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36 Component Seismic Data:
Investigating Translational and Rotational Components in Exploration Seismology

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Abstract

In conventional multicomponent seismic exploration, the wavefield is recorded by measuring translational motions in three directions using three-component sensors. A novel approach in land seismic acquisition is to additionally record the rotational components of the wavefield around the various Cartesian axes and to combine them with translational measurements. Additional rotational measurements provide the opportunity to locally extract valuable information on the propagating wavefield, that either cannot be obtained from conventional translational measurements alone or are challenging to extract. For example, rotational data facilitate wavefield separation, shear-wave (S-wave) imaging, and ground roll suppression because of the direct link between rotation and the S-wave component, but also enable local instantaneous phase velocity estimation.

At the Earth’s free surface, rotational motions can be expressed in terms of spatial seismic wavefield gradients. Wavefield gradients can be estimated by differencing the outputs of closely spaced three-component translational sensors. The same approach can be adapted to source arrays: differencing of recordings from closely spaced translational (directed) sources can be used to simulate rotational sources that primarily emit S-waves. The combination of three components of translation and three components of rotation on both the source and the receiver side leads to a total of 36 measurable seismic components. In this thesis, I first verify that array-derived rotational rates, estimated using spatial seismic wavefield gradients, correspond to direct rotation measurements from rotational sensors. Then, I investigate the value of 36-component seismic data using synthetic as well as real field data. I show that rotational components around the vertical axis mainly contain horizontally polarized S-waves. I found that rotational components around the crossline (transverse horizontal) axis mainly contain ground-roll and vertically polarized S-waves and that these data can be combined with translational data to suppress ground roll. I show that the amplitudes of rotational components are dependent on the angle of incidence of the wavefield and that source-sided rotational components are reciprocal to receiver-sided rotational components.

To accelerate multicomponent acquisition, I furthermore present a new multicomponent seismic vector-source, which uses the Galperin configuration to obtain orthogonal vector sources of equal impact patterns and constant source-coupling. This source allows a fast multicomponent data-acquisition in engineering and environmental exploration seismology.
## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abbreviations and Symbols</td>
<td>vii</td>
</tr>
<tr>
<td>1 Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Expanding the Number of Seismic Observables</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Thesis Objectives and Outline</td>
<td>3</td>
</tr>
<tr>
<td>2 Theory</td>
<td>5</td>
</tr>
<tr>
<td>2.1 36 Component Seismic Data</td>
<td>5</td>
</tr>
<tr>
<td>2.2 Elastic Wave Equation</td>
<td>5</td>
</tr>
<tr>
<td>2.2.1 Stress</td>
<td>5</td>
</tr>
<tr>
<td>2.2.2 Strain</td>
<td>6</td>
</tr>
<tr>
<td>2.2.3 Elastic Two-Way Wave Equation</td>
<td>7</td>
</tr>
<tr>
<td>2.2.4 Elastic Wavefield Separation</td>
<td>8</td>
</tr>
<tr>
<td>2.3 Translational Components</td>
<td>8</td>
</tr>
<tr>
<td>2.4 Rotational Components</td>
<td>8</td>
</tr>
<tr>
<td>2.4.1 Free-Surface Conditions</td>
<td>10</td>
</tr>
<tr>
<td>2.5 Wavefield Gradiometry</td>
<td>10</td>
</tr>
<tr>
<td>2.6 Transfer Functions</td>
<td>12</td>
</tr>
<tr>
<td>3 Array-based Spatial Wavefield Gradient Estimates</td>
<td>13</td>
</tr>
<tr>
<td>3.1 Estimate of Gradients on Receiver Side</td>
<td>13</td>
</tr>
<tr>
<td>3.2 Estimate of Gradients on Source Side</td>
<td>13</td>
</tr>
<tr>
<td>3.3 Optimized Array</td>
<td>14</td>
</tr>
<tr>
<td>3.4 Comparison to Rotational Sensors</td>
<td>14</td>
</tr>
<tr>
<td>3.4.1 Transfer Function for METR-03 Rotational Sensor</td>
<td>15</td>
</tr>
<tr>
<td>4 Numerical Simulation</td>
<td>19</td>
</tr>
<tr>
<td>4.1 Motivation and Goals</td>
<td>19</td>
</tr>
<tr>
<td>4.2 Methods</td>
<td>19</td>
</tr>
<tr>
<td>4.2.1 Finite Difference Scheme</td>
<td>19</td>
</tr>
<tr>
<td>4.2.2 Subsurface Model</td>
<td>19</td>
</tr>
<tr>
<td>4.2.3 Survey Geometry</td>
<td>20</td>
</tr>
<tr>
<td>4.2.4 Simulation Parameters</td>
<td>20</td>
</tr>
<tr>
<td>4.3 Results</td>
<td>20</td>
</tr>
<tr>
<td>5 The Galperin Source</td>
<td>23</td>
</tr>
<tr>
<td>5.1 Galperin Configuration</td>
<td>23</td>
</tr>
<tr>
<td>5.2 Synthetic Studies</td>
<td>25</td>
</tr>
<tr>
<td>5.3 Galperin Source</td>
<td>26</td>
</tr>
<tr>
<td>CONTENTS</td>
<td></td>
</tr>
<tr>
<td>-----------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>5.4 Verification</td>
<td>5.4.1 Common-Source Gathers 26</td>
</tr>
<tr>
<td>5.4.2 Single Trace</td>
<td>27</td>
</tr>
<tr>
<td>5.4.3 Amplitude Spectra</td>
<td>27</td>
</tr>
<tr>
<td>5.4.4 Hodograms</td>
<td>29</td>
</tr>
<tr>
<td>5.4.5 Amplitudes</td>
<td>31</td>
</tr>
<tr>
<td>5.5 Applicability in the Field</td>
<td>31</td>
</tr>
<tr>
<td>5.6 Conclusions</td>
<td>31</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>6 Field Experiments</th>
<th>33</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1 Motivation and Goals</td>
<td>33</td>
</tr>
<tr>
<td>6.2 Acquisition Site</td>
<td>33</td>
</tr>
<tr>
<td>6.3 Equipment</td>
<td>34</td>
</tr>
<tr>
<td>6.4 Layout and Parameters</td>
<td>34</td>
</tr>
<tr>
<td>6.5 Processing</td>
<td>35</td>
</tr>
<tr>
<td>6.6 Arrival Identification</td>
<td>35</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>7 Results</th>
<th>39</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1 Rotational Source Around Vertical Axis, Transverse Translational Receiver: ( S^ω_z R^t_x )</td>
<td>41</td>
</tr>
<tr>
<td>7.1.1 Numerical Simulation</td>
<td>41</td>
</tr>
<tr>
<td>7.1.2 Field Data</td>
<td>42</td>
</tr>
<tr>
<td>7.1.3 Discussion</td>
<td>44</td>
</tr>
<tr>
<td>7.2 Transverse Translational Source, Rotational Receiver Around Vertical Axis: ( S^t_y R^ω_z )</td>
<td>45</td>
</tr>
<tr>
<td>7.2.1 Numerical Simulation</td>
<td>45</td>
</tr>
<tr>
<td>7.2.2 Field Data</td>
<td>46</td>
</tr>
<tr>
<td>7.2.3 Discussion</td>
<td>48</td>
</tr>
<tr>
<td>7.3 Rotation Around the Vertical Axis on Source- and Receiver-Side: ( S^ω_z R^ω_z )</td>
<td>49</td>
</tr>
<tr>
<td>7.3.1 Numerical Simulation</td>
<td>49</td>
</tr>
<tr>
<td>7.3.2 Field Data</td>
<td>50</td>
</tr>
<tr>
<td>7.3.3 Discussion</td>
<td>52</td>
</tr>
<tr>
<td>7.4 Rotation Around the Transversal Axis on Source- and Receiver-Side: ( S^ω_y R^ω_y )</td>
<td>53</td>
</tr>
<tr>
<td>7.4.1 Numerical Simulation</td>
<td>53</td>
</tr>
<tr>
<td>7.4.2 Field Data</td>
<td>54</td>
</tr>
<tr>
<td>7.4.3 Discussion</td>
<td>55</td>
</tr>
<tr>
<td>7.5 Vertical Translational Source, Rotational Receiver around Transversal Axis: ( S^t_y R^ω_y )</td>
<td>57</td>
</tr>
<tr>
<td>7.5.1 Numerical Simulation</td>
<td>57</td>
</tr>
<tr>
<td>7.5.2 Field Data</td>
<td>58</td>
</tr>
<tr>
<td>7.5.3 Discussion</td>
<td>58</td>
</tr>
<tr>
<td>7.6 Rotational Source Around Inline Axis, Translational Receivers: ( S^ω_x R^t )</td>
<td>63</td>
</tr>
<tr>
<td>7.6.1 Numerical Simulation</td>
<td>63</td>
</tr>
<tr>
<td>7.6.2 Field Data</td>
<td>64</td>
</tr>
<tr>
<td>7.6.3 Discussion</td>
<td>64</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>8 Conclusions and Outlook</th>
<th>67</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.1 Summary and Conclusions</td>
<td>67</td>
</tr>
<tr>
<td>8.2 Outlook</td>
<td>68</td>
</tr>
<tr>
<td>8.2.1 36-C Seismic Data</td>
<td>68</td>
</tr>
<tr>
<td>8.2.2 Galperin Source</td>
<td>70</td>
</tr>
</tbody>
</table>

Acknowledgment 71

References 76
<table>
<thead>
<tr>
<th>Appendices</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Appendix A</td>
<td>I</td>
</tr>
<tr>
<td>Appendix B</td>
<td>II</td>
</tr>
<tr>
<td>Appendix C</td>
<td>III</td>
</tr>
<tr>
<td>Appendix D</td>
<td>V</td>
</tr>
</tbody>
</table>
A seismic component, consisting of one source-receiver-pair, is denoted as $S_i^j R_j^i$. $S$ and $R$ denote, if the analyzed component is on source- ($S$) or on receiver ($R$) side. The subscript indicates the investigated axis $x$, $y$ or $z$, whereas the superscript clarifies if translational ($t$) or rotational ($\omega$) motions are considered.

### Acronym Description

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>vector of particle acceleration</td>
</tr>
<tr>
<td>f-k-spectrum</td>
<td>frequency-wavenumber-spectrum</td>
</tr>
<tr>
<td>$k_x, k_y$</td>
<td>wavenumber in inline- and crossline-direction, respectively</td>
</tr>
<tr>
<td>$p$</td>
<td>slowness</td>
</tr>
<tr>
<td>$t$</td>
<td>translation</td>
</tr>
<tr>
<td>$u$</td>
<td>displacement vector</td>
</tr>
<tr>
<td>$v$</td>
<td>vector of particle velocity</td>
</tr>
<tr>
<td>$C$</td>
<td>“component” (e.g. in 3-C: three component)</td>
</tr>
<tr>
<td>$G$</td>
<td>gradient tensor</td>
</tr>
<tr>
<td>MASW</td>
<td>Multichannel Analysis of Surface Waves</td>
</tr>
<tr>
<td>P (-wave)</td>
<td>pressure wave</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>RTR</td>
<td>rotation-to-translation-ratio</td>
</tr>
<tr>
<td>$S$ (-wave)</td>
<td>shear wave</td>
</tr>
<tr>
<td>SH (-wave)</td>
<td>horizontally polarized S-wave</td>
</tr>
<tr>
<td>SV (-wave)</td>
<td>vertically polarized S-wave</td>
</tr>
<tr>
<td>$V_P, V_S$</td>
<td>velocity of P- and S-waves, respectively</td>
</tr>
</tbody>
</table>

### Symbol Description

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon$</td>
<td>stress or error (if specified)</td>
</tr>
<tr>
<td>$\theta$</td>
<td>angle of incidence</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Lamé’s first coefficient or wavelength (if specified)</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Lamé’s second coefficient (shear modulus)</td>
</tr>
<tr>
<td>$\rho$</td>
<td>mass density</td>
</tr>
<tr>
<td>$\tau$</td>
<td>strain or zero-offset arrival time in $\tau$-p filtering</td>
</tr>
<tr>
<td>$\phi$</td>
<td>P-wave potential</td>
</tr>
<tr>
<td>$\psi$</td>
<td>S-wave potential</td>
</tr>
<tr>
<td>$\omega$</td>
<td>vector of rotation rates or angular frequency (if specified)</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>vector of rotation</td>
</tr>
<tr>
<td>$\partial_i$</td>
<td>partial derivative with respect to $i$</td>
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</tbody>
</table>
Erratum

The author would like to apologize for a typing error in Equation 5.1. The equation should read:

\[
\begin{pmatrix}
X \\
Y \\
Z
\end{pmatrix}
= 
\begin{pmatrix}
-cos\alpha_0 & cos\alpha_0 sin\beta & cos\alpha_0 sin\beta \\
0 & cos\alpha_0 cos\beta & -cos\alpha_0 cos\beta \\
-sin\alpha_0 & sin\alpha_0 & sin\alpha_0
\end{pmatrix}
\begin{pmatrix}
U \\
V \\
W
\end{pmatrix}
\]

The error does not affect any of the results, since all computations were performed using the correct equation.

Zurich, September 2017
CHAPTER 1

Introduction

1.1 Expanding the Number of Seismic Observables

In conventional multicomponent seismic exploration the seismic wavefield is recorded by measuring translational motions either by geophones (particle velocity) or accelerometers (Hardage et al., 2011). A new approach in seismic exploration is to record rotational components of the wavefield as well and combine them with translational measurements (e.g. Schmelzbach et al., 2016b). These additional rotational measurements provide the opportunity to extract valuable information about the propagating wavefield, that can not be obtained from conventional translational measurements alone or are difficult to extract. Areas of application include seismic exploration, engineering geophysics or seismic hazard assessment (Takeo and Ito, 1997; Stupazzini et al., 2009; Wang et al., 2009). Very promising aspects are wavefield separation into different wave types (e.g. Robertsson and Curtis, 2002; Van Renterghem et al., 2016) and ground roll suppression (Edme et al., 2013).

Seismologists first noticed rotational ground motions during earthquakes in the second half of the 20th century (Newmark, 1969). Nevertheless, rotational effects were assumed to be negligible and no reliable rotational sensors with sufficient precision were available at the time (Bouchon and Aki, 1982). In the last decades, rotational seismology has experienced increasing interest. For example, Trifunac (1982) characterized incident compressional (P) and vertically and horizontally polarized shear waves (SV, SH, respectively) in terms of their rotational components. Nigbor (1994) performed a six-degree-of-freedom ground motion measurement by recording rotational motions using conventional triaxial translational accelerometers and three rotational velocity sensors (Figure 1.1). Igel et al. (2007) measured rotational components using ring lasers and compared them to translational components to derive wavefield properties. Lee et al. (2009) summarized the advances in rotational seismology to the year 2009. Brokesova and Malek (2015a,b) analyzed the ratio of rotational to translational motions and suggest dependencies on the source type, radiation pattern and structures along the wave’s travel path.

Since rotational motions can be expressed by the spatial gradients of the displacement wavefield (e.g. Robertsson and Curtis, 2002, see also Chapter 2), they can be computed by measuring the wavefield with an array of translational sensors, as for example demonstrated by Cochard et al. (2006). Recent advances in array-based seismology and array-based gradient estimation (Spudich et al., 1995; Langston, 2007a,b,c) helped to improve the estimation of gradients and thus rotational components.

Recently, exploration seismologists discovered the benefits of wavefield gradiometry and rotational seismology for their purposes: Robertsson and Muyzert (1999) and Robertsson and Curtis (2002)
used closely spaced geophones to compute rotational components in order to separate the wavefield into its P- and S-wave-components. Robertsson et al. (2008) introduced a method to increase the effective Nyquist wavenumber significantly in marine seismic acquisition by using a multicomponent streamer. They combine the full particle velocity vector with pressure gradient data to reconstruct the wavefield in the crossline-direction. Due to the close link between wavefield gradients and rotational components, Muyzert and Edme (2012) suggest to use rotational components measured at the Earth’s free surface to reconstruct the wavefield between individual receiver-stations and demonstrated with synthetic data, that the group spacing of land seismic surveys can be increased to above the spatial Nyquist sampling requirement by measuring both rotational and translational components.

Edme and Muyzert (2013) and Edme and Yuan (2016) show how rotational components and wavefield gradients can be used to compute local slowness estimates. Conventional techniques to estimate the local elastic properties of the subsurface require wide-aperture sensor-arrays, such as Multichannel Analysis of Surface Waves (MASW) (Park et al., 1999) and seismic refraction tomography. Measuring rotation rates has the potential to replace large, wide-aperture sensor-arrays by single rotation rate sensors or smaller receiver-arrays in order to measure wavefield gradients. The reduction in array-size is an economic advantage since less field equipment and thus less installation time is required. In addition, it is especially suitable for surveys where the access to the site and the amount of equipment is restricted. Possible applications are therefore mine- and tunnel-seismology, seismic survey on other planets and on moons (Sollberger et al., 2016a) or ocean bottom seismology (Lindner et al., 2015). Barak et al. (2014) showed the benefit of rotational components for separating different wave types. In land seismic data processing, ground roll can be suppressed by using f-k or τ-p filters (Yilmaz, 2001). When these classic methods are not applicable, for example in the presence of side scattered noise or for near-surface problems, rotational components could provide a new approach for separating the wavefield. Edme et al. (2013) showed the successful removal of side-scattered noise by combining crossline rotational data and conventional array-based methods. Recently, Schmelzbach et al. (2016b) presented an optimized receiver array for gradiometry in exploration seismology. Sollberger et al. (2016b) adapted these array-geometries to the source side to simulate rotational sources and thus pure S-wave sources.

Since the implementation of rotational components in exploration seismology looks promising, the implication therefore is to expand the investigations to six degrees of freedom on the source and receiver side for seismic exploration measurements and optimize seismic survey layouts in order to collect efficiently translational and rotational data. Six components on the source side (three translational and three rotational components) and six components on the receiver side lead to a
CHAPTER 1. INTRODUCTION

A total of 36 measurable components (36-C) of the seismic wavefield. This view on seismic data is novel and calls for an extensive investigation and a first baseline study. Potential benefits of analyzing all 36 seismic components include full wavefield splitting into different wave types, ground roll suppression, retrieval of the source direction, retrieval of source characteristics, determination of local elastic parameters, and estimation of the local apparent slownesses.

1.2 Thesis Objectives and Outline

To explore the value of 36-C data, I will simulate, acquire and analyze a 36-C data set. For this purpose, I perform the following six tasks in the framework of this thesis:

1. Simulate and analyze a synthetic 36-C seismic data set with numerical finite-difference modeling. This data set will also be used to verify real field data.
2. Design a new seismic vector source to improve and speed up the multicomponent acquisition for small scale exploration and engineering geophysical purposes.
3. Collect a 36-C data set in a small scale exploration experiment.
4. Compare rotation rates measured with a rotational sensor to rotation rates derived from spatial gradients of the particle velocity measured at the free-surface and derive a transfer function of the specific rotational sensor.
5. Characterize and compare synthetic and field 36-C data and especially compare translational and rotational components.
6. Investigate, if and how rotational components complement or improve traditional exploration seismic surveys and give suggestions, if and in which directions research in 36-C seismic should proceed.

I will start with a brief introduction to translational and rotational components of seismic wavefields, computing wavefield gradients and geophone transfer functions in Chapter 2. Chapter 3 explains how rotational components can be measured in the field, either with rotational sensors or array-based using triaxial geophones. I will also derive the transfer function of a specific rotational sensor to compare sensor data to array-derived rotation rates. I introduce the setup for numerical simulations in Chapter 4. In Chapter 5, I present a new seismic vector source, called the Galperin source, followed by an introduction to field experiments in Chapter 6, where I also present the result of a simple one component forward model, in order to better understand the acquired field data. I present the results from numerical modeling and field experiments in Chapter 7, where I compare and analyze different components on common-receiver gathers, single traces, amplitude spectra and f-k spectra. I discuss a small selection of components only, but the complete overview on all 36 components can be found in Appendix D, where I show the results from numerical simulations and real field data. For components revealing interesting properties, I show additional analyses like dispersion curve plots or the result of subtracting different components from each other. The last chapters are dedicated to an extensive discussion and outlook as to how research in 36-C seismic exploration could proceed.
2.1 36 Component Seismic Data

The combination of rotational and translational components on both the receiver side and the source side leads to a total of 36 measurable seismic components. As stated in Chapter 1, the diversity of these components promises powerful tools for wavefield separation and ground roll suppression. In the following sections, I will first give a theoretical description of translational and rotational seismic components. Next, I provide a brief outline of wavefield gradiometry, which will be seen as an important tool for measuring rotation rates of the seismic wavefield. At the end of this chapter, I briefly introduce the theory of transfer functions, which I will need in Chapter 3 to calibrate a rotational sensor.

2.2 Elastic Wave Equation

The following section is predominantly based on the work by Wapenaar and Berkhout (1989).

2.2.1 Stress

Stress describes the forces per unit area that adjacent particles in a continuous medium exert on each other. Consider an infinitesimal parallelepiped as a sub-volume in a solid medium (Figure 2.1): When a force vector $\tau_x$, called the traction vector, acts across the surface $zy$ (having its unit normal in the $x$-direction) of a solid medium, then this vector can be decomposed into a tensile stress component $\tau_{xx}$ and two tangential or shearing stress components $\tau_{yx}$ and $\tau_{zx}$:

$$\tau_x = \begin{bmatrix} \tau_{xx} \\ \tau_{yx} \\ \tau_{zx} \end{bmatrix}$$  \hspace{1cm} (2.1)

Analogous relations exist for traction vectors $\tau_y$ and $\tau_z$ across the surfaces $xz$ and $xy$, respectively. The three traction vectors build together the stress tensor $\mathbf{\tau}$:

$$\mathbf{\tau} = \begin{bmatrix} \tau_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \tau_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \tau_{zz} \end{bmatrix}$$ \hspace{1cm} (2.2)
The diagonal elements of the tensor in Equation 2.2 represent the tensile stresses, whereas the off-diagonal elements describe shearing stresses.

Figure 2.1: Traction vector \( \tau_x \) causes stresses on an infinitesimal parallelepiped in a solid medium (modified from Wapenaar and Berkhout, 1989).

### 2.2.2 Strain

*Strain* describes the fractional change in length or volume of a continuous material under the exertion of forces. Strain can be decomposed into a tensile and a shearing component: Considering an infinitesimal parallelepiped as a sub-volume in a solid medium in Figure 2.2a, the tensile strain in \( x \)-direction can then be expressed by

\[
\epsilon_{xx} \approx \frac{\delta X}{\Delta X} \tag{2.3}
\]

By defining the space- (x) and time- (t) dependent displacement vector \( \mathbf{u} = [u_x, u_y, u_z]^T \), Equation 2.3 can be rewritten as

\[
\epsilon_{xx} = \lim_{\Delta X \to 0} \frac{u_x \left( x + \frac{\Delta X}{2} \right) - u_x \left( x - \frac{\Delta X}{2} \right)}{\Delta X} = \frac{\partial u_x}{\partial x} \tag{2.4}
\]

Analogously, the other tensile strains \( \epsilon_{yy} \) and \( \epsilon_{zz} \) are given by

\[
\epsilon_{yy} = \frac{\partial u_y}{\partial y}, \quad \epsilon_{zz} = \frac{\partial u_z}{\partial z} \tag{2.5}
\]

Shearing strain is derived analogously to tensile strain and is a measure of change of shape. Considering Figure 2.2b, the shearing strain is defined by

\[
\epsilon_{zx} = \epsilon_{xz} = \frac{1}{2} \left( \frac{\partial u_z}{\partial x} + \frac{\partial u_x}{\partial z} \right) \tag{2.6}
\]
and

\[
\epsilon_{yx} = \epsilon_{xy} = \frac{1}{2} \left( \frac{\partial u_y}{\partial x} + \frac{\partial u_x}{\partial y} \right) \tag{2.7}
\]
and

\[
\epsilon_{zy} = \epsilon_{yz} = \frac{1}{2} \left( \frac{\partial u_z}{\partial y} + \frac{\partial u_y}{\partial z} \right) \tag{2.8}
\]

Tensile strains and shearing strains can be assembled in the *strain tensor* \( \boldsymbol{\epsilon} \):

\[
\boldsymbol{\epsilon} = \begin{bmatrix} \epsilon_{xx} & \epsilon_{xy} & \epsilon_{xz} \\ \epsilon_{yx} & \epsilon_{yy} & \epsilon_{yz} \\ \epsilon_{zx} & \epsilon_{zy} & \epsilon_{zz} \end{bmatrix} \tag{2.9}
\]
which can be summarized by

\[ \epsilon_{ij} = \epsilon_{ji} = \frac{1}{2} \left( \frac{\partial_i u_j + \partial_j u_i}{2} \right), \quad (2.10) \]

where \( i \) (or \( j \)) = 1, 2, 3 correspond to \( x, y \) and \( z \), respectively and \( \partial_i u_j \) denotes the spatial derivative in direction \( i \) of component \( j \) of \( u \).

### 2.2.3 Elastic Two-Way Wave Equation

Stress and strain are related by Hooke’s law, which in its general form is

\[ \epsilon_{ij} = -\sum_{k=1}^{3} \sum_{l=1}^{3} c_{ijkl} \epsilon_{kl}, \quad (2.11) \]

where \( c \) corresponds to the elastic stiffness tensor. In an isotropic solid, Equation 2.11 can be expressed by the Lamé coefficients \( \lambda \) and \( \mu \), where \( \mu \) is also known as the shear modulus. We can write Equation 2.11 in the form

\[ \tau_{ij} = \lambda \delta_{ij} \epsilon_{kk} + 2 \mu \epsilon_{ij}, \quad (2.12) \]

Inserting Equation 2.10 in Equation 2.12 yields:

\[ \tau_{ij} = \lambda \delta_{ij} \partial_k u_k + \mu (\partial_i u_j + \partial_j u_i), \quad (2.13) \]

Newton’s second law gives the equation of motion for wave propagation:

\[ \rho \frac{\partial^2 u_i}{\partial t^2} = \partial_j \tau_{ij}, \quad (2.14) \]

where \( \rho \) is the mass density. Inserting the stress tensor defined in Equation 2.13 into Equation 2.14 and after some algebraic transformation yields

\[ \rho \frac{\partial^2 u_i}{\partial t^2} = \lambda \partial_i \partial_k u_k + \mu \partial_i \partial_j u_j + \mu \partial_j \partial_j u_i, \quad (2.15) \]

The application of vector identities and assuming a homogeneous, isotropic and source-free medium where deformations occur adiabatically leads to the elastic wave equation:

\[ (\lambda + 2\mu) \nabla (\nabla \cdot u) - \mu \nabla \times (\nabla \times u) - \rho \frac{\partial^2 u}{\partial t^2} = 0, \quad (2.16) \]
2.2.4 Elastic Wavefield Separation

In a homogeneous isotropic sub-volume of an elastic solid, a seismic wavefield as expressed in Equation 2.16 can be described by a \( P \)-wave potential \( \phi \) and an \( S \)-wave potential \( \psi \) (Aki and Richards, 2002), such that the total particle displacement is the sum of a pure solenoidal component and a pure rotational component, which is known as the Helmholtz decomposition:

\[
\mathbf{u}(\mathbf{x}, t) = \nabla \phi + \nabla \times \psi
\]  

(2.17)

Here, \( \mathbf{u} \) is the space- \( (x) \) and time- \( (t) \) dependent displacement field. Taking the temporal derivative of the displacement \( \mathbf{u} \) yields particle velocity \( \mathbf{v} \), whereas the second temporal derivative results in particle acceleration \( \mathbf{a} \). In the following analysis, \( \mathbf{u} \) can be replaced by \( \mathbf{v} \) or \( \mathbf{a} \) without loss of validity.

According to Equation 2.17, measuring the spatial gradients of the wavefield therefore allows for a full decomposition into a curl-free \( P \)- and a divergence-free \( S \)-wave component. The divergence and curl of \( \mathbf{u} \) can be stated thus:

\[
\nabla \cdot \mathbf{u} = \nabla^2 \phi = (\partial_x u_x + \partial_y u_y + \partial_z u_z)
\]  

(2.18)

\[
\nabla \times \mathbf{u} = \nabla \times \nabla \times \psi = \begin{pmatrix}
\partial_y u_z - \partial_z u_y \\
\partial_z u_x - \partial_x u_z \\
\partial_x u_y - \partial_y u_x
\end{pmatrix} = \Omega,
\]  

(2.19)

where \( \Omega = [\Omega_x, \Omega_y, \Omega_z]^T \) denotes the vector of rotations around the axes \( x, y \) and \( z \). The displacement gradient tensor of the wavefield can be written as

\[
\mathbf{G} = \begin{bmatrix}
\partial_x u_x & \partial_x u_y & \partial_x u_z \\
\partial_y u_x & \partial_y u_y & \partial_y u_z \\
\partial_z u_x & \partial_z u_y & \partial_z u_z
\end{bmatrix}
\]  

(2.20)

Equation 2.18 shows that building the divergence from gradient measurements (i.e. the diagonal elements of \( \mathbf{G} \)) allows the isolation of the \( P \)-wavefield. Equation 2.19 shows that measuring the rotational ground motion effectively isolates the \( S \)-wave component of the wavefield (i.e. the off-diagonal elements of \( \mathbf{G} \)).

2.3 Translational Components

Translation is the geometric transformation, which moves a point in space along a linear trajectory. Note that the sum of the diagonal elements of the gradient tensor \( \mathbf{G} \) builds the divergence defined in Equation 2.18 and is therefore directly related to the \( P \)-wave potential \( \phi \). Translational motions of a seismic wavefield are usually measured using geophones, which measure particle velocity or accelerometers, which measure particle acceleration.

2.4 Rotational Components

Rotation is the geometric transformation, which moves a point in space on an elliptical trajectory. Note that the off-diagonal elements of the gradient tensor \( \mathbf{G} \) build the rotation defined in Equation 2.19. In terms of particle velocity \( \mathbf{v} \), the rotation rate \( \omega = [\omega_x, \omega_y, \omega_z]^T \) at a specific point can be written as

\[
\omega = \frac{1}{2} \nabla \times \mathbf{v} = \frac{1}{2} \begin{pmatrix}
\partial_y v_z - \partial_z v_y \\
\partial_z v_x - \partial_x v_z \\
\partial_x v_y - \partial_y v_x
\end{pmatrix}
\]  

(2.21)
The most illustrative way to approach rotational components is probably the observation of Rayleigh waves. Rayleigh waves are a coupled pair of inhomogeneous P- and S-waves, forming a surface wave with an elliptical particle trajectory, resulting in rotational motion around the transverse axis \( y \), i.e. \( \Omega_y \neq 0 \) (Figure 2.3). Since all shear waves have particle motion perpendicular to their direction of propagation, it follows from Equation 2.21 that all S-waves hold rotational components. A detailed treatise of rotational components can be found in Box 6.5 in Aki and Richards (2002). An overview of rotational components in the different wave types is given in Table 2.1.

![Diagram of rotational components](image)

**Figure 2.3:** Different wave types and their principal rotational component relative to their propagation direction. SV: Vertically polarized S-wave. Horizontally polarized S-waves (SH) show rotation round the vertical axis, analogous to Love waves (modified from Bolt, 1993).
2.5. WAVEFIELD GRADIOMETRY

Table 2.1: Overview of rotational motions in different wave types, assuming a far-field plane wave in a homogeneous, isotropic medium. In inhomogeneous media Love waves occur as well and show the same properties as the SH wave. The applied coordinate system is shown in Figure 2.3, where the x-axis is parallel to the direction of propagation.

<table>
<thead>
<tr>
<th>Wavetype</th>
<th>Formulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>$\nabla \cdot \mathbf{v} \neq 0$ $\nabla \times \mathbf{v} = 0$</td>
</tr>
<tr>
<td>SV</td>
<td>$\nabla \cdot \mathbf{v} = 0$ $(\nabla \times \mathbf{v})_z = 0$</td>
</tr>
<tr>
<td>SH</td>
<td>$\nabla \cdot \mathbf{v} = 0$ $(\nabla \times \mathbf{v})_z \neq 0$ $v_z = 0$</td>
</tr>
<tr>
<td>Rayleigh</td>
<td>$\nabla \cdot \mathbf{v} \neq 0$ $(\nabla \times \mathbf{v})_z = 0$</td>
</tr>
</tbody>
</table>

2.4.1 Free-Surface Conditions

In the following analysis, I consider a propagating plane wave. At the Earth’s free surface, where most seismic measurements are performed, the stress across the surface becomes zero, i.e.:

$$\tau_z = [\tau_{xz}, \tau_{yz}, \tau_{zz}]^T = 0$$ (2.22)

The vertical gradient of the particle velocity $\mathbf{v}$ can then be expressed in terms of the horizontal spatial gradients, as shown by Robertsson and Curtis (2002):

$$\partial_z v_z = -\frac{\lambda}{\lambda + 2\mu} (\partial_x v_x + \partial_y v_y)$$ (2.23)

$$\partial_z v_y = -\partial_y v_z$$ (2.24)

$$\partial_z v_x = -\partial_x v_z$$ (2.25)

where $\lambda$ and $\mu$ denote Lamé’s first and second coefficient, respectively. Inserting Equations (2.23) to (2.25) into Equation (2.21) yields the expression for the curl at the free-surface, which is denoted by the subscript $FS$:

$$\frac{1}{2} \nabla \times \mathbf{v}_{FS} = \begin{pmatrix} \frac{\partial_y v_z}{2} \\ -\frac{\partial_x v_z}{2} \\ \frac{1}{2} (\partial_x v_y - \partial_y v_x) \end{pmatrix} = \omega_{FS} .$$ (2.26)

$\omega = [\omega_x, \omega_y, \omega_z]^T$ expresses rotation rates around the three Cartesian coordinate axes in $[rad/s]$. Equation 2.26 is therefore an expression to describe the rotation rates of the wave field by measuring three components of translation at the free-surface and taking spatial horizontal gradients.

2.5 Wavefield Gradiometry

The following section gives a short introduction to time-domain wavefield gradiometry. An extensive treatment of wavefield gradiometry is given by a series of papers by Langston (2007a,b,c), on which the subsequent explanation is based.

The two-dimensional wavefield in a Cartesian coordinate system can be expressed by

$$\mathbf{u}(x, y) = S(x, y)f(t - xp_x - yp_y)$$ (2.27)
where \( u \) denotes displacement at location \((x, y)\), \( S(x, y) \) describes the amplitude variation in \( x\)- and \( y\)-direction (e.g. due to wavefront curvature or damping) and \( f \) describes the phase variation as a function of time \( t \) and position \((x, y)\), where \( p_x \) and \( p_y \) are the slownesses in \( x \) and \( y \) direction, respectively. The slowness is defined as the reciprocal of the velocity. Taking spatial derivatives in the \( x \) and \( y \) directions of Equation 2.27 yields

\[
\frac{\partial u(t, x, y)}{\partial x} = A_x u(t, x, y) - p_x \frac{\partial u(t, x, y)}{\partial t} \tag{2.28}
\]

and

\[
\frac{\partial u(t, x, y)}{\partial y} = A_y u(t, x, y) - p_y \frac{\partial u(t, x, y)}{\partial t} , \tag{2.29}
\]

where \( A_x \) and \( A_y \) are the normalized spatial gradients of the wavefield amplitudes, such that

\[
A_x(x, y) = \frac{\partial S 1}{\partial x} \frac{S}{S} \tag{2.30}
\]

and

\[
A_y(x, y) = \frac{\partial S 1}{\partial y} \frac{S}{S} \tag{2.31}
\]

Langston thereby suggests the use of sensor arrays consisting of supporting stations around a central sensor to estimate spatial gradients at the central station and using the mean between all differences between central and supporting stations. For a linear array of three stations this is equivalent to the centered finite-difference operator by the first-order Taylor series expansion around the central station at location \( x \):

\[
\frac{\partial u}{\partial x}\bigg|_x = \frac{u(t, x + \Delta x) - u(t, x - \Delta x)}{2\Delta x} + \epsilon \tag{2.32}
\]

This operator has second-order accuracy. The remaining truncation error-term \( \epsilon \) is

\[
\epsilon = -\frac{1}{6} \frac{\partial^3 u}{\partial x^3} \bigg|_x \Delta x^3 \tag{2.33}
\]

By assuming a plane wave in a loss-less medium, Equations 2.28 and 2.29 simplify to

\[
\frac{\partial u(t, x, y)}{\partial x} = -p_x \frac{\partial u(t, x, y)}{\partial t} \tag{2.34}
\]

and

\[
\frac{\partial u(t, x, y)}{\partial y} = -p_y \frac{\partial u(t, x, y)}{\partial t} \tag{2.35}
\]

It follows from Equations 2.34 and 2.35 that the spatial gradient is a slowness-scaled version of the particle acceleration \( a = \frac{\partial u}{\partial t} \). For this, the assumption must be valid that \( p_x \) and \( p_y \) are constant within the array. It also follows that the spatial gradient and the temporal gradient are directly proportional. The following Fourier transform (FT) pairs exist for spatial and temporal derivatives:

\[
\partial_x \leftrightarrow ik_x \quad \partial_y \leftrightarrow ik_y \quad \partial_t \leftrightarrow i\omega , \tag{2.36}
\]

where \( k \) denotes the wavenumber and \( \omega \) the angular frequency. As a consequence, taking spatial or temporal derivatives leads to a relative increase of higher spatial and temporal frequencies, due to the multiplication with \( ik \) and \( i\omega \), respectively. Further, temporal frequencies and wavenumbers (spatial frequencies) are directly related by

\[
\omega p_x = k_x \quad \omega p_y = k_y \tag{2.37}
\]
2.6 Transfer Functions

The response of a sensor in the frequency domain is given by

\[ C(\omega) = H(\omega)U(\omega) \quad , \tag{2.38} \]

where \( C \) denotes the signal registered at the sensor, \( U \) describes the "true" wavefield in the propagation medium and \( \omega \) the angular frequency. \( C \) and \( U \) are linked by the transfer function \( H \). A transfer function is the relation between the input and the output of a system. In case of geophysical sensors such as geophones, \( U \) is the input and \( C \) is the output. \( H \) is a function of the sensor design and may depend, for example, on the natural frequency of the sensor, the coil resistance and damping factors. If the technical details of the sensor are known, the transfer function can be computed. The true wavefield can then be recovered by spectral division:

\[ U(\omega) = \frac{C(\omega)}{H(\omega)} \quad \tag{2.39} \]

If the transfer function is not known, but there are reasons to assume that the true wavefield \( U \) is known, then the transfer function can be computed by

\[ H(\omega) = \frac{C(\omega)}{U(\omega)} \quad \tag{2.40} \]

Equation 2.40 can be stabilized by the complex conjugate of \( U \), denoted with an asterisk (*):

\[ H(\omega) = \frac{C(\omega)U^*(\omega)}{U^*(\omega)U(\omega)} \quad \tag{2.41} \]

From Equation 2.41 it follows that \( H \) is not defined for those frequencies where \( U \) is zero. To solve this, a stabilization term \( \epsilon \) can be added to the denominator in Equation 2.41:

\[ H(\omega) = \frac{C(\omega)U^*(\omega)}{U^*(\omega)U(\omega) + \epsilon} \quad \tag{2.42} \]
3.1 Estimate of Gradients on Receiver Side

While in practice horizontal spatial gradients can simply be computed by differencing the outputs of closely spaced sensors (geophones), estimating the vertical derivative requires the installation of vertically displaced sensors, for example, in a borehole. Robertsson and Muyzert (1999) successfully demonstrated the decomposition on the airwave-induced ground motion by using a tetrahedron of four receivers at the surface and one receiver buried below the midpoint. Equations 2.23 to 2.25 make use of the free-surface condition to express the vertical spatial gradients by horizontal spatial gradients. Therefore, all spatial derivatives at the surface can be computed by using a surface-based array of three component (3-C) sensors only. Cochard et al. (2006) and Barak et al. (2014) show applications of this approach.

A challenge is the accuracy of gradient estimates, which is a function of source- and receiver coupling variations, orientation- and positioning errors, background noise, station spacing and the interference of different arrivals. In the present study, I will follow the approach of Langston (2007a), as described in Section 2.5, which also found application in recent studies, for example in Poppeliers and Evans (2015). The approach makes use of a central-finite difference algorithm by incorporating several supporting stations around a main station, where the gradient is computed. This method works for arrays of irregular geometries (Spudich et al., 1995; Liang and Langston, 2009).

3.2 Estimate of Gradients on Source Side

In an inhomogeneous medium, the Helmholtz decomposition into a curl-free component and a divergence-free component (Equation 2.17) is no longer valid, i.e. P- and S-waves are coupled. For example, a diving P-wave in an inhomogeneous medium converts into S-waves (P to SV) along its path. These S-waves arrive at a receiver significantly before the first pure S-wave arrival. As a result, the pure S-wave is hard to be identified. Rotational components measured at the free-surface contain various mode-converted wavefronts. Rotational sources might solve this problem, since they effectively are pure S-wave sources. Sollberger et al. (2016b) transferred this approach to the source side. They simulated rotational motions by using a source-array and computing spatial derivatives analogous to the receiver side (see Section 3.1). Using this method, P-wave arrivals were signifi-
3.3 Optimized Array

Schmelzbach et al. (2016b) used a differential evolution algorithm (Price et al., 2005) in order to optimize the receiver-array, given a certain number of receivers, noise level and wavelength. They conclude, that a minimum number of three supporting stations is required to minimize the truncation error resulting from finite differencing (ignoring wavefield curvature effects). They suggest a $d/\lambda$ ratio of 5-10% for moderate noise conditions ($\sim 40\,\text{dB}$ white noise), where $d$ is the characteristic length of the array and $\lambda$ is the wavelength. An array consisting of four supporting stations results in an even smaller truncation error and can be more practical in an exploration survey design, since every supporting station can be used for two adjacent central stations (see Chapter 6). In the following treatise, I always consider a cross-array with open limbs towards the source-receiver-line (Figure 3.1). The geometry for source-arrays is identical.

Muijs et al. (2002) analyzed the sensitivities of array-derived gradient estimates to misorientation and mislocation of geophones. They suggest a required positioning accuracy within 10% of the side length of the array and that orientation should be accurate within $2^\circ$ to obtain significant results.

**Figure 3.1**: Cross array consisting of four supporting stations with distance $d$ to a main station, where the gradient is computed. Green triangles denote geophones.

3.4 Comparison to Rotational Sensors

Muyzert and Edme (2012) compared rotation rates estimated by taking spatial gradients at the free-surface (Equation 2.26) to rotation rates measured directly using rotational sensors. They employed the Eentec R-1 sensor and applied a matching filter and a bandpass filter from 10 Hz to 40 Hz to obtain a good match between rotation sensors and array-derived data. They also state that these sensors are not yet robust and sensitive enough for large scale seismic surveys. Bernauer et al. (2012) tested the R-1 sensor and state a strong temperature-dependency of the sensor and that the sensitivity of the R-1 sensor is one order of magnitude too low for applications in weak motion seismology. Schmelzbach et al. (2016b) compared spatial-gradient derived data with rotation rate sensors R-1 (Eentec) and METR-03 (R-sensors LLC). The R-1 sensor has a limited recording bandwidth from 0.03 Hz to 50 Hz, whereas the METR-03 sensor works within a frequency range from 0.03 Hz to 100 Hz. Unfortunately, the exact transfer function of the METR-03 is not known. The manufacturer provides a rough transfer function only without phase information (Figure 3.4) and the rotational sensor data did not match the array-derived rotation rates.
3.4.1 Transfer Function for METR-03 Rotational Sensor

In the framework of this thesis, I developed a field-data driven method to estimate the transfer function of the METR-03 rotational sensor. The underlying assumption for this method is that the rotation rates estimated by differencing the output of closely-spaced 3-C geophones at the free-surface are indeed the true rotation rates of the wavefield. The relation between array-derived rotation rates and rotational sensor data is therefore

\[ C(\omega) = R(\omega)F(\omega), \tag{3.1} \]

where \( C \) is the frequency spectrum of the array-derived rotation rates, \( R \) denotes the frequency spectrum of the rotational rate sensor and \( F \) denotes the unknown transfer function. Considering the stabilization techniques introduced in Section 2.6, the unknown transfer function becomes

\[ F(\omega) = \frac{C(\omega)R^*(\omega)}{R^*(\omega)R(\omega) + \epsilon} \tag{3.2} \]

The data used for this calibration experiment was acquired during a field campaign of the Exploration and Environmental Geophysics Group at ETH Zurich outside the framework of this thesis in summer 2015.

The METR-03 sensor was installed in the center of a circle consisting of 32 3-C geophones (GS-11D, central frequency 4.5 Hz). The specifications of the GS-11D and therefore the transfer function for the GS-11D sensor are well known. The radius of the circle was 1m. In the center, additional 3-C sensors were employed, right next (∼30 cm) to the rotation rate sensors (Figure 3.2). The fundamental idea of employing 32 geophones in a circle is to average over many finite-difference computations which reduces errors due to coupling variations and increases the signal-to-noise ratio. Sources were directed from eight different azimuths with 45° intervals by striking a metal plate with a sledgehammer at three different offsets from the center point: 12.5m, 25m and 50m. I will focus on the rotation around the \( y \)-axis and therefore neglect the shots from 0° and 180° azimuth, since I do not expect significant rotation energy around the source-receiver inline axis for these source-positions. Each shot was processed and analyzed separately (Figure 3.3).

I applied a zero-phase low-pass filter to 75 Hz to both data sets because the METR-03 rotation sensor showed decreasing energy above 75 Hz. I applied the geophone response function for the GS-11D 3-C sensors and estimated spatial gradients, i.e. rotation rates, using all sensors of the
circle. For the important central station, three closely spaced geophones were employed in order to compute an average trace and increase the signal to noise ratio. In order to obtain the transfer function of the METR-03 sensor, I computed the cross-spectrum between array derived rotation and METR-03 sensor data using Equation 3.2 with $\varepsilon = 0.0001$. Function $F(\omega)$ was computed for every shot. In the next step, the spectra were slightly smoothed with a running average to reduce large variations in the spectra. The total of 18 functions was averaged and smoothed again, which leads to the general transfer function (Figure 3.4).

This function $F(\omega)_{\text{averaged}}$ (supposed to be the response function of the METR-03 sensor) was then applied to an independent second experiment: a 1m walk-away survey was performed, while the wave field was recorded with a cross-array of 3-C geophones and rotational sensors next to the center point (Schmelzbach et al., 2016b). I obtained a good match between the array-derived and measured rotation rates for the ground-roll ($A$ in Figures 3.5 and 3.6). Nevertheless, for small ($< 9$ m) and large ($> 35$ m) offsets, the signals show deviations ($B$ in Figure 3.5), probably related
to the violation of the plane wave assumption and the averaging over three offsets. In addition, the corrected sensor signals show consistent arrivals of about two periods before the first dominant arrival recorded by the 3-C array (C in Figure 3.5). The raw data of the rotational sensors show weak signals in this time-window with similar apparent velocities as the refracted P-arrivals. The array-derived data contains similar events as well, but with significantly weaker amplitudes. These events are interpreted as either P-S conversions at the free-surface or translational motions, recorded by poor performance of the rotational sensor.

The comparison shown in Figure 3.5 gives additional support that taking spatial gradients at the free-surface is indeed an adequate method to estimate rotational motions. However, whereas the transfer function performs well on surface wave arrivals, earlier arrivals like P-S mode-converted waves show a misfit between data from a rotational sensor and array-derived rotational data. I do not claim that the derived transfer function is the technically correct transfer function, which should be derived in a more sophisticated way by considering the technical specifications of the sensor. In addition, the derived transfer function is based on the assumption that the array-based rotation rates are the true reference solution, which is not absolutely true. For example, wave curvature, truncation errors from finite-differencing, receiver coupling variations and positioning errors may degrade the quality of the gradient estimates.
3.4. COMPARISON TO ROTATIONAL SENSORS

Figure 3.5: Common receiver gather of the walk-away experiment by Schmelzbach et al. (2016b). Black traces show array-derived rotation rates, while red traces show the METR-03 data. a) before and b) after applying an instrument transfer function for the METR-03 sensor. Note the good match for surface wave signals (A), which is decreasing for small and large offsets (B). Events at C are interpreted as P-S conversions or spurious translational events, which are not preserved when applying the transfer function.

Figure 3.6: Trace at 25m offset in the receiver gather shown in Figure 3.5 before and after applying the derived instrument transfer function. Note the good match for surface wave signals (A) and the supposed P-S conversions at C, which are not preserved when applying the transfer function.
CHAPTER 4
Numerical Simulation

4.1 Motivation and Goals
To explore the value of the additional rotational source- and receiver components, I studied synthetic data from two different models using a finite-difference simulation: The first model was a full 36-C survey with the objective to verify the rotational components from field data and to narrow the focus of interest when analyzing real data. The second model was a 9-C survey, i.e. a simulation of multicomponent sources and receivers on a line without using sources or receivers with lateral offset to the line (i.e. without using source- or receiver arrays). This second survey served the purpose to simulate the field experiments carried out in the framework of this project to understand the recorded source gathers and to identify different wave types.

This chapter focuses on the full 36-C simulation. The parameters of the second model simulating real field conditions are given in Section 6.2.

4.2 Methods

4.2.1 Finite Difference Scheme
The simulation was performed using a time-domain finite difference scheme, provided by the software Matterhorn by ETH Zurich. Matterhorn uses a staggered grid scheme to solve the elastic wave equation and allows implementing multicomponent sources and receivers (Broggini and Manukyan, 2013). The software allows for a very accurate treatment of the free-surface boundary condition (Robertsson, 1996).

4.2.2 Subsurface Model
To obtain a variety of wave modes and arrivals while keeping the complexity of the data on a low level, I designed a simple 1D model with a constant velocity gradient from the surface down to a high impedance contrast at 75m depth. Velocities and density can be read in Table 4.1. The $V_P$ to $V_S$ ratio is constant and given by $V_S = V_P / \sqrt{3}$. 

4.3. RESULTS

Table 4.1: P-wave velocities and densities in the synthetic model.

<table>
<thead>
<tr>
<th>Depth [m]</th>
<th>$V_P$ [m/s]</th>
<th>Density [kg/m$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>600</td>
<td>1200</td>
</tr>
<tr>
<td>75</td>
<td>1200</td>
<td>2100</td>
</tr>
<tr>
<td>&gt; 75</td>
<td>3000</td>
<td>2600</td>
</tr>
</tbody>
</table>

4.2.3 Survey Geometry

I set up three parallel receiver-lines each consisting of 497 stations with 1m spacing in both horizontal directions and a source-array comprising five source positions at sufficient distance to the model boundary (Figure 4.1). This geometry permits calculating spatial gradients on source- as well as on receiver-side by using a cross array with one central and four supporting stations, leading to 495 locations for receiver sided gradient computation.

![Survey Layout](image)

Figure 4.1: Zoom-in of survey layout for synthetic studies: The source and receiver array geometry allows computing spatial gradients using a cross consisting of four supporting and one central station.

4.2.4 Simulation Parameters

The source was simulated by a directed pressure point source (separately in $X, Y, Z$), acting on the velocity grid, convolved with a Ricker wavelet with 40 Hz central frequency. The simulation considered the elastic wave equation in 3D using a fourth order finite-difference scheme. Free-surface boundary conditions were implemented at the model surface. Perfectly matched layer (PML) conditions on all other sides damp reflections from the side walls of the model. Table 4.2 gives an overview of the most important parameters.

4.3 Results

An interpretation of the most important wave fronts is given in Figure 4.2. Since a large variety of different wave types is observed, the simulated data can be seen to be suitable for further analysis of its rotational components. Data resulting from source and receiver sided rotation are given in Chapter 7, where they are compared to field data.

Results from the second model, simulating real field data, is given when introducing the field campaign in Section 6.2.
Table 4.2: Simulation parameters for the synthetic study (36-C).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>model size [cells]</td>
<td>X: 2000, Y: 100, Z: 500</td>
</tr>
<tr>
<td>cell size [m]</td>
<td>0.25</td>
</tr>
<tr>
<td>simulation</td>
<td>elastic, isotropic, 3D</td>
</tr>
<tr>
<td>source</td>
<td>directed pressure point source</td>
</tr>
<tr>
<td>source position [cells]</td>
<td>X: 600, Y: 50, Z: 0</td>
</tr>
<tr>
<td>source wavelet</td>
<td>Ricker, 40 Hz</td>
</tr>
<tr>
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</tr>
<tr>
<td>spatial operator</td>
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</tr>
<tr>
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<tr>
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<tr>
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</tr>
<tr>
<td>PML power</td>
<td>4.0</td>
</tr>
<tr>
<td>PML frequency [Hz]</td>
<td>40.0</td>
</tr>
<tr>
<td>PML damping velocity [m/s]</td>
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</tr>
</tbody>
</table>

Figure 4.2: Interpretation of the most important wave fronts in the $S_t^z R_t^z$ component (vertical source, vertical receiver): A: direct (diving) P-wave, B: reflected P-wave, C: refracted P-wave, D: multiples E: mode-converted waves, F: direct (diving) S-wave, G: refracted S-wave, H: reflected S-wave, I: ground roll (surface waves).
5.1 Galperin Configuration

The computation of rotational motions around all three Cartesian axes requires multicomponent sources in all three Cartesian directions, i.e. the source vectors need to be orthogonal to each other. In practice, vertically directed sources can be obtained for example by using Vibroseis trucks, weight droppers or by hitting a metal plate with a heavy hammer (Figure 5.1a). Horizontal sources can be achieved for example by striking a shear beam end-on with a sledge hammer (Figure 5.1b). Another approach is the summation and subtraction of two 45° directed hammer strikes on two sides of a metal wedge (hereafter called the prism), which is for example used by Sollberger et al. (2014) and Schmelzbach et al. (2016a) (Figure 5.1c). Summation of two opposite directed strikes results in a cancellation of the horizontally-directed energy, resulting in a vertically-directed source. Subtraction leads to an enhancement of horizontally-directed motion and suppression of vertically-directed signal (Figure 5.2). By turning the prism 90° in the horizontal plane and repeating the strikes, energy in all three coordinate-directions is released. By doing so, the vertical source is obtained twice. Because the source coupling is changed when rotating the prism, which may additionally violate the orthogonality of the three source-vectors, I developed a new seismic vector source with the aim to overcome this problem. In addition, avoiding the redundancy of the vertical component would speed up the acquisition by 25%, since only three instead of four strikes are required.

Classic multicomponent seismic exploration techniques rely on the use of three component geophones with three orthogonal components \((X,Y,Z)\), oriented in the Cartesian coordinate system. Galperin (1955) first introduced a three-component seismometer consisting of three identical sensors \((U,V,W)\), which all are orthogonal to each other with an angle of 54.74° to the vertical axis and spaced 120° apart in the horizontal plane (Figures 5.3 and 5.4). This configuration is rotated to the Cartesian coordinate system with the rotation matrix given in Equation 5.1. The Galperin configuration brings the advantage of identical design for all sensors. The idea found industrial applications for example in the Streckeisen triaxial seismometer STS-2 or the GS-ONE 3-C Galperin geophone by Geospace. Graizer (2009) gives a demonstrative introduction into the Galperin configuration and studies its sensitivity to rotational motions.

The transformation from the Galperin coordinate system \((U,V,W)\) to the cardinal system \((X,Y,Z)\) is given by:

\[
\begin{pmatrix}
X \\
Y \\
Z
\end{pmatrix} =
\begin{pmatrix}
\cos \alpha_0 & \cos \alpha_0 \sin \beta & \cos \alpha_0 \sin \beta \\
0 & \cos \alpha_0 \sin \beta & \cos \alpha_0 \sin \beta \\
\sin \alpha_0 & \sin \alpha_0 & \sin \alpha_0
\end{pmatrix}
\begin{pmatrix}
U \\
V \\
W
\end{pmatrix},
\]  

(5.1)
5.1. GALPERIN CONFIGURATION

Figure 5.1: a) Metal plate, used for vertical source vectors, b) wooden shear beam, used for horizontal sources, c) 45° metal prism source as used, for example, in Sollberger et al. (2014), b) The Galperin source, a metal-wood construction using the Galperin configuration.

Figure 5.2: Prism configuration: The summation of strikes A and B on the metal prism results in a cancellation of the horizontally-directed energy and to a vertically-directed source-vector (V). Subtraction yields a horizontally-directed source-vector (H) by canceling the vertical components.
Figure 5.3: Sketch of three one-component geophones arranged in the Galperin configuration. Figures from Ralston and Steeples (2002).

Figure 5.4: Galperin configuration: a) Plan view from top along the vertical Z-axis. b) Lateral view along the horizontal Y-axis. Panel c) shows the lateral view when the geometry is applied to the source side. V and W axes are overlapping but shown separated for visualization (Figures a) and b) from Graizer, 2009).

where $\alpha_0 = 35.26^\circ (90^\circ - 54.74^\circ)$ is the angle of the Galperin axes $(U, V, W)$ to the horizontal plane and $\beta = 30^\circ$ denotes the angle between the projections of the V and Y axes onto the horizontal plane. From Equation 5.1 it follows that uncertainties either in the transformation angles (due to inaccurate construction or positioning) or in one of the Galperin vector amplitudes $(U, V, W)$ introduce errors in all vectors in the cardinal system, which is the main drawback of the Galperin configuration. For example, one noisy sensor in a Galperin geophone degrades all rotated data of the entire station. In the following section, I show that the orientation-errors should be kept below $3^\circ$ in azimuth and orientation to keep the total amplitude variations below 5%.

5.2 Synthetic Studies

I performed a synthetic study to evaluate the sensitivity of a Galperin sensor to orientation errors. I simulated a simple sinusoidal signal from both horizontal directions and from the vertical direction and applied orientation errors from $-45^\circ$ to $+45^\circ$ for dip $(\alpha_0)$ as well as for azimuth $(\beta)$ before rotating from the Galperin configuration to the Cartesian coordinate system. I then computed the relative RMS error for the maximum amplitude between the unperturbed solution and the data including...
5.3. GALPERIN SOURCE

orientation errors. Figure 5.5 shows the mean error for different source directions. Note that a signal parallel to the X (Galperin: U) axis is equally sensitive to errors in dip and azimuth, whereas the Y axis is primarily sensitive to azimuth-errors. Vertically incoming waves are only sensitive to errors in dip. To keep the amplitude error below 5%, the error in dip and azimuth must not exceed 3°.

Figure 5.5: a) Relative RMS error for a sinusoidal, monochromatic signal along the X-direction, b) Y-direction and c) Z-direction.

5.3 Galperin Source

I adapted the Galperin configuration to the source side in order to achieve a multicomponent vector source, whose components have identical generation-mechanisms and identical source-coupling. I designed the prototype for applications using a heavy sledgehammer, as it is standard for near-surface engineering and environmental seismic surveys. The source consists of three 20cm x 20cm steel plates of 12 mm thickness, whose normal vectors are orthogonal to each other and point to the center at the bottom of the source (Figure 5.1d). The plates are tilted by 55° to the horizontal axis, leading to the required 35° inclined force-vector when hitting the plate. Thinner plates in between the main plates and a thick base plate counteract deformation of the source. The metal frame is filled with wooden blocks to simulate the impedance of the ground and to damp acoustic noise in the air. Seven spikes below the base plate help to avoid lateral slipping and increase the ground-coupling. A hook on top allows manageable transport of the source. Since manufacturing accuracy is estimated to be about 1°, the angles were rounded to an integer value (i.e. \( \alpha_0 = 35^\circ \)). This construction uncertainties introduce a small error when rotating the data to the Cartesian coordinate system.

5.4 Verification

I compared the Galperin source to the prism, a conventional metal plate and a wooden shear beam, all struck with the same hammer. I focus here on the main diagonal components of translation \( S^r_x R^t_x \), \( S^r_y R^t_y \) and \( S^r_z R^t_z \), i.e. on pairs with equal source and receiver components. \( S \) and \( R \) denote, if the analyzed component is on source- (S) or on receiver (R) side. The subscript indicates the investigated axis \( x, y \) or \( z \), whereas the superscript clarifies if translational (t) or rotational (\( \omega \)) motions are considered. Note that the \( S^r_z R^t_z \) component is multiplied by \(-1\). This is necessary in order to correct for the fact that Equation 5.1 is valid for an upward pointing, right-handed system, whereas I am considering a downward pointing system for all analyses in this thesis. In addition, the vectors on the receiver side (Figure 5.4b) have opposite sign to those on the source side (Figure 5.4c).

The only processing step applied is a zero-phase bandpass filter with the -3dB points on low and high-end of 0.05 Hz and 75 Hz, respectively. I chose this band-width to make the data comparable to prior experiments at the same site location.
5.4.1 Common-Source Gathers

The analyzed common-source gathers consist of 32 triaxial receivers with an inline-spacing of 2 m and a minimum source-receiver offset of 11 m. The X-coordinate is parallel to the source-receiver-line (inline). More details on the experimental setup are given in Chapter 6. Every trace is the sum of five sequential strikes, in order to increase the signal-to-noise ratio. The individual gathers in Figure 5.6 show a plate, prism and Galperin source, recorded with a vertical receiver ($S_t^1 R_s^1$ component). Note that channel number 30 was broken (68 m offset). For the horizontal components, the shear beam was used instead of the plate. These figures are given in Appendix A (Figures A1 and A2).

The source gathers look very comparable and individual events are well recovered. The refracted P waves are less pronounced when using the Galperin source (events $A$ in Figure 5.6), whereas an interpreted S-wave arrival is less distinct when using a plate source (events $B$ in Figure 5.6).

![Common-source gathers generated using a metal plate, a metal prism and the new Galperin source. Note the high degree of congruency between the different sources. Nevertheless, the refracted P-wave arrival is less pronounced when using the Galperin source. Individual traces were normalized by their RMS value for better display.](image)

5.4.2 Single Trace

Figure 5.7 shows trace number 15 of the specified source gather, i.e. a trace from the center of the array at about 39 m offset. Prism and Galperin source are in good agreement for all components, although a small time shift can be observed on the horizontal components. These deviations may be the result of small differences in the exact source positions. The Galperin source shows smaller amplitudes than the prism source. The plate source shows very good agreement with the other sources, with the match slightly better for the prism. The shear beam shows significantly lower amplitudes and is partly out of phase compared to the other sources.

5.4.3 Amplitude Spectra

I compare amplitude spectra of a metal plate, shear beam, prism and Galperin source in Figure 5.8. Input data are the entire source gathers given in Figure 5.6. Overall, the spectra are very similar, although the prism and Galperin sources are more consistent.

Figure 5.9 shows spectral coherence for individual traces between the prism and Galperin source. Coherence is a measure for expressing the similarity of two signals in the frequency domain. Signals of identical frequency spectra show a coherence of 1. The coherence is good ($\sim 1$) for all three components for frequencies between 5 and 60 Hz across the entire source gather. For horizontal components, the coherence is high even for frequencies up to 90 Hz. The vertical component shows a band of weak coherence between 65 Hz and 75 Hz.
5.4. VERIFICATION

Figure 5.7: Trace 15 of the source gather in Figure 5.6 at about 39m offset for different source-receiver pairs and different source types. Note the high degree of congruency between prism and plate source. The shear beam (blue line in $S^1_x R^1_x$ and $S^1_x R^1_y$ component) releases significantly less energy than the other sources and is therefore remarkably lower in amplitude.

Figure 5.8: Amplitude spectra of the source gathers in Figure 5.6.
CHAPTER 5. THE GALPERIN SOURCE

5.4.4 Hodograms

Hodograms are crossplots of two components of particle motion over a time window. Figure 5.10a shows hodograms in the X-Z plane for signals of trace 15 (∼39 m offset), generated by vertical sources using a metal plate, the prism and the Galperin source. The first time-window from 60 ms to 90 ms shows P-wave refractions (see source gathers in Figure 5.6). All sources show the same trajectory of particle motion and clearly reflect the near-vertical motion of arrivals implying a small angle of incidence in the case of P-waves. Nevertheless, the Galperin source is slightly lower in amplitude.

The second and third time-windows from 180 ms to 210 ms and 330 ms to 360 ms, respectively, show elliptical trajectories of particle motion. These events most probably correspond to an SV-wave and a Rayleigh wave, respectively. Note that the amplitude is more than one order of magnitude higher compared to the P-wave arrival. Whereas plate and prism sources are very comparable, the Galperin source deviates by about 15° for the semi-major axis of the ellipse and shows lower amplitudes.

Figure 5.10b shows hodograms in the X-Y plane for signals of trace 15 (∼39 m offset), generated by transversal horizontal sources using a shear beam, the prism and the Galperin source. The first time window contains the refracted P-wave, which is beneath recognition threshold when using transversal horizontal sources. Hence, these events are classified as background noise.

The second and third time-windows from 180 ms to 210 ms and 330 ms to 360 ms, respectively, show dominant trajectories in the Y-direction. These events most probably correspond to SH or Love waves. Note that the amplitude of these events is more than one magnitude higher compared to the P-wave arrival. The shear beam shows significantly smaller amplitudes. Whereas prism and Galperin source exhibit the same trajectories of particle motion for the 180 ms to 210 ms time window, they deviate in the third time window.

Figure 5.9: Spectral coherence between the prism and Galperin source of the source gathers in Figure 5.8. Signals of identical frequency spectra show a coherence of 1. All components show very high coherence in the frequency band between 5 and 60 Hz.
Figure 5.10: Hodograms of trace 15 (39m offset) in the a) XZ-plane and b) XY-plane. Note, that the shear beam induces significantly less energy than other sources, as can be seen in panel b).
5.4.5 Amplitudes

For the accurate estimation of wavefield gradients, source- and receiver-coupling variations must be minimized. Therefore, repeatable sources within a source-array are crucial. In addition, amplitude-fluctuations within the Galperin configuration should be minimized in order to successfully transform the Galperin configuration to the Cartesian coordinate frame (see Section 5.1). Consistent amplitudes between repeated strikes on the source are therefore an important criterion for the applicability of the Galperin source. To evaluate the repeatability of a sledgehammer-strike on the Galperin source, I summed up the absolute amplitudes of one source gather resulting from one single hammer-strike. I continuously increase the number of stacked strikes, \( n \), and compute the mean value of the amplitude. This value is compared to the mean amplitude resulting from twenty individual stacks using the relative RMS-error. The average of twenty strikes is seen as a reference solution, because variations between individual strikes should have averaged-out. The error \( \epsilon_n \) for \( n \) strikes is thus given by:

\[
\epsilon_n = \sqrt{\frac{\left( \sum_{i=1}^{n} A_i - \sum_{i=1}^{20} A_i \right)^2}{\sum_{i=1}^{20} A_i^2}},
\]

where \( A \) denotes the sum of the absolute amplitudes in a common-source gather. I show the relative RMS-error between the mean volume involving \( n \) strikes and the reference solution using twenty strikes in Figure 5.11. After stacking eight impacts, the resulting total error drops below 5% for all source-directions. I additionally computed the unbiased coefficient of variation \( c_v \) given by

\[
c_v = \left( 1 + \frac{1}{4n} \right) \frac{\sigma_x}{\bar{x}},
\]

where \( \sigma_x \) denotes the standard deviation of data \( x \) and \( \bar{x} \) is the mean-value of data \( x \). The coefficient of variation is on average about 0.07.

The data used for the amplitude-analysis was acquired in a separate experiment conducted by the Exploration and Environmental Geophysics Group at ETH Zurich outside the field campaigns shown in this thesis. The experiment consists of one line of 16 3-C geophones. The source was located at 2 m minimum offset to the spread. Acquisition parameters are identical to the surveys described in Chapter 6. The survey was conducted in an area close-by to the survey described in this thesis.

5.5 Applicability in the Field

The Galperin source showed good practicality in field. An important observation is that the spikes coupling the source to the ground need to be completely buried, i.e. the base plate needs to lie directly on the ground. Otherwise, the source tends to tilt during hammering, because the center of mass is rather high. For surveys on harder soil, where the spikes cannot be completely buried, the source should be modified to avoid tilting (e.g. heavier base plate or additional cantilevers).

5.6 Conclusions

I compared the plate, prism and shear beam impact sources with the new Galperin source. Due to poor source coupling, the shear beam deployed produced too low amplitudes for a significant comparison.

The Comparison of common-source gathers, individual traces and frequency content leads to the conclusion that plate, prism and Galperin sources provide very comparable results. I found that the idea of transferring the Galperin geophone geometry to the source side is feasible in order to achieve
5.6. CONCLUSIONS

Figure 5.11: Relative RMS-error between the mean of summed amplitudes in a shot gather using $n$ strikes and a reference solution including twenty strikes.

A multicomponent vector source. Although hodograms show similar trajectories, the Galperin source often deviates slightly from the plate and prism sources. This deviation probably arises from the higher sensitivity of the Galperin source to orientation and amplitude errors. I observed in the field that striking the Galperin source at the right angle and with consistent force is more difficult to achieve compared to using the plate or prism. Although the source was carefully leveled, the field conditions did not always allow a positioning-accuracy within 3°. The analysis of single strikes shows that there are variations between individual hammer-strikes and that five stacks are not enough to compensate for amplitude-variations. I suggest additional effort in normalizing the applied force to keep amplitude variations on the source side as low as possible, for example by using a tilted (automatic) accelerated weight dropper or vibrator. Due to these uncertainties in data produced using the Galperin source, I will focus on data acquired using the prism source when analyzing the 36 component dataset (Chapter 7).
6.1 Motivation and Goals

In order to acquire 36-C seismic data and examine the Galperin source in the field, I conducted two field campaigns in the framework of this thesis near the ETH campus H"onggerberg. The first survey was meant for testing a prototype of the Galperin source and to collect 36-C data on a few shot positions. The second survey was designed to provide a longer 2D section and to apply an optimized version of the Galperin source. The goals and aims of the second survey can be summarized by the following points:

- Acquire first 36-C seismic 2D line data.
- Compare different sources, namely metal plate, shear beam and metal prism with the new Galperin source.
- Verify the applicability and benefits of the Galperin source for the acquisition of 36-C data in the field.
- Shoot along the receiver line for potential future applications like travel time tomography, multicomponent seismic imaging or local slowness estimation.

In the following sections and chapters, I will show data from the second survey only. However, descriptions for acquisition site and equipment are identical for both surveys.

6.2 Acquisition Site

The survey site is located on H"onggerberg in the City of Zurich (CH), close to the ETH Campus H"onggerberg (coordinates in CH1903/LV93: 679725 / 251680) at an elevation of 525m above sea level. The site is a completely flat grass field, which is part of a shooting range (Figure 6.1). The geology on the site is a few meters soil and quaternary deposits (moraine) on top of Molasse (sandstone and conglomerates) (Pavoni et al., 1992).

To better understand the field data, I modeled a 9-C multicomponent survey, i.e. three-component vector sources and three component receivers using a time-domain finite-difference simulation (see Chapter 4). The subsurface model was built based on previous surveys at the same location (Schmelzbach et al., 2016b). A simple first break travel time analysis was performed to obtain thickness and velocities of the layered ground. A rough analysis showed a two-layer-model with P-wave velocities of \( V_{P1} = 840 \text{ m/s} \) and \( V_{P2} = 2900 \text{ m/s} \). These layers are likely to correspond
to quaternary deposits and Molasse underneath. Due to the strong velocity contrast between both layers, it is well possible that an additional third layer is hidden in between, e.g. weathered Molasse with intermediate velocity. The simulation parameters are given in Table B2 in Appendix B.

6.3 Equipment

The seismic survey was performed using GS-11D three-component geophones (3-C) from Geospace Technologies with a natural frequency of 4.5 Hz (coil resistance 380 Ohms, shunt damping 70%) combined with the Geode system from Geometrics. A sledgehammer together with either a metal plate, a metal prism, a wooden shear beam or the Galperin source served as seismic sources (see Figure 5.1). For positioning, I used a Leica GPS system with RTK support.

6.4 Layout and Parameters

The layout (illustrated in Figure 6.2) consists of three parallel receiver lines, each containing 32 3-C geophones. The inline-spacing is 2 m. Since the middle line is staggered by 1 m relative to the outer lines, this geometry allows computing spatial gradients along the central line by using four supporting stations with a distance of 1.4 m ($\sqrt{2}$) to the main station. This finally leads to 31 receiver locations (60 m spread), where spatial gradients and rotations can be derived. The geophones were laid out in a way that the X-axis is inline to the source direction (radial) with the perpendicular Y-axis (crossline, transversal).

The grid spacing of 1m was defined based on the findings of Schmelzbach et al. (2016b): I calculated an average signal to noise ratio of 40 dB, which yields an optimized grid-spacing for the cross-array of about 7 % of the wavelength. For slow ground-roll, I computed wavelengths of about 7 m (25 Hz, 250 m/s), while refracted P-waves can reach 65 m (45 Hz, 2900 m/s). By choosing a grid-spacing of $\sqrt{2}$ m, the ratio of grid-spacing to wavelength is between 2 % and 15 %, which keeps the truncation error below 10 % for all arrivals.

The initial goal was to collect the entire dataset applying the Galperin source every 12 m along the line. At several positions, the prism-source had to be deployed, due to technical problems with
the Galperin source. At two locations, I performed a full comparison of steel plate, wooden shear beam, prism and Galperin source. An overview of all shot positions is given in Appendix B. The survey parameters are given in Table 6.1.

Table 6.1: Survey parameter of the field experiment on Höngherberg.

<table>
<thead>
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<th>Value</th>
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</tr>
<tr>
<td>sampling interval</td>
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</tr>
<tr>
<td>in-field stacks</td>
<td>5</td>
</tr>
<tr>
<td>filters</td>
<td>none</td>
</tr>
<tr>
<td>trigger delay</td>
<td>0 s</td>
</tr>
</tbody>
</table>

Table 6.2: Velocities of interpreted events in Figure 6.4.

<table>
<thead>
<tr>
<th>Arrival</th>
<th>Interpretation</th>
<th>Velocity [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>direct P</td>
<td>840</td>
</tr>
<tr>
<td>B</td>
<td>refracted P</td>
<td>2900</td>
</tr>
<tr>
<td>F</td>
<td>direct S</td>
<td>260</td>
</tr>
<tr>
<td>G</td>
<td>refracted S</td>
<td>1160</td>
</tr>
<tr>
<td>I</td>
<td>ground roll</td>
<td>250 to 500</td>
</tr>
<tr>
<td>Z</td>
<td>Love wave (?)</td>
<td>400</td>
</tr>
</tbody>
</table>

Figure 6.2: Seismic 36-C experiment on Höngherberg. Coordinates were rotated to an East-West orientation and computed relatively to receiver station 33 (point 0, 0). Note the cross-array for sources and receivers to calculate spatial gradients at the midpoint.

6.5 Processing

The only processing step applied is a zero-phase bandpass filter with the -3dB points on low and high-end of 0.05 Hz and 75 Hz, respectively. I chose this band-width to make the data comparable to prior experiments on the same site location (see Section 3.4.1).

6.6 Arrival Identification

I interpreted arrivals on two common-source gathers using a vertical source and vertical receivers ($S^v_t R^v_y$) and a transversal source and transversal receivers ($S^t_y R^t_y$), respectively. The synthetic data serves as an interpretation support. The results from synthetic studies are shown in Figure 6.3 and real field data are presented in Figure 6.4. In Figure 6.4a, direct and refracted P wave arrivals are well detectable, whereas the S-wave arrivals are more difficult to interpret. The section shows strong ground roll, which probably includes also multiples and wave guide signals, due to the very shallow and strong impedance contrast. Figure 6.4b clearly shows the direct and refracted S-waves, whereas no P-wave arrivals are visible. The subsequent S-wave and surface wave train is again rather complex. I interpreted a very distinct arrival, labeled with Z in Figure 6.4b, as Love-wave signals. Table 6.2 summarizes apparent velocities picked in Figure 6.4.
Figure 6.3: Synthetic data: Interpretation of arrivals on a) a source gather with vertical source and receivers and b) on a source gather with transversal source and receiver. A: direct P-wave, B: refracted P-wave, C: reflected P-wave (not interpreted) D: multiples, E: mode-converted waves, F: direct S-wave, G: refracted S-wave, H: reflected S-wave (not interpreted) I: ground roll, J: guided wave.
Figure 6.4: Real field data: Interpretation of arrivals on a) a gather with vertical source and receiver and b) on a gather with transversal source and receiver. A: direct P-wave, B: refracted P-wave, C: reflected P-wave (not interpreted) D: multiples, E: mode-converted waves, F: direct S-wave, G: refracted S-wave, H: reflected S-wave (not interpreted) I: ground roll, J: guided wave, X: maybe P-S mode-converted wave, Y: probably guided wave, Z: guided wave or Love wave. The shot gather in panel b) shows flipped polarity for better visibility of first arrivals.
In this chapter I present the results of the synthetic studies and the field experiments for selected components. For every analyzed component, I include a short discussion and give an attempt to explain the observed characteristics and to delineate potential applications. Traces of the common-source gathers of both synthetic data and real field data were normalized individually by the root mean square (RMS) of each trace. If not stated differently, the shown field data correspond to source-ID 15 and were acquired using the prism-source at about 11 m minimum offset at source position 11 (see Figure 6.2). A number of receiver channels were broken, which are set to zero. I muted the corresponding central station at locations, where broken channels of the supporting stations were degrading the quality of the gradient estimate. Alternatively, one could compute gradients using less than four supporting stations. Nevertheless, I decided to only consider receiver stations where a consistent number of supporting stations was available. Source-receiver-pairs are denoted for example as $S_x^z R_y^t$. $S$ and $R$ denote source- ($S$) or receiver ($R$), respectively. The subscript indicates the investigated axis $x$, $y$ or $z$, where $x$ is in the horizontal source-receiver inline direction. The superscript clarifies if translational ($t$) or rotational ($\omega$) motions are considered. Since the synthetic model does not show lateral variations in velocities, no side-scattered signals are expected, which results in $\partial_y = 0$. Table 7.1 shows the translational and rotational components that are expected in the results of the numerical simulation. The f-k plot in this chapter only consider positive offsets.

![Figure 7.1: Coordinate system and orientation of source and receivers in the model used for synthetic data.](image-url)
Table 7.1: Translational and rotational components expected for the synthetic data including direct and reflected waves (see Chapter 2). The horizontal source-receiver-inline-axis corresponds to the X-axis, therefore $\partial_y = 0$. At an angle of incidence of $\theta = 0^\circ$, all horizontal spatial derivatives and thus rotational components at the free-surface vanish.

<table>
<thead>
<tr>
<th>Arrival</th>
<th>Translation</th>
<th>Rotation in Body</th>
<th>Rotation at Free-Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>SV / Rayleigh-wave</td>
<td>$v_{SV} = \begin{pmatrix} v_x \ 0 \ v_z \end{pmatrix}$</td>
<td>$\omega_{SV} = \frac{1}{2} \begin{pmatrix} 0 \ \partial_z v_x - \partial_x v_z \ 0 \end{pmatrix}$</td>
<td>$\omega_{SV,FS} = \begin{pmatrix} 0 \ -\partial_x v_z \ 0 \end{pmatrix}$</td>
</tr>
<tr>
<td>SH / Love-wave</td>
<td>$v_{SH} = \begin{pmatrix} 0 \ v_y \ 0 \end{pmatrix}$</td>
<td>$\omega_{SH} = \frac{1}{2} \begin{pmatrix} -\partial_z v_y \ 0 \ \partial_x v_y \end{pmatrix}$</td>
<td>$\omega_{SH,FS} = \begin{pmatrix} 0 \ 0 \ 0.5(\partial_x v_y) \end{pmatrix}$</td>
</tr>
</tbody>
</table>
CHAPTER 7. RESULTS

7.1 Rotational Source Around Vertical Axis, Transverse Translational Receiver: $S_z^\omega R_y^t$

7.1.1 Numerical Simulation

In Figures 7.2 I compare the common-source gathers of the components $S_y^t R_y^t$ and $S_z^\omega R_y^t$. The $S_y^t R_y^t$ component clearly shows S-wave reflections, S-wave refractions and mode-converted (P-S) arrivals prior to the reflections. Since a transversal source and transversal receivers are used, the S-waves will be polarized mainly in the horizontal plane (SH-waves). The $S_z^\omega R_y^t$ component also clearly reveals the reflected and refracted S-wave, but mode-converted (P-S) signals are not visible anymore. However, the ratio between S-wave reflections on the $S_y^t R_y^t$ and $S_z^\omega R_y^t$ components is in the same order of magnitude as the ratio between mode-converted waves on the $S_y^t R_y^t$ and $S_z^\omega R_y^t$ components. Since the mode-converted waves generally lower amplitudes, they are not displayed in the $S_z^\omega R_y^t$ component anymore. Events with negative offset show opposite polarity. Reflections vanish for very small offsets. The analysis of a single trace in Figure 7.3 shows an apparent phase rotation of $\pi/2$ and a slight amplitude reduction of the S-wave refraction, although this signal is not completely removed. Note that the amplitudes of the $S_z^\omega R_y^t$ component are in general slightly lower than the amplitudes of the $S_y^t R_y^t$ component but are in the same order of magnitude.

Figure 7.4a shows the amplitude spectra and Figure 7.4b the f-k-spectra of both the $S_y^t R_y^t$ and the $S_z^\omega R_y^t$ component. The $S_z^\omega R_y^t$ component shows a frequency shift of up to 6 Hz towards higher frequencies. The f-k-spectrum also shows a small shift towards higher frequencies and wavenumbers.

![Figure 7.2: Simulated source gathers of the $S_y^t R_y^t$ and $S_z^\omega R_y^t$ components. Note the removed mode-converted signals in the $S_z^\omega R_y^t$ component. A: direct (diving) P-wave, D: multiples, E: mode-converted wave, F: direct (diving) S-wave, G: refracted S-wave, H: reflected S-wave, I: ground roll.](image-url)
7.1. ROTATIONAL SOURCE AROUND VERTICAL AXIS, TRANSVERSE TRANSLATIONAL RECEIVER: $S_Z^T R_Y$.

**Figure 7.3:** Traces at 225 m offset of source gathers shown in Figure 7.2 of the $S_y^T R_y^t$ and $S_z^z R_y^t$ components. a) full time window, b) zoom-in. Note the apparent $\pi/2$ phase rotation between both components. D: multiples, F: direct (diving) S-wave, G: refracted S-wave, H: reflected S-wave, I: ground roll.

**Figure 7.4:** a) Amplitude spectra and b) f-k-spectra of the components $S_y^T R_y^t$ and $S_z^z R_y^t$. Note the shift of up to 6 Hz for the $S_z^z R_y^t$ component.

### 7.1.2 Field Data

The $S_y^T R_y^t$ and $S_z^z R_y^t$ components are analyzed on real field data common-source gathers in Figure 7.5. The interpreted refracted S-wave is suppressed, whereas the surface waves (ground roll) are well recovered. The event marked with H is more distinct in the $S_z^z R_y^t$ component and shows an approximately hyperbolic shape. Possible guided wave signals appear to have higher frequency content in the $S_z^z R_y^t$ component, leading to better separation of individual events. These observations are also visible in the comparison of selected traces (Figure 7.6). An apparent phase rotation of about $\pi/2$ between both components is notable for the rotational source. The interpreted refracted S-wave is not removed completely.

The comparison of amplitude spectra in Figure 7.7a shows a frequency shift of about $+5$ Hz for frequencies between 5 Hz and 50 Hz. The f-k plot (Figure 7.7b) shows a shift towards higher wave numbers and frequencies, resulting in spatial aliasing for frequencies higher than 30 Hz.
CHAPTER 7. RESULTS

Figure 7.5: Field data source gathers of components $S_{y}^{R_{t}}$ and $S_{z}^{R_{t}}$. G: refracted S-wave, H: reflected S-wave, K: wave guide signals (ground roll).

Figure 7.6: Traces at four different offsets extracted from the $S_{y}^{R_{t}}$ and $S_{z}^{R_{t}}$ component common-source gathers shown in Figure 7.5. G: refracted S-wave, I: ground roll. Note the apparent $\pi/2$ phase rotation between both components.
7.1. ROTATIONAL SOURCE AROUND VERTICAL AXIS, TRANSVERSE TRANSLATIONAL RECEIVER: $S_\omega R_y^T$

Figure 7.7: a) Amplitude Spectra and b) f-k-spectra of the components $S_y^t R_y^t$ and $S_\omega^r R_y^t$. Note the frequency shift of $+5$ Hz and the shift towards higher wavenumbers for the $S_\omega^r R_y^t$ component.

### 7.1.3 Discussion

The detection of direct P-waves and mode-converted waves in the $S_y^t R_y^t$ component is probably surprising. First, a pure P-wave should not contain transversal motions. However, the implemented horizontal source is not a pure SH-source, but shows a certain radiation pattern in all directions. In addition, the finite-difference simulation itself can be subject to inaccuracies due to the model-discretization, the staggered nature of the grid and the finite-difference approximation. In theory, rotational sources should correspond to S-wave sources and therefore suppress P-waves and P-S mode-converted waves. This property could not be observed in the $S_\omega^r R_y^t$ component, since the relative reduction in amplitude is equal to the relative reduction of reflected (pure) S-waves in the $S_\omega^r R_y^t$ component. Due to the horizontal transverse source vector (mainly SH), the amplitudes of P-S mode-converted events are generally rather low. The decrease of amplitudes for arrivals at small offsets will be discussed in Section 7.3.3. The hyperbolic event on real data in Figure 7.5 could be interpreted as a (multiple) reflected S-wave.

The shift towards higher wavenumbers and higher frequencies is a consequence of computing derivatives (see Chapter 2, Section 2.5 Wavefield Gradiometry). Due to the relation $k_a = 2\pi f/c_a$, where $k_a$ is the horizontal wavenumber, $f$ the frequency and $c_a$ the apparent velocity, $f$ has to change proportionally with $k_a$, if the velocity stays constant. Both simulated and real field data show an apparent phase rotation of $\pi/2$ when using a rotational source. However, the simulation shows an apparent phase rotation of opposite polarity than the real data. This is due to fact that the analyzed trace on the synthetic data has positive offset but the real data has in fact negative offsets with respect to the coordinate axis, i.e. the X-coordinate is decreasing with increasing offset (see Figure 6.2). I show traces of a shot from the opposite end of the receiver spread in Figure C1 in Appendix C. It is visible, that the phase shift has the same direction for both components.
7.2 Transverse Translational Source, Rotational Receiver Around Vertical Axis: $S^t_y R^\omega_z$

7.2.1 Numerical Simulation

In Figure 7.8, I compare synthetic common-source gathers of the component $S^t_y R^t_y$ with $S^t_y R^\omega_z$. The $S^t_y R^\omega_z$ component is identical to the $S^t_y R^t_y$ component shown in Figure 7.2, but with opposite polarity. The same applies for the analysis of a single trace in Figure 7.9: The $S^t_y R^\omega_z$ component is identical to the $S^t_y R^t_y$ component with the exception of opposite polarity. In the frequency domain, the $S^t_y R^\omega_z$ component is equal to the $S^t_y R^t_y$ component (compare Figure 7.10 with Figure 7.4).

![Figure 7.8: Simulated source gathers $S^t_y R^t_y$ and $S^t_y R^\omega_z$ components. Note the suppressed refraction and the removed mode-converted signals in the $S^t_y R^t_y$ component. A: direct (diving) P-wave, B: refracted P-wave, C: reflected P-wave, D: multiples, E: mode-converted wave, F: direct (diving) S-wave, G: refracted S-wave, H: reflected S-wave, I: ground roll.](image)

![Figure 7.9: Trace at 225 m offset of source gathers shown in Figure 7.8 of $S^t_y R^t_y$ and $S^t_y R^\omega_z$ components. a) full time window, b) zoom-in. D: multiples, F: direct (diving) S-wave, G: refracted S-wave, H: reflected S-wave, I: ground roll.](image)
7.2. TRANSVERSE TRANSLATIONAL SOURCE, ROTATIONAL RECEIVER AROUND VERTICAL AXIS: $S^T_y R^z$  

\[(a)\]

\[\text{Amplitude Spectra} \]

\[
\begin{array}{c}
\text{Normalized Amplitude} \\
0 & 0.2 & 0.4 & 0.6 & 0.8 & 1 \\
0 & 20 & 40 & 60 & 80 & 100 & 120 \\
\end{array}
\]

\[\text{Frequency [Hz]}\]

\[\text{f-k-spectra of } S^T_y R^t_y \text{ and } S^T_y R^z \omega. \text{ Note the phase shift of up to 6 Hz for the } S^T_y R^z \omega \text{ component.}\]

\[\text{Figure 7.10: a) Amplitude Spectra and b) f-k-spectra of the components } S^T_y R^t_y \text{ and } S^T_y R^z \omega. \text{ Note the phase shift of up to 6 Hz for the } S^T_y R^z \omega \text{ component.}\]

7.2.2 Field Data

I analyze the same $S^T_y R^t_y$ and $S^T_y R^z$ components on real field data common-source gathers in Figure 7.11. The ground roll compares well whereas the refracted S-wave is reduced. This source gather suffers from various broken receiver channels. This hampers a complete analysis. These observations are also visible in the comparison of selected traces (Figure 7.12). As for the rotational source, the rotational receiver shows an apparent phase rotation of about $\pi/2$ compared to the $S^T_y R^t_y$ component, but with opposite sign than the rotational source. As for the rotational source, the S-wave refraction is not removed completely. The $S^T_y R^z$ component shows a slight shift towards higher frequencies in the amplitude spectrum, as visible in Figure 7.13a. This shift is smaller than for the $S^T_y R^t_y$ component, which goes along with less pronounced spatial aliasing (Figure 7.13b).
CHAPTER 7. RESULTS

Figure 7.11: Field data source gathers of components $S_y^t R_y^t$ and $S_y^t R_z^\omega$. G: S-wave refraction.

Figure 7.12: Traces at four different offsets of the $S_y^t R_y^t$ and $S_y^t R_z^\omega$ component common-source gathers shown in Figure 7.11. G: refracted S-wave, I: ground roll. Note the apparent $\pi/2$ phase rotation between both components.
7.2. TRANSVERSE TRANSLATIONAL SOURCE, ROTATIONAL RECEIVER AROUND VERTICAL AXIS: $STyRz$

Figure 7.13: a) Amplitude Spectra and b) f-k-spectra of the components $S_y^t R_y^t$ and $S_y^t R_z^c$.

7.2.3 Discussion

The synthetic study shows that the $S_y^t R_y^t$ and $S_y^c R_z^c$ components are identical up to a sign change. This comparison demonstrates experimentally that reciprocity also holds for the combination of rotational and translational sourced and receivers. Figure 7.14 shows both synthetic and real field data for the reciprocal pair of components $S_y^t R_z^c$ and $S_z^c R_y^t$.

Figure 7.14: a) Synthetic data and b) real field data of the reciprocal pair of components $S_y^t R_z^c$ and $S_z^c R_y^t$. The $S_z^c R_y^t$ component is multiplied by $-1$ for better comparison.
7.3 Rotation Around the Vertical Axis on Source- and Receiver-Side: $S_z^w R_z^w$

7.3.1 Numerical Simulation

In Figure 7.15, I compare common-source gathers of the $S_y^t R_y^t$ and $S_z^w R_z^w$ components. The $S_y^t R_y^t$ component clearly shows reflected and refracted S-waves. In the $S_z^w R_z^w$ component, the S-wave reflection and its multiples are still visible, while mode-converted arrivals are suppressed. However, important to note is, that reflections vanish completely at zero offset. The amplitudes of the S-wave refractions are reduced. The analysis of a single trace in Figure 7.16 confirms these observations: The $S_z^w R_z^w$ component is very comparable to the $S_y^t R_y^t$ component for ground roll and reflections, although reflections are slightly weaker. Both components appear to be in-phase, although the waveforms of the $S_z^w R_z^w$ are narrower. The S-wave refractions are removed.

Figure 7.17a shows the amplitude spectra and Figure 7.17b the f-k-spectra of both components. The $S_z^w R_z^w$ component shows a shift of up to 8 Hz towards higher frequencies and thus a shift towards higher wavenumbers.

![Figure 7.15: Simulated common-source gathers of the $S_y^t R_y^t$ and $S_z^w R_z^w$ component. A: direct (diving) P-wave, D: multiples, E: mode-converted waves, F: direct (diving) S-wave, G: refracted S-wave, H: reflected S-wave, I: ground roll. Note the suppressed refraction and the reduced mode-converted signals in the $S_z^w R_z^w$ component.](image)
7.3. ROTATION AROUND THE VERTICAL AXIS ON SOURCE- AND RECEIVER-SIDE: $S^y R^r_y$ and $S^w R^w_z$

Figure 7.16: Traces at 225 m offset of source gathers shown in Figure 7.15 of the $S^y R^r_y$ and $S^w R^w_z$ components. a) full time window, b) zoom-in. D: multiples, F: direct (diving) S-wave, G: refracted S-wave, H: reflected S-wave, I: ground roll.

Figure 7.17: a) Amplitude Spectra and b) f-k-spectra of the components $S^y R^r_y$ and $S^w R^w_z$. Note the phase shift of up to 8 Hz for the $S^w R^w_z$ component.

7.3.2 Field Data

The same $S^y R^r_y$ and $S^w R^w_z$ components are analyzed on real field data. The common-source gathers in Figure 7.18 shows similar characteristics as the simulation: The surface wave train compares well, whereas the refracted S-wave is suppressed. These observations are also visible in the comparison of selected traces (Figure 7.19). Note that the amplitudes of the $S^w R^w_z$ component are one to two orders of magnitude lower than the amplitudes of the $S^y R^r_y$ component. The comparison of amplitude spectra in Figure 7.20a shows a distinct shift of $+5$ Hz to $+10$ Hz for the $S^w R^w_z$ component. The effect in the f-k spectra in Figure 7.20b is a shift towards higher wave numbers and higher frequencies, leading to spatial aliasing for frequencies higher than 30 Hz.
Figure 7.18: Field data common source gathers of the $S^R_y R^I_y$ and $S^\omega_z R^\omega_z$ components. Note the suppression of refracted S-wave signals (G) in the $S^\omega_z R^\omega_z$ component.

Figure 7.19: Traces at four different offsets extracted from the $S^R_y R^I_y$ and $S^\omega_z R^\omega_z$ components common-source gathers shown in Figure 7.18. Note the significant suppression of the refracted S-wave (G) in the $S^\omega_z R^\omega_z$ component and the very similar surface wave train (I).
7.3. ROTATION AROUND THE VERTICAL AXIS ON SOURCE- AND RECEIVER-SIDE: $S_Z^ωR_Z^ω$.

![Image](74x586 to 296x749)

![Image](299x586 to 522x749)

**Figure 7.20:** a) Amplitude Spectra and b) f-k-spectra of the components $S_y^tR_y^t$ and $S_z^ωR_z^ω$. Note the phase shift of +5 to +10 Hz and the spatial aliasing for the $S_z^ωR_z^ω$ component.

7.3.3 Discussion

As observed in Figure 7.15, events with small angle of incidence like refractions or reflections at small offsets are suppressed in the $S_z^ωR_z^ω$ component.

The horizontal apparent slownesses $p_x$ and $p_y$ are zero for vertically incoming waves (i.e. $θ = 0°$). It follows from Equations 2.34 and 2.35 that the horizontal gradients vanish if the slowness is zero. Since the rotational component around the vertical axis is given by $ω_z = 0.5 (∂_x v_y - ∂_y v_x)$ (see Equation 2.26) and the spatial gradients for a plane wave with an angle of incidence of $θ = 0°$ are zero, the rotation around the vertical axis indeed vanishes. $ω_z$ is therefore $θ$-dependent.

The higher amplitudes of reflections in the one-sided rotational components at small offsets can be explained by the fact that these components still involve one translational component, which does not vanish at zero offset. Surface waves (e.g. Love waves) and direct SH-waves have an angle of incidence of 90°. Therefore, these signals are not suppressed and gain relatively in amplitude, compared to reflections and refractions.

Rotational components on both the source and the receiver side involve two times a spatial derivative. This leads therefore to a larger shift towards higher frequencies and wavenumbers.
7.4 Rotation Around the Transversal Axis on Source- and Receiver-Side: $S_y^\omega R_y^\omega$

7.4.1 Numerical Simulation

In Figures 7.21, I compare common-source gathers of the components $S_z^t R_z^t$ and $S_y^\omega R_y^\omega$. The two-sided rotational component around the transversal axis suppresses the refracted P-wave, whereas refracted S-waves are still visible. At small offsets, the amplitudes of reflections are remarkably reduced. At larger offsets, direct and reflected P-waves are weaker compared to direct and reflected S-waves, ground roll and refracted S-waves. However, the P-wave does not vanish. The analysis of a single trace in Figure 7.22 shows in detail how the ground roll is nearly matched and earlier arrivals like direct or refracted P-waves are suppressed.

![Figure 7.21: Simulated source gathers of the $S_z^t R_z^t$ and $S_y^\omega R_y^\omega$ component. A: direct (diving) P-wave, B: refracted P-wave, C: reflected P-wave, D: multiple reflected P-wave, E: mode-converted wave, F: direct (diving) S-wave, G: refracted S-wave, H: reflected S-wave, I: ground roll.](image)

![Figure 7.22: Trace at 225 m offset of source gathers shown in Figure 7.21 of the $S_z^t R_z^t$ and $S_y^\omega R_y^\omega$ components. A: direct (diving) P-wave, B: refracted P-wave, C: reflected P-wave, D: multiple, F: direct (diving) S-wave, G: refracted S-wave, I: ground roll.](image)
7.4. ROTATION AROUND THE TRANSVERSAL AXIS ON SOURCE- AND RECEIVER-SIDE: $\mathbf{S}_\mathbf{Y} \mathbf{R}_\mathbf{Y}$

7.4.2 Field Data

The same $S_{z}^l R_{z}^l$ and $S_{y}^\omega R_{y}^\omega$ components are analyzed on real data common-source gathers in Figure 7.23. The ground roll compares well to a wide extent whereas direct and refracted P-waves are suppressed. These observations are also visible in the comparison of selected traces (Figure 7.24). Note that P-wave arrivals are effectively removed. For large offsets, the fit between both components in the ground roll time window decreases and refracted P-waves are not completely removed anymore. The first arrivals of the $S_{y}^\omega R_{y}^\omega$ component correspond to an S-wave arrival, although a clear identification of the wave type is difficult. No phase shift can be observed between both components, whereas the frequency spectra in Figure 7.25a shows a shift of about $+5$ Hz for frequencies between 5 Hz and 50 Hz for the $S_{y}^\omega R_{y}^\omega$ component. Nevertheless, this shift does not introduce significant spatial aliasing, as can be seen in the f-k-plot (Figure 7.25b).

![Figure 7.23: Field data source gathers of components ($S_{z}^l R_{z}^l$) and ($S_{y}^\omega R_{y}^\omega$). A: direct P-wave, B: refracted P-wave, F: direct S-wave.](image_url)
CHAPTER 7. RESULTS

7.4.3 Discussion

In general, the observations considering phase and frequency shifts between the components $S^t_z R^t_z$ and $S^o_y R^o_y$ are analogous to the observations made for the $S^t_y R^t_y$ and $S^o_z R^o_z$ component (see Section 7.3). Since the spatial gradients vanish at zero offset, arrivals with small angle of incidence vanish, whereas lateral propagating waves, such as ground roll, is preserved. Rotational components on both the source and the receiver side should result in a pure S-wavefield. However, P-wave arrivals are still visible. They can be related to P-S mode-conversions at the free-surface. In such a S-wave data set, first arrivals would correspond to first S-wave arrivals. However, due to the coupling of P- and S-waves in an inhomogeneous medium, this interpretation is not completely valid. Interpreting the observations that reflections and refractions, especially from P-waves, are suppressed and ground roll is amplified when computing source- and receiver-sided rotational components around the transversal axis, then the $S^o_y R^o_y$ component should mainly contain ground roll and thus surface waves. In engineering geophysics, surface waves are analyzed to extract geotechnical parameters like elastic moduli. One method is the Multichannel Analysis of Surface Waves (MASW). With this technique,
7.4. ROTATION AROUND THE TRANSVERSAL AXIS ON SOURCE- AND RECEIVER-SIDE: 
$S_\omega R_\omega$

one computes, for example, dispersion curves to obtain local S-wave velocities (Park et al., 1999). Source gathers mainly containing ground roll should have more dominant dispersive characteristics, since less non-dispersive body-waves are recorded. Therefore, I expect dispersion curves to be more focused and better detectable in the $S_\omega R_\omega$ component. Figure 7.26 shows dispersion curves of the conventional $S^t_t R^t_z$ component and of the $S_\omega R_\omega$ component. The curve of the $S_\omega R_\omega$ component is indeed more pronounced. However, signals with frequencies below 10 Hz are heavily suppressed. In addition, it is important to note that the treated time-window is 500 ms only and therefore not sufficient for a sophisticated surface wave analysis.

Rotational components around the transversal axis (or crossline) are derived by using the spatial derivative in x-direction of the z-component of the wavefield, thus $\omega_y = -\partial_x u_z$. Therefore, this component can be obtained by a standard single-component line acquisition.

(a) Displacement Analysis $S^t_t R^t_z$  (b) Displacement Analysis $S_\omega R_\omega$

Figure 7.26: Dispersion analysis of a) $S^t_t R^t_z$ and b) $S_\omega R_\omega$ component. Figures produced by roXplore (2016).
CHAPTER 7. RESULTS

7.5 Vertical Translational Source, Rotational Receiver around Transversal Axis: $S^t_z R^\omega_y$

7.5.1 Numerical Simulation

As already observed on the $S^\omega_y R^t_z$ and $S^t_y R^\omega_z$ components in Sections 7.2 and 7.1, the receiver-sided rotational components show the same events and properties as the source-sided rotational components with exception of a polarity flip and a constant factor for the amplitudes, i.e. they are reciprocal. Therefore, I only treat the $S^t_y R^\omega_z$ component in this section, while the $S^\omega_y R^t_z$ component can be found in Appendix D. The common-source gather in Figure 7.27 displays, that the $S^t_y R^\omega_z$ contains the same events as the $S^t_z R^t_z$ component. Nevertheless, the relative amplitudes of the different wave types changed. Namely, the S-wave reflections and refractions gain in amplitude. Upgoing arrivals at zero offset vanish. One single trace is of the $S^t_y R^\omega_z$ is presented in Figure 7.28, where the relative suppression of refracted P-wave arrivals is visible.

Figure 7.27: Simulated source gathers of the $S^t_z R^t_z$ and $S^t_y R^\omega_z$ component. A: direct (diving) P-wave, B: refracted P-wave, C: reflected P-wave, D: multiple reflected P-wave, E: mode-converted wave, F: direct (diving) P-wave, G: refracted S-wave, H: reflected S-wave, I: ground roll.
7.5. VERTICAL TRANSLATIONAL SOURCE, ROTATIONAL RECEIVER AROUND TRANSVERSAL AXIS: $S_T^R R_{xy}$

![Image](image_url)

(a) Figure 7.28: Trace at 225 m offset of source gathers shown in Figure 7.27 of the $S_T^R R_{xy}$ components. A: direct (diving) P-wave, B: refracted P-wave, C: reflected P-wave, D: multiple, F: direct (diving) S-wave, G: refracted S-wave, I: ground roll.

Table 7.2: Rotation-to-translation-ratios for selected events picked on synthetic data of the single trace shown in Figure 7.28.

<table>
<thead>
<tr>
<th>Event</th>
<th>Wave Type</th>
<th>Time on trace 225 [ms]</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>direct P-wave</td>
<td>326</td>
<td>0.38</td>
</tr>
<tr>
<td>B</td>
<td>refracted P wave</td>
<td>268</td>
<td>0.15</td>
</tr>
<tr>
<td>C</td>
<td>reflected P wave</td>
<td>305</td>
<td>0.28</td>
</tr>
<tr>
<td>F</td>
<td>direct S wave</td>
<td>542</td>
<td>0.67</td>
</tr>
<tr>
<td>G</td>
<td>refracted S wave</td>
<td>458</td>
<td>0.26</td>
</tr>
<tr>
<td>I</td>
<td>ground roll</td>
<td>543</td>
<td>0.94</td>
</tr>
</tbody>
</table>

7.5.2 Field Data

Common-source gathers of components $S_T^R R_{xy}$ and $S_T^R R_{yz}$ are given in Figure 7.29 and single traces are shown in Figure 7.30. The surface waves of both components are very comparable, whereas P-wave arrivals are suppressed in the $S_T^R R_{yz}$ component, although not as effectively as in the $S_T^R R_{xy}$ component. An apparent phase rotation of $\pi/2$ is observable.

7.5.3 Discussion

In order to quantify the relative changes in amplitude, I took the temporal derivative of the $S_T^R R_{xy}$ component, i.e. computed the particle acceleration, to bring the peak amplitudes of the arrivals in phase with the $S_T^R R_{yz}$ component. I then calculated the ratio of selected peak amplitudes of the RMS-normalized traces. The results are given in Table 7.2 and indicate, that ground roll has an normalized rotation-to-translation-ratio (nRTR) of almost one, while refracted P-waves are characterized by a very low nRTR. Rotational and translational components are linked by the local slowness by

$$\frac{\mathbf{v}}{\partial x} = -p_x \frac{\partial \mathbf{v}}{\partial t}, \quad \frac{\mathbf{v}}{\partial y} = -p_y \frac{\partial \mathbf{v}}{\partial t}$$

(7.1)

(see Equations 2.34 and 2.35). Therefore, the ratio of rotational to translational components can be used for local slowness estimation. I used an algorithm by Sollberger (2016) to compute the local slownesses based on the temporal derivative of the $S_T^R R_{xy}$ and the $S_T^R R_{yz}$ component (Figure 7.31): For simulated data, the local slowness of the ground roll is 0.0023 s/m, for direct P-wave at 100 ms about 0.0014 s/m and for the refracted P-wave about 0.00034 s/m. This slownesses correspond to apparent velocities of about 450 m/s, 700 m/s and 3000 m/s, which recovers the underlying velocity model very well. On field data, the dominant local slowness is about 0.003 s/m, which is equivalent to an apparent velocity of 300 m/s to 400 m/s. The refracted P-waves show an apparent local slowness of about 0.0004 s/m, which corresponds to 2500 m/s. These values are very similar to the velocities derived from travel time analysis (see Table 6.2).
Figure 7.29: Field data source gathers of components $S^t_z R^t_z$ and $S^t_z R^\omega_y$. A: direct P-wave, B: refracted P-wave, F: direct S-wave.

Figure 7.30: Traces at various offsets of source gathers shown in Figure 7.29 of the source-receiver pairs $S^t_z R^t_z$ and $S^t_z R^\omega_y$. A: direct P-wave, B: refracted P-wave, F: direct S-wave, G: refracted S-wave, I: ground roll.
Since ground roll is the dominant signal in the $S_z^r R_{z}^c$ component, it could be used for subtracting noise on the $S_z^c R_{z}^l$ component. Here, I present a brief outline of such a procedure: I first took the temporal derivative of the $S_z^l R_{z}^l$ component to compensate for differences in phase and amplitude. Then, I applied a trace normalization by the RMS value on every trace on both components. I then multiplied the amplitudes of the $S_z^l R_{z}^c$ component by a factor of 0.91 to match the ground roll signals of both components. This factor was found by trial and error. Finally, I subtracted the $S_z^l R_{z}^c$ component from the $\partial_t S_z^l R_{z}^l$ component. The result of the subtraction is given in Figure 7.32.

It can be observed that ground roll is indeed reduced and reflections, refractions and multiples are enhanced. The relative amplitude gain of reflections compared to ground roll is clearly visible where both events are intersecting: While ground roll was masking reflections in the $S_z^l R_{z}^l$ component, the reflections appear to be much more continuous in the difference plot (marked squares in Figure 7.32).

I applied the same procedure to real field data and show the result in Figure 7.33. In contrary to the synthetic study, I additionally applied a zero-phase bandpass filter from 1.5 Hz to 60 Hz to reduce numerical noise introduced by the subtraction. Further, I directly used the RMS-normalized traces for subtraction without applying an additional multiplication factor. The resulting difference plots clearly show the enhanced signal for P-wave refractions. However, the subtraction is not perfect. I expect two reasons for that: First, the scaling by RMS is a very simple approach and a much better match is probably obtained when using unnormalized data and the local slowness of the arrival which should be removed as a scaling factor. Second, the amplitude spectra of both components are not identical, as shown in Figure 7.34. Since the $S_z^l R_{z}^c$ component has a wider frequency spectrum, the wavelet is narrower, leading to an imperfect match. Note that such a ground roll suppression scheme can be applied in a trace-by-trace fashion and does not require any spatial sampling criteria to be fulfilled, unlike conventional coherent noise suppression techniques (e.g. f-k- or $\tau$-p-filtering).

---

**Figure 7.31:** Local apparent slowness estimation in inline-direction of a) synthetic data and b) real field data.
CHAPTER 7. RESULTS

Figure 7.32: Difference plot between $\partial_t S^1 R^t_{zz}$ and $S^1 R^\omega_{yz}$ components. A: direct (diving) P-wave, B: refracted P-wave, C: reflected P-wave, D: multiple reflected P-wave, E: mode-converted wave, F: direct (diving) S-wave, G: refracted S-wave, H: reflected S-wave, I: ground roll.

Figure 7.33: Difference plot between $\partial_t S^1 R^t_{zz}$ and $S^1 R^\omega_{yz}$ components. A: direct P-wave, B: refracted P-wave, F: direct S-wave.
Figure 7.34: a) Amplitude spectra of the $\partial_t S_z^1 R_z^1$ and $S_z^1 R_\omega^\gamma$ components of synthetic data and b) zoom-in of a trace of these components.
7.6 Rotational Source Around Inline Axis, Translational Receivers: $S_x^\omega R^t$

7.6.1 Numerical Simulation

In Figures 7.35, I compare common-source gathers of the components $S_z^t R_z^l$ and $S_z^\omega R_z^l$. At a first sight, direct waves and ground roll are completely removed, while P-wave reflections, refractions and their multiples are enhanced. The single trace in Figure 7.36 shows the relative amplification of reflections and their multiples (note the amplitude difference). However, the peak amplitudes of refracted and reflected signals of the $S_z^\omega R_z^l$ component are three to four orders of magnitude lower than other components with rotational components on either source- or receiver-side (e.g. $S_z^l R_y^w$, see Figure 7.28) or the pure translational $S_z^l R_z^l$ component.

![Figure 7.35](image-url): Simulated source gathers of the $S_z^l R_z^l$ and $S_z^\omega R_z^l$ components. A: direct (diving) P-wave, B: refracted P-wave, C: reflected P-wave, D: multiples, E: mode-converted waves, F: direct (diving) S-wave, G: refracted S-wave, H: reflected S-wave.

![Figure 7.36](image-url): Trace at 225m offset of source gathers shown in Figure 7.35 of the $S_z^l R_z^l$ and the $S_z^\omega R_z^l$ components. A: direct (diving) P-wave, B: refracted P-wave, C: reflected P-wave, D: multiples, E: mode-converted waves, F: direct S-wave, G: refracted S-wave, H: reflected S-wave, I: ground roll.
7.6. ROTATIONAL SOURCE AROUND INLINE AXIS, TRANSLATIONAL RECEIVERS: SxRXT

7.6.2 Field Data

Field data common-source gathers in Figure 7.37 and selected traces in Figure 7.38 confirm the observation from the synthetic data analysis that ground roll is less consistent and P-wave refractions are enhanced when using a rotational source around the inline axis. However, since I could not identify distinct reflections, I could not evaluate the effect on reflections and their multiples on real data. The Sω x RxT component shows a higher noise-level than the Sω x RxT component. A second source gather of this component is shown in Figure C2 in Appendix C, where again the P-wave refractions are enhanced.

Figure 7.37: Field data source gathers of components SωxRxT and SωxRxT. Note the enhanced P-wave refractions on the SωxRxT component.

7.6.3 Discussion

The detection of signal in the inline-rotational component (ωx) on the synthetic data is surprising. The rotational components around the inline axis in the body and at the free-surface are

\[ ω_x = \frac{1}{2} (\partial_y v_z - \partial_z v_y) \quad ω_x,FS = \partial_y v_z \]  (7.2)

respectively (see Equations 2.21 and 2.26). If the inline is exactly the source-receiver-line and side-scattering or laterally incoming reflections, for example because of a dipping reflector, are excluded, then \( \partial_y \) vanishes and therefore the rotational component around the inline-axis as well (see Table 7.1). Since the model used for the synthetic studies does not contain a dipping reflector and the source-receiver-line is exactly parallel to the x-axis, the events shown in Figure 7.35 are most probably numerical artifacts. This is additionally supported by the low amplitudes of the SωxRxT component. It follows from Equation 7.2 that inline-rotational components do exist for SH-waves with small angles of incidence apart from the free-surface. The inline-rotational component remains due to the vertical gradient of \( v_y \). I assume that either the array-size for estimating the spatial gradients was chosen
CHAPTER 7. RESULTS

Figure 7.38: Traces at four different offsets extracted from the common-source gathers of components $S_t R_z$ and $S_w R_z$ shown in Figure 7.37. B: refracted P-wave, F: direct S-wave, I: ground roll.

too large or that the grid-parametrization is too coarse for implementing the free-surface boundary-conditions adequately, leading to a poor estimation of the spatial gradients at the free-surface. On the other hand, the removal of direct body-waves and surface waves is physically meaningful, since they do not have a rotational component around the inline-axis.

Nevertheless, the real field data example shows effectively a slight suppression of (direct) surface waves and a relative amplification of refracted P-waves. I suppose that direct ground roll, for example Rayleigh waves, is suppressed by the rotational source, whereas the rough and probably tilted surface of the refractor causes transversally propagating P-waves. The remaining ground roll could be explained by side-scattered surface waves. However, the uncertainty of inaccurate estimations of the spatial gradients at the free-surface remains, which could lead to a remaining P-wave refraction, even if no transversally propagating waves are present.

Similar characteristics are visible when analyzing the component using a rotational source around the inline-axis and a transversal translational receiver ($S_w R_y$): Whereas the ground roll is partly removed, the signal (e.g. the refracted S-wave) remains well detectable when comparing to the $S_t R_y$ component, as can be seen in Figure 7.39. A second shot gather is given in Figure C3 in Appendix C.
7.6. ROTATIONAL SOURCE AROUND INLINE AXIS, TRANSLATIONAL RECEIVERS: $S_x^c R_y^T$

Figure 7.39: Field data common-source gathers of components $S_y^l R_y^l$ and $S_x^c R_y^l$. Note the distinct S-wave refraction on the $S_x^c R_y^l$ component. F: direct S-wave, G: refracted S-wave.
Conclusions and Outlook

8.1 Summary and Conclusions

In this thesis I analyzed 36-component seismic data, which entails three translational and three rotational components relative to the three Cartesian coordinate axes on both the source- and the receiver-side. I simulated a full 36-C data set using finite-difference modeling and also acquired real field data during two field campaigns. I used multi-component sources and multi-component receivers arranged in arrays in order to estimate spatial gradients on both the source- and the receiver-side. Spatial gradients of a seismic wavefield measured at the Earth’s free surface correspond to the rotational component of the wavefield. In the following explanations, the x-axis corresponds to the horizontal source-receiver-inline-axis (radial), whereas the y-axis is the transverse or horizontal crossline-axis and perpendicular to the x-axis. The z-axis is orthogonal to the x- and y-axes and corresponds to the vertical axis. The main findings of this thesis are:

- Rotational components on the source and receiver side are reciprocal but show a change in polarity (e.g. $S^t_z R^a_y = -S^a_y R^t_z$).
- Rotational components around the transverse axis ($\omega_y$) mainly contain Rayleigh waves and S-waves.
- The $\omega_y$ components can be used as a noise-model, which can be subtracted from the translational components (e.g. $S^t_z R^a_y$) in order to reduce ground roll and enhance the underlying signal.
- Rotational components enable estimates of the local slownesses.
- Crossline rotational components ($\omega_y$) can focus the surface wave dispersion curves.
- Inline rotational components ($\omega_x$) can be used to reduce horizontally and sub-horizontally propagating waves in the inline direction.
- The expected suppression of P-S mode-converted waves when using rotational sources could not be verified.

In addition, I designed a new seismic vector source device for speeding up and improving the multicomponent seismic data acquisition. This source uses the Galperin configuration, which is known, for example, from the Streckeisen triaxial seismometer STS-2. The source is therefore called the Galperin source. This configuration permits orthogonal source vectors with equal inclination angles and has the advantage of constant source-coupling. I compared data acquired using the Galperin source with a sledgehammer impact to data acquired using a metal prism, a wooden shear beam and a metal plate, all struck with the same sledgehammer. Using the Galperin source produces
very similar data as when using a metal prism or a metal plate, i.e. common-source gathers and frequency spectra compare very well. However, hodograms reveal that data based on the Galperin source have a slightly different polarization than data based on a metal prism or a metal plate. I attribute these variations to orientation errors and amplitude variations between the three strikes on the source.

As a small sub-project of this thesis I derived the approximate transfer function of the METR-03 rotational sensor. This transfer function was determined by taking rotation rates computed by differencing the outputs of closely-spaced geophones at the Earth’s free surface as a reference solution. After applying the transfer function to data from an independent experiment, surface waves and S-waves show a good match between rotation rates measured with the rotational sensor and the array-derived rotational rates. Nevertheless, the application of the transfer function leads to a larger misfit for weaker signals prior to the first S-wave arrivals.

8.2 Outlook

8.2.1 36-C Seismic Data

Based on the conclusions of this thesis and the findings of other rotational seismology studies (see Section 1.1), I assert that the inclusion of rotational components as well as traditional translational measurements in exploration seismology offers a significant benefit in arrival identification and imaging. Here, I present a selection of promising lines of research suggestions for potential future work:

- In this thesis, I followed a mainly experimental approach to explore the value of rotational components in exploration seismology. For future research, it will be instructive to derive the mathematical concepts to describe in detail the translational and rotational motions of different wave types as a function of angle of incidence, offset and azimuth to the source-receiver-axis.
- The synthetic studies in this thesis are based on very simplified subsurface models. I therefore suggest more advanced and extended synthetic studies, where also more complex geology and noise are considered.
- An additional modeling effort should be made for investigating the radiation patterns of rotational sources. This is important to better understand which wave types are generated in which directions and therefore which part of the subsurface is illuminated by those waves.
- The accurate estimation of spatial gradients is crucial for the computation of rotational components. However, this estimation may be degraded by coupling and positioning errors of the geophones within the receiver array. In addition, random noise on one receiver in the array, for example, due to a broken receiver channel, degrades the gradient estimate of the entire receiver-position. Similar issues may occur on the source-side. It is therefore necessary to develop algorithms which a) correct for coupling and positioning errors (Sollberger et al., 2015) and b) evaluate and qualify the traces within a receiver- or source-array and decide which sensors or sources should be used for computing the gradient, how they should be weighted and which order of finite-difference scheme is most appropriate.
- In the framework of this project, only a few source positions were analyzed. Since certain components show an amplification of reflections and refractions, they could be used for an improved imaging procedure or traveltime picking of both P- and S-waves for seismic refraction tomography.
- All field studies in this project were small-scale surveys with maximum source-receiver-offsets of 100 m. At these distances, the plane wave assumption is not always met due to the wavefront curvature. In addition, at short offsets many different wave types overlap in time, which hampers a detailed analysis of the wavefield. The shallow and high-contrast refractor at the survey location at H"onggerberg adds further complexity to the recorded data, for example, strong surface waves. A similar experiment but using larger offsets with higher-energy sources such as an accelerated weight-dropper or Vibroseis truck would be valuable to verify the synthetic
results. It is important to realize that 50% of all components can be obtained by just using vertical sources and multicomponent receivers. Since components with a reciprocal source-receiver-combination (e.g. $S^\omega_x R^\omega_y$ and $S^\omega_y R^\omega_x$), involving one rotational and one translational component are identical with the exception of a change in polarity, the number of measurable components increases to 75%. The only components necessarily requiring horizontal sources are purely translational components involving horizontal sources and two-sided rotated data involving rotation around the vertical axis. This is very promising for surveys, where no horizontal sources are available (e.g. extraterrestrial measurements) or where their application is economically not feasible. Conversely, it is also possible to obtain 75% of all components by using multicomponent sources and vertical receivers only.

- If rotational components can be used to suppress surface waves and to estimate the local slowness, then large and dense receiver arrays are obsolete for this purpose. One rotational sensor (or a small 1-C or 3-C geophone array) for measuring rotational components and one multicomponent geophone would be sufficient. For mini-arrays consisting of a few geophones or one rotational sensor and one 3-C geophone, nodal receivers might be a very valuable alternative to conventional, line-bound 3-C geophones. However, large aperture arrays are still needed for migrating steep dips.

- Since the array-based estimation of rotational components relies on the low-order Taylor-series expansion and the assumption that all receivers are planted equally and exactly at the free-surface, further development of rotational sensors has huge potential. Also, all 3-C geophones are subject to rotational motions themselves, which introduced an additional error to the spatial gradient estimation. If rotational sensors provide sufficient accuracy, one rotational sensor can replace the 3-C receiver array and thus present an economic advantage. Currently, new rotational sensors are under development (Bernauer et al., 2016, e.g.).

- Once reliable rotational sensors are available, they can also be applied in boreholes or buried in the subsurface, where the free-surface boundary-condition does not apply, which adds geometric freedom to the survey design. Furthermore, it would be interesting to compare these new rotation rate sensors with array-based rotation rates. In addition, buried 3-C geophones or sensors lowered in boreholes could be used to verify the current approach of expressing the vertical spatial derivative in terms of horizontal spatial gradients at the free-surface in order to obtain rotation rates.

- In general, rotational exploration seismology can be extended to borehole applications. For example, downhole seismic is a popular method for estimating local elastic parameters. Applying rotational sources could help to suppress mode-converted waves and therefore facilitate the detection of S-wave arrivals. For example, Langston and Ayele (2016) recently introduced vertical seismic wave gradiometry using boreholes.

- The ratio of translational to rotational components (RTR) might be indicative of specific wave types which could be useful for wavefield analysis. However, RTRs might be influenced by many factors, such as source type, source-receiver-distance and signal frequency (see Brokesova and Malek, 2015a).

- The components mainly amplifying surface waves and suppressing body waves (e.g. $S^\omega_x R^\omega_y$ or $S^\omega_y R^\omega_x$) can be used as a noise model and can be subtracted from noise-contaminated but signal-bearing components (e.g. $S^\omega_z R^\omega_x$). Rotational components around the crossline or transversal axis ($\omega_y$) can be used for suppressing ground roll, whereas inline rotation ($\omega_x$) could remove side-scattered noise (see Edme et al., 2013).

- Classic ray-based seismic tomography uses first arrival times to invert for the subsurface velocity. Whereas P-wave first arrival travel times are used for obtaining the P-wave velocity, the S-wave travel times are the input data for S-wave tomography. By using rotational sources and receivers, P-S mode-converted waves should be suppressed, which then facilitates the picking of
S-wave first arrivals. However, the analysis in this work showed that this is not straight-forward.

- Full-waveform inversion uses the complete or an enlarged part of the recording of the seismic signal to invert for the velocity and density distribution. Additional rotational components could be used for a joint-full-waveform inversion of multiple components to better constrain the inversion algorithm.
- Since the surface wave dispersion curves of rotational data analyzed in this thesis are indeed more focused than dispersion curves based on translational data, further investigation of the dispersive characteristics of rotational components might be beneficial for classic MASW techniques.
- Spatial gradients of the wavefield measured at the free-surface do not only allow the computation of rotational components, but also the divergence and thus the P-wave component $\nabla \phi$ of the wavefield. The simulated data and the data acquired in the field could therefore be used for isolating the P-wavefield from the S-wavefield.

### 8.2.2 Galperin Source

Although the idea of transferring the Galperin geophone configuration to the source side is valid to obtain a true multicomponent vector source, the source developed in the framework of this thesis could still be improved and adapted for other applications. I suggest the following investigations and additional modifications:

- Since the coordinate transformation from the Galperin configuration to the Cartesian system is sensitive to amplitude errors, all of the three strikes on the different faces of the source must have identical energy. In addition, the strikes must be normal to the faces. These conditions may not be perfectly given when using a hand-held sledgehammer. An accelerated weight-dropper, whose impact-direction can be tilted by 55°, may be useful for generating such repeatable strikes. However, strong source vectors with an angle of 35° to the horizontal plane are probably difficult to achieve and might lead to safety issues, since the source could move laterally.
- In principle, the Galperin configuration can also be achieved by using Vibroseis technology. Vibroseis signals could generate repeatable signals and are probably easier to apply than heavy weight-droppers.
- Besides amplitude variations, errors in azimuth and dip of the source position are crucial as well. In the field, it is not always possible to perfectly orient the source. A built-in tool on the source for measuring the orientation and tilt of the Galperin source might be useful to correct for these errors.
- The Galperin source developed in this project might be already suitable for small-scale seismic surveys with applications in engineering or environmental geophysics. However, the spikes at the base which couple the source to the ground need to be completely buried in order to avoid lateral movements or tilting of the source.
- All studies involving the Galperin source up to now were small-scale experiments under favorable conditions. To verify the technical, physical and economical applicability of the source, it should be employed during an industry project and compared to conventional techniques.
Acknowledgment

I express my sincere gratitude to my supervisors, Dr. Cédric Schmelzbach and David Sollberger for their expert and patient support during the entire project. They were always available for my questions, ideas and field-campaigns. Without their dedicated guidance, scientific creativity and critical questions, this thesis could have never been realized. It was a pleasure to work with you.

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Finally, but very fundamental, I extend my big thank-you to my parents Monica and Alex. Thanks to their support, my mathematical problems during my studies never involved monetary units.


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73


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Appendix

Appendix A

Figure A1: Common-source gathers of the $S_t^R R_x^i$ component generated using a shear beam, a metal prism and the new Galperin source. Note the high degree of congruency between the different sources.

Figure A2: Common-source gathers of the $S_t^R R_y^i$ component generated using a shear beam, a metal prism and the new Galperin source. Note the high degree of congruency between the different sources.
Appendix B

Table B1: Simulation parameters for synthetic study of Hönggerberg-survey.

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<th>Value</th>
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<td>simulation</td>
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<td>source</td>
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Table B2: Overview on source positions of the 36-C seismic survey on Hönggerberg. Accuracy of offset (GPS-accuracy): (±0.03m)

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<tr>
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<td>1</td>
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</tr>
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Appendix C

Figure C1: Traces at four different offsets of source ID 6 of the $S_y^R R_y^l$ and $S_z^W R_y^l$. Note the apparent $\pi/2$ phase rotation between both components. The same shift appears on the synthetic data shown in Figure 7.3.
Figure C2: Field data source gathers of components $S_z^t R_z^t$ and $S_x^o R_z^o$ (source ID 6). Note the distinct P-wave refraction on the $S_x^o R_z^o$ component.

Figure C3: Field data source gathers of source ID 7, showing $S_y^t R_y^t$ and $S_x^t R_y^t$ components.
Appendix D
Figure D1: Common-source gather of the $S^t_x R^t_x$ component. a) synthetic data, b) real field data.

Figure D2: Single trace of the $S^t_x R^t_x$ component. a) Synthetic (225 m offset) and b) real field data.

Figure D3: Frequency spectrum and f-k plot of the $S^t_x R^t_x$ component (real field data).
Figure D4: Common-source gather of the $S_x^t R_y^t$ component. a) synthetic data, b) real field data.

Figure D5: Single trace of the $S_x^t R_y^t$ component. a) Synthetic (225 m offset) and b) real field data.

Figure D6: Frequency spectrum and f-k plot of the $S_x^t R_y^t$ component (real field data).
Figure D7: Common-source gather of the $S^t_x R^t_z$ component. a) synthetic data, b) real field data.

Figure D8: Single trace of the $S^t_x R^t_z$ component. a) Synthetic (225 m offset) and b) real field data.

Figure D9: Frequency spectrum and f-k plot of the $S^t_x R^t_z$ component (real field data).
Figure D10: Common-source gather of the $S_y R_x^t$ component. a) synthetic data, b) real field data.

Figure D11: Single trace of the $S_y R_x^t$ component. a) Synthetic (225 m offset) and b) real field data.

Figure D12: Frequency spectrum and f-k plot of the $S_y R_x^t$ component (real field data).
Figure D13: Common-source gather of the $S_y R_y^t$ component. a) synthetic data, b) real field data.

Figure D14: Single trace of the $S_y R_y^t$ component. a) Synthetic (225 m offset) and b) real field data.

Figure D15: Frequency spectrum and f-k plot of the $S_y R_y^t$ component (real field data).
Figure D16: Common-source gather of the $S^t_y R^t_z$ component. a) synthetic data, b) real field data.

Figure D17: Single trace of the $S^t_y R^t_z$ component. a) Synthetic (225 m offset) and b) real field data.

Figure D18: Frequency spectrum and f-k plot of the $S^t_y R^t_z$ component (real field data).
Figure D19: Common-source gather of the $S_t R_t^t$ component. a) synthetic data, b) real field data.

Figure D20: Single trace of the $S_t R_t^t$ component. a) Synthetic (225 m offset) and b) real field data.

Figure D21: Frequency spectrum and f-k plot of the $S_t R_t^t$ component (real field data).
Figure D22: Common-source gather of the $S_z^t R_y^t$ component. a) synthetic data, b) real field data.

Figure D23: Single trace of the $S_z^t R_y^t$ component. a) Synthetic (225 m offset) and b) real field data.

Figure D24: Frequency spectrum and f-k plot of the $S_z^t R_y^t$ component (real field data).
Figure D25: Common-source gather of the $S_z R_z$ component. a) synthetic data, b) real field data.

Figure D26: Single trace of the $S_z R_z$ component. a) Synthetic (225 m offset) and b) real field data.

Figure D27: Frequency spectrum and f-k plot of the $S_z R_z$ component (real field data).
Figure D28: Common-source gather of the $S_t^x R_x^\omega$ component. a) synthetic data, b) real field data.

Figure D29: Single trace of the $S_t^x R_x^\omega$ component. a) Synthetic (225 m offset) and b) real field data.

Figure D30: Frequency spectrum and f-k plot of the $S_t^x R_x^\omega$ component (real field data).
**Figure D31:** Common-source gather of the $S^I_{x,y}R^o_{y}$ component. a) synthetic data, b) real field data.

**Figure D32:** Single trace of the $S^I_{x,y}R^o_{y}$ component. a) Synthetic (225 m offset) and b) real field data.

**Figure D33:** Frequency spectrum and f-k plot of the $S^I_{x,y}R^o_{y}$ component (real field data).
Figure D34: Common-source gather of the $S^T_x R^\omega_z$ component. a) synthetic data, b) real field data.

Figure D35: Single trace of the $S^T_x R^\omega_z$ component. a) Synthetic (225 m offset) and b) real field data.

Figure D36: Frequency spectrum and f-k plot of the $S^T_x R^\omega_z$ component (real field data).
Figure D37: Common-source gather of the $S^t_y R^\omega_x$ component. a) synthetic data, b) real field data.

Figure D38: Single trace of the $S^t_y R^\omega_x$ component. a) Synthetic (225 m offset) and b) real field data.

Figure D39: Frequency spectrum and f-k plot of the $S^t_y R^\omega_x$ component (real field data).
Figure D40: Common-source gather of the $S_y^t R_y^\omega$ component. a) synthetic data, b) real field data.

Figure D41: Single trace of the $S_y^t R_y^\omega$ component. a) Synthetic (225 m offset) and b) real field data.

Figure D42: Frequency spectrum and f-k plot of the $S_y^t R_y^\omega$ component (real field data).
Figure D43: Common-source gather of the $S_y \omega R_z$ component. a) synthetic data, b) real field data.

Figure D44: Single trace of the $S_y \omega R_z$ component. a) Synthetic (225 m offset) and b) real field data.

Figure D45: Frequency spectrum and f-k plot of the $S_y \omega R_z$ component (real field data).
Figure D46: Common-source gather of the $S^I_z R_x^\omega$ component. a) synthetic data, b) real field data.

Figure D47: Single trace of the $S^I_z R_x^\omega$ component. a) Synthetic (225 m offset) and b) real field data.

Figure D48: Frequency spectrum and f-k plot of the $S^I_z R_x^\omega$ component (real field data).
**Figure D49**: Common-source gather of the $S_t^R R_y^w$ component. a) synthetic data, b) real field data.

**Figure D50**: Single trace of the $S_t^R R_y^w$ component. a) Synthetic (225 m offset) and b) real field data.

**Figure D51**: Frequency spectrum and f-k plot of the $S_t^R R_y^w$ component (real field data).
Figure D52: Common-source gather of the $S^I_z R^\omega_z$ component. a) synthetic data, b) real field data.

Figure D53: Single trace of the $S^I_z R^\omega_z$ component. a) Synthetic (225 m offset) and b) real field data.

Figure D54: Frequency spectrum and f-k plot of the $S^I_z R^\omega_z$ component (real field data).
APPENDIX

Figure D55: Common-source gather of the $S_{x}^{\omega}R_{x}^{t}$ component. a) synthetic data, b) real field data.

Figure D56: Single trace of the $S_{x}^{\omega}R_{x}^{t}$ component. a) Synthetic (225 m offset) and b) real field data.

Figure D57: Frequency spectrum and f-k plot of the $S_{x}^{\omega}R_{x}^{t}$ component (real field data).
Figure D58: Common-source gather of the $S_{xy}^{-} R_t^i$ component. a) synthetic data, b) real field data.

Figure D59: Single trace of the $S_{xy}^{-} R_t^i$ component. a) Synthetic (225 m offset) and b) real field data.

Figure D60: Frequency spectrum and f-k plot of the $S_{xy}^{-} R_t^i$ component (real field data).
Figure D61: Common-source gather of the $S^\omega_x R^t_z$ component. a) synthetic data, b) real field data.

Figure D62: Single trace of the $S^\omega_x R^t_z$ component. a) Synthetic (225 m offset) and b) real field data.

Figure D63: Frequency spectrum and f-k plot of the $S^\omega_x R^t_z$ component (real field data).
Figure D64: Common-source gather of the $S_y^\omega R_x^\ell$ component. a) synthetic data, b) real field data.

Figure D65: Single trace of the $S_y^\omega R_x^\ell$ component. a) Synthetic (225 m offset) and b) real field data.

Figure D66: Frequency spectrum and f-k plot of the $S_y^\omega R_x^\ell$ component (real field data).
Figure D67: Common-source gather of the $S^\omega_{y}R^t_{y}$ component. a) synthetic data, b) real field data.

Figure D68: Single trace of the $S^\omega_{y}R^t_{y}$ component. a) Synthetic (225 m offset) and b) real field data.

Figure D69: Frequency spectrum and f-k plot of the $S^\omega_{y}R^t_{y}$ component (real field data).
Figure D70: Common-source gather of the $S_y^\omega R_z^t$ component. a) synthetic data, b) real field data.

Figure D71: Single trace of the $S_y^\omega R_z^t$ component. a) Synthetic (225 m offset) and b) real field data.

Figure D72: Frequency spectrum and f-k plot of the $S_y^\omega R_z^t$ component (real field data).
**Figure D73**: Common-source gather of the $S_z^R R_x^t$ component. a) synthetic data, b) real field data.

**Figure D74**: Single trace of the $S_z^R R_x^t$ component. a) Synthetic (225 m offset) and b) real field data.

**Figure D75**: Frequency spectrum and f-k plot of the $S_z^R R_x^t$ component (real field data).
Figure D76: Common-source gather of the $S_{z}^{R} R_{y}^{f}$ component. a) synthetic data, b) real field data.

Figure D77: Single trace of the $S_{z}^{R} R_{y}^{f}$ component. a) Synthetic (225 m offset) and b) real field data.

Figure D78: Frequency spectrum and f-k plot of the $S_{z}^{R} R_{y}^{f}$ component (real field data).
Figure D79: Common-source gather of the $S_z^w R_z^t$ component. a) synthetic data, b) real field data.

Figure D80: Single trace of the $S_z^w R_z^t$ component. a) Synthetic (225 m offset) and b) real field data.

Figure D81: Frequency spectrum and f-k plot of the $S_z^w R_z^t$ component (real field data).
Figure D82: Common-source gather of the $S_{x}^{\omega} R_{x}^{\omega}$ component. a) synthetic data, b) real field data.

Figure D83: Single trace of the $S_{x}^{\omega} R_{x}^{\omega}$ component. a) Synthetic (225 m offset) and b) real field data.

Figure D84: Frequency spectrum and f-k plot of the $S_{x}^{\omega} R_{x}^{\omega}$ component (real field data).
Figure D85: Common-source gather of the $S_{x}^{\omega} R_{y}^{\omega}$ component. a) synthetic data, b) real field data.

Figure D86: Single trace of the $S_{x}^{\omega} R_{y}^{\omega}$ component. a) Synthetic (225 m offset) and b) real field data.

Figure D87: Frequency spectrum and f-k plot of the $S_{x}^{\omega} R_{y}^{\omega}$ component (real field data).
Figure D88: Common-source gather of the $S^x_R R^o_z$ component. a) synthetic data, b) real field data.

Figure D89: Single trace of the $S^x_R R^o_z$ component. a) Synthetic (225 m offset) and b) real field data.

Figure D90: Frequency spectrum and f-k plot of the $S^x_R R^o_z$ component (real field data).
Figure D91: Common-source gather of the $S_y^\omega R_x^\omega$ component. a) synthetic data, b) real field data.

Figure D92: Single trace of the $S_y^\omega R_x^\omega$ component. a) Synthetic (225 m offset) and b) real field data.

Figure D93: Frequency spectrum and f-k plot of the $S_y^\omega R_x^\omega$ component (real field data).
Figure D94: Common-source gather of the $S_y^\omega R_y^\omega$ component. a) synthetic data, b) real field data.

Figure D95: Single trace of the $S_y^\omega R_y^\omega$ component. a) Synthetic (225 m offset) and b) real field data.

Figure D96: Frequency spectrum and f-k plot of the $S_y^\omega R_y^\omega$ component (real field data).
Figure D97: Common-source gather of the $S_{y}^\omega R_{z}^\omega$ component. a) synthetic data, b) real field data.

Figure D98: Single trace of the $S_{y}^\omega R_{z}^\omega$ component. a) Synthetic (225 m offset) and b) real field data.

Figure D99: Frequency spectrum and f-k plot of the $S_{y}^\omega R_{z}^\omega$ component (real field data).
Figure D100: Common-source gather of the $S^ωR^ω_z$ component. a) synthetic data, b) real field data.

Figure D101: Single trace of the $S^ωR^ω_z$ component. a) Synthetic (225 m offset) and b) real field data.

Figure D102: Frequency spectrum and f-k plot of the $S^ωR^ω_z$ component (real field data).
Figure D103: Common-source gather of the $S_z^\omega R_y^\omega$ component. a) synthetic data, b) real field data.

Figure D104: Single trace of the $S_z^\omega R_y^\omega$ component. a) Synthetic (225 m offset) and b) real field data.

Figure D105: Frequency spectrum and f-k plot of the $S_z^\omega R_y^\omega$ component (real field data).
Figure D106: Common-source gather of the $S^ω_z R^ω_z$ component. a) synthetic data, b) real field data.

Figure D107: Single trace of the $S^ω_z R^ω_z$ component. a) Synthetic (225 m offset) and b) real field data.

Figure D108: Frequency spectrum and f-k plot of the $S^ω_z R^ω_z$ component (real field data).
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