control points, except for final checking, and does not estimate any additional parameters for the correction of the interior and exterior orientation. For this reason, the accuracy of this method depends on the accuracy of the external and
internal orientation data. Theoretically the use of GPS and INS is very powerful, because it could allow point positioning without ground information. The GPS and INS data must be transformed into the camera reference system with the knowledge of the systems displacements and misalignments. Moreover the measurements provided by these instruments may contain systematic errors that must be modelled and compensated. Therefore in practice up to day the positioning systems can only greatly reduce, but not completely eliminate the need for ground control. This is more valid in case of airborne pushbroom sensors, because of the vibrations and the instability of the platform's trajectory. Since the need for ground control points cannot be eliminated with the use of GPS, the integration of positioning systems, that is the integration of GPS and INS observations, into a bundle adjustment became a subject of research in this field.

The alternative orientation method, based on indirect georeferencing, is used if the sensor external and internal orientation is not available or not enough accurate for high-precision photogrammetric mapping. This approach is a self-calibrating bundle adjustment, but modified according to the pushbroom sensors' characteristics. The sensor position and attitude are modelled with 2nd order piecewise polynomial functions (PPM) depending on time. Constraints on the segment borders assure the continuity of the functions, together with their first and second derivatives. Using pseudo-observations on the PPM parameters, the polynomial degree can be reduced to one (linear functions) or even to zero (constant functions). If GPS and INS are available, they are integrated in the PPM. In this case the constant terms are used to correct the data from the misalignments between the GPS/INS systems and the camera frame, while the 1st and 2nd order terms describe other systematic errors contained in the observations. For the self-calibration, additional parameters (APs) are used to model the lens internal parameters and distortions and the linear arrays displacements in the focal plane.

The parameters modelling the internal and external orientation, together with the ground coordinates of the tie points, are estimated through a least-squares bundle adjustment using well distributed ground control points. The use of pseudo-observations allows the user to run the adjustment fixing any unknown parameters to certain values. This option is very useful not only for the external orientation modelling, but also for the analysis of the single self-calibration parameters' influence. The weights for the observations and pseudo-observations are determined according to the measurement accuracy.

A blunder detection procedure is integrated for the automatic detection of wrong image coordinate measurements. The false measurements removal is manual.

The adjustment results are analyzed in terms of internal and external accuracy. The APs to be estimated are chosen according to their correlations with the other unknown parameters (ground coordinates of tie points and PPM parameters).

The model has been developed under Unix environment in C language. The software reads files with predefined formats and extensions, containing information on the camera geometric characteristics, the acquisition time of each image line, the external orientation data, any calibration parameters and the image and ground coordinates of the tie points (Appendix C). The object reference systems accepted are the fixed cartesian geocentric (ECR), the geographic system and any local tangent systems. The algorithms for the coordinates transformation from one system to the other have also been included.

Working with satellite imagery, the ECR system is used. In case of airborne imagery, the local tangent systems are adopted as reference frame.

One fundamental requirement for this model was the flexibility, that is, the possibility to be used for the orientation of a wide class of pushbroom sensors. In order to demonstrate it, the model was tested on different pushbroom imagery. The results obtained from an airborne dataset, pre-
presented in Poli, 2002b, demonstrated the need of modelling the systematic errors contained in the GPS and INS measurements through a bundle adjustment. On the other hand, the results obtained from satellite imagery were reported in Chapter 6. The sensors used in our tests were MOMS-P2, SPOT-5/HRS, ASTER, MISR and EROS-A1. It can be noted that these sensors have different characteristics (single-lens and multi-lens optical systems, various number of linear arrays, synchronous and asynchronous acquisition modes), covering a wide range of possible acquisition geometries. For each dataset both the direct and indirect models have been used and in all cases the direct georeferencing was not accurate enough for high accurate mapping. The indirect model has been applied with different ground control points distributions (when possible), varying the PPM configurations (number of segments, polynomials degree) and with and without self-calibration. Excluding EROS-A1, all the imagery has been oriented with sub-pixels accuracy in the check points using a minimum number of 6 ground control points. In case of EROS-A1, an accuracy in the range of 1 to 2 pixels has been achieved, due the lack of information on the geometry of the sensor asynchronous acquisition. The self-calibration is usually recommended.

New cameras can be easily integrated in the model. In fact the required sensor information (number of linear arrays, number of lenses, focal length, number of detector elements in each line, viewing angles) are accessible in literature as well as in the web. If no information on the sensor internal orientation is available, the model supposes that the CCD lines are parallel to each other in the focal plane and perpendicular to the flight direction and estimates any systematic error through the self-calibration. Concerning the external orientation, in case of spaceborne sensors the satellite’s position and velocity vectors, usually contained in the ephemeris, are required in order to compute the initial approximations for the PPM parameters. If this information is not available, the orbit’s Keplerian elements can be used to estimate the nominal trajectory. For pushbroom scanners carried on airplane or helicopter the GPS and INS measurements are indispensable, due to the unpredictability of the trajectory.

In conclusion, in this thesis the rigorous sensor model for pushbroom sensors has been presented and its flexibility demonstrated through a variety of tests.

7.2 OUTLOOK

Further investigations could be carried out in order to improve the sensor model’s potentials. For the satellite sensors the calculation of the platform position based on the Keplerian elements can be improved by taking into account the orbit oscillations. In fact the assumptions of the used theory is that the satellite movement is caused by the gravity force only. In practise other forces take part and cause secondary effects that can be modeled by combination of sinusoidal and polynomial functions. The size of these effects must be investigated. Future work includes also a further study on the determinability of the additional parameters used in the self-calibration. With the current software the user can analyze the correlation between the parameters and choose which parameters must be fixed. This operation could be automated by means of determinability and significance tests at each iteration. The blunder detection and removal could also be improved and made automatic.

Even if the model flexibility has been demonstrated, more tests are suggested in order to take into account other acquisition geometries of pushbroom sensors. For example the sensors with across-track stereo capability could be included in the model. In this case the number of trajectories to be modelled is two instead of one, as in the along-track stereo sensors, but constraints between consecutive trajectories can be imposed according to the orbit’s geometry (inclination, period).
Another possible development is the implementation of a user-friendly interface. This interface should contain the following functions: selection of the input files containing the sensor characteristics, the calibration data and the external orientation data, definition of reference system for object points and external orientation, choice of reference systems for bundle adjustment, introduction of initial values for self-calibration parameters, selection of external and internal orientation parameters to be fixed, choice of number of iterations.

Now these information are introduced through a UNIX shell or by means of input files containing the information themselves. A difficulty often encountered with satellite sensors is that the metadata files containing information about the scenes (acquisition time, ephemeris, internal geometry, etc.) have a different format for each sensor. In order to render the model more user-friendly, the automatic extraction of the required information from the metadata files could be implemented.
Appendix A

ACRONYMS

A.1 Sensors and Missions

AATSR: Advanced Along Track Scanning Radiometer
ADEOS: Advanced Earth Observation Satellite
ADS: Airborne Digital Sensor
AirMISR: Airborne Multi-Angle Imaging SpectroRadiometer
ALOS: Advanced Land Observation Satellite
ASTER: Advanced Spaceborne Thermal Emission and Radiation Radiometer
BIRD: Bispectral Infrared Detector
CASI: Compact Airborne Spectrographic Imager
CERES: Clouds and the Earth’s Radiant Energy System
DPA: Digitales Photogrammetrisches Auswertesystem
EOS: Earth Observing System
EROS: Earth Resources Observation Satellite
ETM+: Enhanced Thermic Mapper Plus
GLI: Global Imager
HRG: High Resolution Geometry
HRSC: High Resolution Stereo Camera
HRV: High Resolution Visible
IRS: Indian Remote Sensing Satellite
MEOSS: Monocular Electro-Optical Stereo Scanner
MISR: Multi-Angle Imaging SpectroRadiometer
MODIS: Moderate-Resolution Imaging Spectroradiometer
MOMS-02: Modular Optoelectronic Multispectral Scanner
MOPITT: Measurements Of Pollution In The Troposphere
Appendix A. ACRONYMS

PRISM: Panchromatic Remote-sensing Instrument for Stereo Mapping  
R21: Resource 21  
SPOT: Système Pour l'Observation de la Terre  
TLS: Three-Line Scanner  
WAAC: Wide-Angle Airborne Camera  
WAOSS: Wide-Angle Optoelectronic Stereo Scanner

A.2 Space Agencies and Remote Sensing Organizations

CCRS: Canada Centre for Remote Sensing  
CEOS: Committee on Earth Observation Satellites  
CNES: Centre National d'Etudes Spatiales  
DARA: Deutsche Agentur für Raumfahrtangelegenheiten  
DASA: Daimler Benz AeroSpace  
DLR: Deutsches Zentrum für Luft- und Raumfahrt  
JAXA: Japan Aerospace Exploration Agency  
NASA: National Aeronautics and Space Administration  
NASDA: National Space Development Agency of Japan  
USGS: United States Geological Survey

A.3 Other acronyms

CCD: Charge Coupled Device  
CMOS: Complementary Metal-Oxide Semiconductor  
CP: Check Point  
DGPS: Differential GPS  
GCP: Ground Control Point  
GPS: Global Positioning System  
INS: Inertial Navigation System  
LSM: Least Squares Matching  
MPGC: Multi-Photo Geometrically Constraint  
PC: Perspective Center  
RMSE: Root Mean Square Error  
TP: Tie Points
Appendix B

REFERENCE SYSTEMS

In the following Sections the reference systems used in this thesis are summarized.

B.1 Image coordinate system

It is a 2 dimensional system describing a point position in an image. The origin is at the centre of the left top pixel; the pixel position is defined by its row ($u$) and column ($v$). The image dimensions are called with $N_p$ (width, number of pixels contained in a row) and $N_r$ (height, number of column rows).

![Image System Diagram]

Figure B.1. Image system.

B.2 Scanline system

It is a 2D system defined for each image line. It is centered in the mean pixel of the line, with $y_s$ axis parallel to the image line and $x_s$ axis perpendicular to $y_s$ axis, close to the flight direction.
Appendix B. REFERENCE SYSTEMS

Assuming an ideal case without lens distortions and geometric errors in the CCD line, the coordinate \( y_s \) can be calculated with the transformation

\[
y_s = \left( v - \frac{N_p}{2} \right) p_y
\]

(8.1)

where \( p_y \) is the pixel dimension in \( y_s \) direction and \( N_p \) is the number of pixels in each line. The coordinate \( x_s \) is fixed equal to zero.

If the pre-flight laboratory calibration results are available, the given exact position of each CCD line in the focal plane are used as \( x_s \) and \( y_s \) values (Figure B.2).

![Scanline system](image)

Figure B.2. Scanline system.

The time of acquisition \( t_i \) of line \( i \) can be calculated using the time of acquisition of a line of reference (indicated by the subscript 0, usually the first line) and the integration time (\( \Delta t \)), that is, the time required by the optical system to scan one line on the ground

\[
t_i = t_0 + (u_i - u_0) \Delta t
\]

(B.2)

\( u_i \) and \( u_0 \) stand for the row numbers of line \( i \) and 0 and \( t_0 \) is the time of acquisition of the reference line.

### B.3 Camera system

The camera system (indicated with letter C) is a 3D system centered in the perspective center (PC) of each lens. The axis \( x_c \) and \( y_c \) are parallel to \( x_s \) and \( y_s \). The \( z \)-axis \( z_c \) is upwards directed and completes a right-hand coordinate system. The value of \( z_c \) is equal to the lens focal length. Each lens consisting the optical system has its own camera reference system (example of three-line sensor, Figure B3).

![Camera system](image)

Figure B.3. Camera system in case of one lens (right) and more-lens (left) optical systems.

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B.4 Geocentric inertial coordinate system (ECI)

The origin is in the centre of gravity of the Earth, the Z-axis points toward the North Pole, the X-axis lies in the equatorial plane and is directed toward the vernal equinox (JR2000), the Y-axis completes a right handed orthogonal system by a plane 90° east of the X-axis and its intersection with the Equator.

Figure B.4. Geocentric Cartesian Inertial coordinate system.

B.5 Geocentric fixed coordinate system (ECR)

The origin is in the centre of gravity of the Earth, the Z-axis points toward the North Pole, the X-axis is defined by the intersection of the plane defined by the prime meridian (Greenwich) and the equatorial plane, the Y-axis completes a right handed orthogonal system by a plane 90° East of the X-axis and its intersection with the Equator.

Figure B.5. Geocentric Cartesian coordinate system.

B.6 Geographic coordinates

They are described by latitude, longitude, height (\(\varphi, \lambda, h\)). The Prime Meridian and the Equator are the reference planes used to define latitude and longitude. The geographic latitude of a point is the angle from the equatorial plane to the vertical direction of a line normal to the reference ellipsoid. The geographic longitude of a point is the angle between a reference plane and a plane passing through the point, both planes being perpendicular to the equatorial plane. The geodetic
height at a point is the distance from the reference ellipsoid to the point in a direction normal to the ellipsoid.

\[ X = (N + h)\cos \varphi \cos \lambda \]
\[ Y = (N + h)\cos \varphi \sin \lambda \]
\[ Z = [N(1 - e^2) + h] \sin \varphi \]  

where \( e^2 = \frac{a^2 - b^2}{a^2} \) is the eccentricity of the Earth ellipsoid (being \( a \) and \( b \) the major and minor Earth radius) and \( N = \frac{a}{1 - (\sin \varphi)^2} \) is the radius of curvature of a point with latitude \( \varphi \) in the prime vertical.

### B.7 Local coordinate system

A local coordinate system is a right-hand system centered at a chosen point \( P \) with \( X \)-axis tangent to the local parallel and looking toward East, \( Y \)-axis tangent to the local meridian and looking toward North and \( Z \)-axis upwards directed.

Calling \( X_P, Y_P, Z_P \) the geocentric coordinates of the origin of the ground local system (point \( P \)) and \( \varphi_P \) and \( \lambda_P \) its latitude and longitude, the transformation from the geocentric to the ground local system is \( (Wang, 1999, p.152) \)

\[
\begin{bmatrix}
X_L \\
Y_L \\
Z_L
\end{bmatrix} = \begin{bmatrix}
X - X_P \\
Y - Y_P \\
Z - Z_P
\end{bmatrix} = R_x(90 - \varphi_P)R_y(90 - \lambda_P)
\]

where \((X, Y, Z)\) are the coordinates in the geocentric system, \((X_L, Y_L, Z_L)\) in the ground local system.
B.8 Orbit system

The orbit coordinate system (Figure B.7) is a right-hand coordinate system with its origin at the spacecraft’s center of mass. The z-axis is aligned with the spacecraft-to-Earth pointing vector. The x-axis points along the satellite trajectory, therefore in the direction of the spacecraft velocity vector. The y-axis is defined by the cross product of the z-axis and the x-axis.

![Figure B.7. Orbit system and Inertial Geocentric system.](image)

B.9 Orbital plane

The orbital plane system is a two-dimensional frame with origin in the focus of the orbit occupied by the Earth; x-axis lies on the semi-major axis and points towards the perigee, while the y-axis lies in the orbital plane and is perpendicular to x-axis.

![Figure B.8. Orbit plane system. f is the true anomaly, c is the focal distance.](image)

B.10 GPS coordinate system

The GPS system is a local system (Section B.7) centered in the GPS antenna.

B.11 INS coordinate system

The INS system is a local system (Section B.10) centered in the INS instrument.
The direct georeferencing software is called `push_model_direct` and the indirect georeferencing software is called `push_model_indirect`. They have been developed in C language in Unix environment. The two programs follow the same logic for the input and output files.

In input, the programs ask for a `base`. For simplicity, the `base` is usually the name of the sensor (for example, `misr`, `aster`, `hrs`, ...), but any name can be used. From the `base`, two files are automatically identified:

- `base.data` contains information about the sensor characteristics (number of lenses, number of viewing directions, image dimension in pixels) and for each viewing direction: an integer number that identifies the viewing direction, the viewing angle in degrees, the focal length of the corresponding lens (in mm) and the pixel size in the row and column direction (in mm). All these data are easily accessible from the web, from literature or from the metadata files. New sensors can be added to the model if the corresponding `base.data` files are available. Here is the `misr.data` file for MISR sensor:

```plaintext
9 9 /*number of lenses, number of viewing directions*/
4801 1504 /*image dimension (number of rows and columns)*/
/*identifier, viewing angle, focal length, pixel size*/
1 -70.500 123.800 0.021 0.018
2 -60.000 95.300 0.021 0.018
3 -45.600 73.400 0.021 0.018
4 -23.3186 59.025 0.021 0.018
5 -0.0314 58.944 0.021 0.018
6 23.2778 58.903 0.021 0.018
7 45.600 73.400 0.021 0.018
8 60.000 95.300 0.021 0.018
9 70.500 123.800 0.021 0.018
```

If the images have different dimensions, like for ASTER, the code `99999` is used in place of the image dimensions and the dimensions of each image are written at the end of the file.
Appendix C. SOFTWARE DESCRIPTION

• `base.ip` contains the image coordinates of the points observed in the images. Each point can be observed in a variable number of images. The image coordinates are given in format: name, viewing direction number (same notation used in `base.data`), image coordinates (column, row) in pixels. In order to read the points automatically, the code 99999 is used to separate them. Here is an example with 2 image points:

```
2
1
4  682.438000  48.438000
5  687.158000  16.763000
6  702.721000  9.298000
99999
2
4  731.625000  64.875000
5  740.982000  33.006000
6  751.608000  25.900000
99999
```

Then few questions are asked about the available external orientation (with or without GPS and INS, reference system) and the calibration.

According to these answers, files with fixed suffix are found:

- `base_pos.xxx` and `base_att.xxx`: files with position and attitude data; we can have one file for each viewing direction or one file for the aircraft or spacecraft position/attitude. According to this format and the reference system (Geocentric, Geographic, local), the corresponding files are read. For example, in case of one file for position and attitude in local system, the program will search for files `base.pos.loc` and `base.att.loc`. Further questions are asked in order to distinguish if the position and attitude are for each image-line or if the position and attitude are not synchronised with the acquisition times (in this case cubic splines interpolate the data and the value for the time of interest is calculated and additional files containing the time of acquisition of each image-lines are required).

- `base_n.cal`, where `n` is the line/lens number: files with calibration data, that is, position of each pixel in the focal plane.

For the indirect georeferencing model the program also asks: the numbers of Ground Control Points (GCPs), Tie Points (TPs) and Check Points (CPs), the maximum number of iterations, the external and self-calibration parameters to estimate, the weights for the image observations, the external and internal orientation approximations and the GCP coordinates, the number of segments for the PPM and the thresholds to use to stop the adjustment.

The GCPs are contained in:

- `base_gcp.xxx`: according to the reference system, the files that can be read are `base_gcp.geoc` for Geocentric system, `base_gcp.geog` for Geographic system, `base_gcp.loc` for local systems.

In output, the solutions are stored files with pre-defined name.

In case of direct georeferencing, we have:

- `base_fi.ground`: file with forward intersection results (object coordinates of points in `base.ip`).

In case of indirect georeferencing, the output files are:

- `base.eo`: file with estimated external orientation parameters
- `base.sc`: file with estimated self-calibration parameters
- `base.tp`: file with estimated object coordinates of GCPs and TPs
- `base.iter`: file with statistics for each iteration
- `base.sum`: file with summary of input and output data and adjustment performances (sigma naught a posteriori, sigma of estimated parameters, RMSE of CPs).
The references are listed in alphabetic order. The following abbreviations are used:
ACRS: Asian Conference of Remote Sensing
ASPRS: American Society of Photogrammetry and Remote Sensing
EaRSeL: European Association of Remote Sensing Laboratories
IAPRS: International Archives of Photogrammetry and Remote Sensing
ISPRS: International Society of Photogrammetry and Remote Sensing
PE&RS: Photogrammetric Engineering and Remote Sensing


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