Two element interferometer with TV-antennas observing the sun at 435 MHz

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Two Element Interferometer with TV-antennas observing the sun at 435 MHz

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Abstract
The aim of this work was to build a two element interferometer with conventional instruments such that it would be accessible for amateur radio telescopy. As spectrometer we mainly used the in house built CALLISTO, but we also used the Argos FFT-Spectrometer and the AR5000 to compare and improve the measurements. After adjusting and solving a few problems which occurred at the beginning of the experiment, the first few measurements with the CALLISTO spectrometer were done and calculating the length of the baseline was possible. But the signal was not clean enough to do further calculations, such as the angular size of the sun. It is only at the end of this work, that the measurements with the AR5000 were improved to the point that further calculations were possible. Finally the results from the different spectrometers were compared.
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1 Introduction

It was in the experiments of Karl G. Jansky that radio astronomy had its beginnings in the early 1930s. Jansky was an engineer at the Bell Telephone Laboratories and was assigned the problem of studying the direction of arrival of thunderstorm static. The first results Jansky reported, he identified three groups of static: (1) static from local thunderstorm, (2) static from distant thunderstorm and (3) "... a steady hiss type static of unknown origin." The third type showed peaks occurring in 20-min intervals as the antenna beam swept through the plane of our galaxy. Finally one discovered that the signal actually came from the center of the Milky Way and shortly after that one realized that the sun was a radio wave emitting object too. Grote Reber, another pioneer of radio astronomy, did very significant work in repeating Jansky’s work and conducting the first sky survey in the radio frequencies. After World War II substantial improvements in radio astronomy technology were made especially in Europe, the United States and Australia and the field of radio astronomy began to blossom.

One of the most notable developments came in 1946 with the introduction of radio interferometry. An interferometer out of radio telescopes is used to reach a higher angular resolution such that pictures of closely situated or spatially broad radio sources get a higher resolution. The signals from all radio telescopes are then brought together and superimposed and can then be evaluated by fourier transformation.

So to build an interferometer one needs at least two telescopes or as in the case of this work two TV-antennas, which obviously receive radio waves too. For observing a moving object in the sky, such as the sun, one can either follow it, i.e. the telescopes move and are always directed towards the object, or one can stay fixed on a point of its path - mostly the highest point above the horizon. In this experiment the second possibility was used and it yields an interferometer pattern which changes in intensity, rising when the object is moving towards the point the telescopes are fixed on and decreasing when moving away. With these interferometer pattern one is able to draw conclusions over the size of the object and the length of the baseline - line on which the telescopes are situated. Here the baseline was situated on a east-west line, in order to simplify the interpretation of the data.

2 Theory

Interferometry has proven to be crucial in attaining high angular and spectral resolution for certain classes of observation, particularly in mapping at radio frequencies and measuring the angular sizes of stars. In this experiment the sun was observed with a two-element interferometer and in the following a brief section shall introduce the theory.

![Figure 1: A basic two-element interferometer](image)

The figure above illustrates a simple two-element interferometer, where $L$ is the length of the
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baseline, $\phi$ the angle between baseline and wave front from source and $\Delta s$ is the difference of the path length which leads to the phasendifference between the two antenna signals. Assuming one had a point source and monochromatic radiation the voltage at the two antennas would be:

\[
V_A(t) = E_0 \cdot e^{i(\omega t - \Theta)},
\]
\[
V_B(t) = E_0 \cdot e^{i\omega t},
\]

where

\[
\Theta = 2\pi \frac{\Delta s}{\lambda} = 2\pi \sin(\phi) \frac{L}{\lambda}
\]

is the phasendifference. The two antenna signals are first added, then quadratically detected and fed through the integrator with the integration time $\tau$. In the case of the experiment logarithmic detectors (CALLISTO and AR5000) were used, but the figures below are qualitative and so the conclusions stay the same.

For the output voltage $U_R$ one gets:

\[
U_R \propto S = \frac{1}{\tau} \int_0^\tau (V_A(t) + V_B(t)) \cdot (V_A(t) + V_B(t))^* dt
\]
\[
= 2E_0^2(1 + \cos(\Theta))
\]
\[
= 2E_0^2(1 + \cos(2\pi \sin(\phi) \frac{L}{\lambda}))
\]

Therefore the output voltage depends on $\phi$ and we get a interferometer pattern which looks like figure 2.

![Figure 2: Interferometer pattern](image)

But this is only the case if the antennas track the source. When the antennas are fixed to one point in the sky, hence a transit instrument, the interferometer pattern will be as shown in figure 3. Since in this experiment the sun will be observed, an interferometer pattern such as (b) is expected.

![Figure 3: Interferometer pattern](image)

The values indicated in (b) enable the calculation of the visibility function and consequential the angular size of the sun.
3 Setup

The general setup of the experiment is shown in figure 2. During the experiment certain things were changed depending on the measurements which were done and throughout the report any explained changes will always refer to this figure.

At first the antennas were placed at a distance $s$ of about 71 m and a frequency program (FQP) was written around 510 MHz, since the radio-noise was relatively low there. But then a few problems with the amplifiers occurred, with the main problem that the factor of amplification was too low compared to the loss in the cables and the contacts. Finally the LNA 435 amplifiers were installed and a FQP was written around 435 MHz. At this moment the experiment was like in the figure above, but then another problem occurred. The measurements did not show any fringes in the interferometer pattern, it was as if one was measuring DC. Some calculations showed that because of the size of an object such as the sun a high resolution can be disadvantageous, since one is in principle measuring two fringes at once. As a result of that we shortened the baseline length $s$ to roughly 29.5 m and we shortened the cables to half the length such that the loss was about half as high. Moreover an equidistant FQP was written to simplify the later analysis of the data. The FQP was generally in steps of 0.25 MHz from 430 to 440 MHz, depending on the daily interferences certain frequencies were left out.

The Bias-T’s were used to feed the amplifiers situated just after the antennas with electrical current from a Power-Supply-Unit (PSU1) of 12 V.

The cables coming from the antennas were brought together with a Power Combiner, that was a $\lambda/4$-Transformer for 70 cm.

After going through another amplifier (Kuhne +20 dB), which was fed by PSU2 of again 12 V, and an attenuator (-10 dB) the signal was brought in to CALLISTO. From CALLISTO the signal was taken out on a RS232 and connected to the host (conventional PC).

When using the Argos FFT Spectrometer the signal was taken from CALLISTO. First it passed a high-pass filter with a threshold frequency of 300 MHz and then it went through a low-pass filter with a threshold frequency of 1000 MHz which gave a band-pass filter from 300 MHz to 1000 MHz. Finally the signal was amplified again (Kuhne +20 dB, 5-1500 MHz) before reaching Argos.

When the AR5000 was used the signal did not go through CALLISTO and the attenuator was

Figure 4: General setup of the experiment
taken out. Hence the signal was taken directly after the Kuhne amplifier and connected to AR5000. From there the signal was taken out on a 10.7 MHz output and passed through a logarithmic detector (25 mV/dB) converting the signal to volts. Then it went through the Digital-Multimeter TTL1705 before finally reaching the host by a RS232 connection.

3.1 Instruments

As was said in the introduction, the experiment was mainly built with conventional instruments. Here all the used devices are listed and described how they work or how they were mounted.

3.1.1 TV-Antennas

For the experiment two EB 66 UHF TV-antennas were used. They work on the channels 21-37, the half power beam width is 28° for the horizontal and 31° for the vertical polarization and their length is approximately 3 m. To make sure that they actually receive in the expected range, they were measured with the Network-Analyser (NWA) and confirmed that there is a good reception between 400 and 600 MHz. The measurements for both antennas are shown in the following figure.

![Measurement of east antenna](image1)

![Measurement of west antenna](image2)

**Figure 5:** Standing wave measurements of antennas with NWA

Due to the fact that the baseline had to be reduced the east antenna was mounted on the shack and the west antenna was mounted on the scaffolding as shown in figure 6(b).

![Antennas](image3)

**Figure 6:** The two antennas (a) and their mounting (b)
3.1.2 Amplifiers

Shortly after the antennas the signal was amplified with the LNA 435 amplifiers. They were supplied with a 12 V current coming from the shack. With a Bias-T the current was first put in the cable and just before the amplifier taken out with a second Bias-T. Over a cable (the red cable in the figure) the current was then fed to the amplifier.

![Image of amplifiers with Bias-T](image)

**Figure 7:** The low noise amplifiers with the Bias-T

Measuring them out with the NWA, they showed as expected a maximum amplification of +15 dB at 435 MHz, but the amplification dropped fast around 435 MHz, such that the amplifiers act as filters. As one can see in figure 8 (a) the signal gets damped with -7.1 dB at 500 MHz. Therefore the frequency band on which the measurements took place had to be relatively narrow. So the measurements were done between 430 and 440 MHz.

![Image of gain measurements](image)

(a) Measurement of east amplifier (#1)  
(b) Measurement of west amplifier (#2)

**Figure 8:** Gain measurements of amplifiers with NWA

3.1.3 Cables

The used cables were normal 50 m coaxial cables which were purchased in a supermarket. After reducing the length of the baseline the cables were shortened to 25 m and measured out again with the NWA to see how big the loss is. For the east cable the loss at 435 MHz was -7.9 dB and for the west cable it was -6.3 dB. The measurements are shown in figure 9. The cables were then brought together with a Power Combiner as shown in the setup above.

3.1.4 CALLISTO

The radio spectrometer CALLISTO (Compact Astronomical Low-frequency, Low-cost Instrument for Spectroscopy in Transportable Observatories) is a dual-channel frequency-agile receiver based on
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Figure 9: Attenuation measurements of cables with NWA

commercially available consumer electronics. Its major characteristic is the low price for hardware and software, and the short assembly time, both two or more orders of magnitude below existing spectrometers. The instrument is sensitive at the physical limit and extremely stable. The total bandwidth is 825 MHz (45-870 MHz) and the width of individual channel is 300 kHz. A total of up to 1000 measurements can be made per second. The spectrometer is well suited for solar low-frequency radio observations pertinent to space weather research. Five instruments of the type were constructed until now and put into operation at several sites, including Bleien (Zurich) and NRAO (USA).[1]

3.1.5 Argos FFT-Spectrometer

ARGOS is a FFT radio spectrometer using one of the latest designed FPGA circuits containing huge hw-resources, and a GHz sampler from Acqiris company in Geneve. The sampler is working with 2 Gigasamples per second producing a datastream of 8 bits. These 2 Gigabytes/sec data stream will be fourier-transformed in real time within the FPGA. The complex results of the FFT will then be converted into intensity and integrated during about 2msec. Every 2msec we can get a full spectrum with 1 GHz bandwidth having up to 16384 channels. Other input frequencies above 1GHz can be observed using a heterodyne down-converter.[4]

3.1.6 AR5000

The AR5000 receiver has a high sensitivity and a strong signal handling across a large frequency bandwidth of 10 kHz - 2.6 GHz. The width of an individual channel is 220 kHz. It has an all mode reception of AM, FM, USB, LSB and CW and is equiped with a Numeric-Controlled-Oscillator (NCO) with tuning steps down to 1 Hz.[5]

Figure 10: (a) CALLISTO Spectrometer; (b) Receiver AR5000
4 Results

The results are listed according to the Spectrometer which was used. The first measurements were done with the Callisto Spectrometer and on a few days measurements were done simultaneously with the Argos FFT-Spectrometer. After that the AR5000 Spectrometer was used alone.

The interferences which had the most influence on the measurements were the amateur radio, the weather and the temperature variations in the shack. A lot of the amateur radio was exactly in the bandwidth the measurements took place in and it is especially on weekends were the interference was highest. The weather is a natural influence where not much can be done about. The temperature in the shack was regulated by an air conditioner and since the instruments were not insulated a certain temperature difference can have an effect on the detectors. Throughout the day it was not a problem, but at night an effect was visible as will be shown later.

4.1 With CALLISTO

The first usable measurements presented in figure 11 show the fringes of the sun around the culmination point. Throughout the measurement there was a lot of interference, therefor the section which was used for further analysis is only 40 minutes. The time of the first few measurements was from 10:00 UT to 12:00 UT were the main thing was to see the fringes. The first two graphs in the figure (b) show the signal first in digits and then the conversion to decibel (dB). Then the signal is entlogarithmized and Fast-Fourier-transformed (FFT), what is shown in the last graph of the figure (b). The peak gives us the fringefrequency $f$.

With the fringefrequency $f = 0.002917$ Hz the baseline length $L$ can be calculated and the result was $L_{21th} = 29.4 \pm 0.5$ m. This is close to the value $L_{meas.} = 29.5 \pm 0.2$ m which was measured manually.

For the following days the time of the measurements was increased from 08:30-14:00 UT to see if the slope of the visibility function is observable. A selection of measurements done with Callisto are shown in figure 12.

Unfortunately the rise of the visibility function was not observable, in some cases such as on may 27th even a drop of intensity in the patterns was visible. This of course excludes any calculation concerning the angular size of the sun. All measurements with CALLISTO were influenced by interferences and showed that something on the setup had to be improved, if any further calculations wanted to be done. Nevertheless in most of the measurements the interferometer pattern was visible and analyzable. For each evaluated interferometer pattern the baseline length was calculated and the average value was $\langle L \rangle = 29.79 \pm 0.30$ m, which is not that far away from the manually measured baseline length.
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4.2 With Argos FFT Spectrometer

Unfortunately the measurements with the Argos FFT Spectrometer were done on days were the interference was particularly high. But quiet astonishingly fringes were well visible and calculating the baseline length did not cause any problems. Out of the measurements which were done the result from may 24th is shown in figure 13 and looking at the analysis of the best part of the signal one can see that the fringefrequency is \( f = 0.00283 \) Hz. This leads to a calculated baseline length of 28.6 ± 0.5 m.

The average baseline length of the measurements done with Argos was \( \langle L \rangle = 28.72 \pm 0.30 \) m, which is not as good as the length obtained from the measurements with CALLISTO. But considering the interference there was on those days, the result is acceptable. To show how much interference there was the measurement with CALLISTO on may 24th is shown in the figure 14.

As one can observe, there is a huge difference between the interferometer pattern done with Argos in figure 13(a) and the one with CALLISTO in figure 14. The reason for this lies most likely in the different bandwidths the two spectrometers have. Whereas CALLISTO has a bandwidth of 300 kHz, the Argos FFT-Spectrometer has a bandwidth of 61 kHz allowing it to be much more precise.
4.3 With AR5000

After the measurements with CALLISTO and Argos, the communication receiver AR5000 was connected directly after the Kuhne without the attenuator and without passing through CALLISTO (figure 4). Here the measurements were slightly better especially concerning the visibility function, but as one can see in the graphs of figures 15 and 16 there was still a lot of interferences. It is to be remarked that the measurements from May 30th were done at 431.63 MHz, whereas the measurements of June 4th and 5th were done at 436.75 MHz.

Out of all evaluated interferometer patterns the average baseline length of the measurements done with AR5000 was \( \langle L \rangle = 30.02 \pm 0.30 \) m. This result is higher than the one with the measurements with CALLISTO and it is further away from the measured length of 29.5 m. There can be different reasons for this. On one hand, the calculation for the baseline length is very sensitive to the fringe frequency \( f \) such that changes of the magnitude \( 10^{-4} \) can change the length by over a meter. That means that defining \( f \) is always bound to an error of at least \( \pm 40 \) cm for the length. On the other hand, not all measurements have the same quality, depending mainly on the weather and the amount of interference there was on the day of that measurement.

For the visibility function three measurements out of five were usable. In figure 16 (a) one can see a nice rise to a peak which is situated just after 10:30 UT. To determine the visibility \( V \), one has to determine \( S_{\text{max}} \) and \( S_{\text{min}} \), which are the maximum and minimum values of the fringes at the peak respectively, and then subtract the background \( S_B \), such that \( S_{\text{max}} \) and \( S_{\text{min}} \) are normalized. The values shown in the graphs are given in a power factor, because the signal first had to be entlogarithmized. With the wavelength \( \lambda \) at which the measurements took place and the length of the baseline, where \( L_{\text{meas.}} \) was used, the angular size \( \phi \) of the sun can be calculated. The result was the following:

<table>
<thead>
<tr>
<th>Date</th>
<th>( S_{\text{max}} )</th>
<th>( S_{\text{min}} )</th>
<th>( S_B )</th>
<th>( V )</th>
<th>( \lambda ) (m)</th>
<th>( \phi ) (Degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 30th</td>
<td>23.594</td>
<td>21.340</td>
<td>12.337</td>
<td>0.11123</td>
<td>0.69504</td>
<td>0.992 \pm 0.130</td>
</tr>
<tr>
<td>June 4th</td>
<td>17.014</td>
<td>14.655</td>
<td>12.823</td>
<td>0.39157</td>
<td>0.68689</td>
<td>0.811 \pm 0.130</td>
</tr>
<tr>
<td>June 5th</td>
<td>17.914</td>
<td>16.383</td>
<td>14.191</td>
<td>0.25883</td>
<td>0.68689</td>
<td>0.896 \pm 0.130</td>
</tr>
</tbody>
</table>

The average angular size is therefore \( \langle \phi \rangle = 0.900 \pm 0.08 \) degrees, which is slightly too high. More precise experimental data shows that the angular size of the sun for radio waves is around 10-20% higher than the angular size of the sun at optical wavelengths. That means that the size here should be between 0.55 and 0.6 degrees.

It is only at the end of this work that by connecting CONRAD in-line amplifiers of +10 dB directly after the LNA 435 amplifiers, to improve the SNR, and measuring at the frequency 458.7 MHz with a slightly shorter baseline of \( L_{\text{meas.}} = 22.4 \pm 0.1 \) m, that the interferometer pattern showed a very low amount of interference. The result is shown in figure 17 and comparing it to the figures 15 (a) and 16 (a) one can see that the interferometer pattern was improved significantly. The calculations gave a baseline length of \( L = 22.58 \pm 0.30 \) m, which is extremely close to the measured baseline length, and an angular size of \( \phi = 0.570 \pm 0.050 \) degrees. The angular size of the sun is precisely in the range of expectation and is therefore a very good result.
Figure 15: Measurements of May 30th 2006 with AR5000

Figure 16: Measurements of June 5th 2006 with AR5000

Figure 17: Measurements of June 19th 2006 with AR5000
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On June 8th a signal was measured between 17:00 and 24:00 UT. Since the signal was too strong to be coming from the sky, it had to be some kind of interference. One found out that it was the air conditioner which was situated directly above the detector which caused the measured fringes shown below.

![Figure 18: Influence of temperature changes on measurements (June 8th 2006)](image)

5 Comparing the Results

Before comparing the results, the differences between the Spectrometers have to be illustrated again and the most important are listed in the following table:

<table>
<thead>
<tr>
<th></th>
<th>CALLISTO</th>
<th>Argos FFT Spectrometer</th>
<th>AR5000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Frequency agile</td>
<td>Digital Frequency -&gt; FFT</td>
<td>Single Frequency</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>300 kHz</td>
<td>61 kHz</td>
<td>220 kHz</td>
</tr>
<tr>
<td>Detector</td>
<td>logarithmic</td>
<td>linear</td>
<td>logarithmic</td>
</tr>
</tbody>
</table>

Comparing first the results between CALLISTO and Argos, one can observe that the interferometer patterns are very much alike. The big difference was that on days with a lot of interference measurements with Argos were still conclusive whereas for CALLISTO the patterns showed so much interference that it excluded any further analysis. This quiet certainly due to the smaller bandwidth of Argos. Nevertheless, since the measurements with both spectrometers did not show any rise in the pattern, especially the ones with Argos, one knew that the signal had to be improved, if a rise ought to be observed.

Consequently the biggest difference between the previous results and AR5000 is in terms of the visibility function. The previous measurements did not show any rise in the interferometer pattern and therefore the visibility function and with that the angular size could not be determined. Connecting the AR5000 and removing the attenuator improved the signal and a rise in the interferometer pattern was visible. It seems that the AR5000 was able to handle the stronger signal better than the CALLISTO, where one should not forget that the AR5000 only reads a single frequency. During the measurements with CALLISTO the attenuator of -10 dB was once replaced by an attenuator of -3 dB, but the signal was too strong and the interferences were too high, to the point that nothing was observable. As consequence the attenuator of -10 dB was put in again. With the AR5000 the attenuator was not necessary and that must be the reason why the signal in the interferometer pattern was improved.

Nevertheless the results of the baseline length with the measurements from CALLISTO were good and were even slightly better than the results from Argos and AR5000.

As explained before, at the end of this work a second amplifier was connected just after the LNA 435 amplifier and had an extraordinary effect on the measurements. The influence of the interferences was less visible, the fringes were clear and a nice rise in the interferometer pattern was observable (figure 17). What would be interesting now is to see what the effect of this setup would have on measurements with CALLISTO.
6 Conclusion

The measurements done with CALLISTO and Argos were only suitable for calculating the length of the baseline. Since the interferometer pattern did not show any rise the visibility function and hence the angular size of the sun could not be determined. But one should note that the reason for this was the bad signal, since the measurements with Argos, which is much more powerful, did not show any difference. Consequently the best measurements were done with the AR5000, where additionally the calculation of the angular size was possible. The results were far from being perfect with a average baseline length of 30.02 m and an average angular size of 0.90 degrees, but nevertheless calculations were possible.

At the end of this work the measurements with the AR5000 were improved further and the calculations were more precise and as said before, it would be interesting doing measurements with the same setup with CALLISTO. This might improve the interferometer pattern even though measuring on a bandwidth of again 10 MHz might increase the interferences.

The biggest problems were mainly the strong influence of the interferences, the weather and the temperature. The signal was improved by connecting a further amplifier just after the antennas. This showed that it is essential to amplify the signal enough just after the antenna. On the other hand further improvements could be done by insulating the instruments, such that the temperature influence is kept to a minimum. And obviously there is a higher probability of doing good measurements on clear sunny days.

References


Appendix

A Calculations

For all the calculations in this report Matlab was used. For the analysis of the signal by Fast-Fourier-Transformation m-files were written for the different spectrometers respectively and are to be found in the following sections. In the last two sections the calculation of the baseline length and the visibility function with the angular size is shown.

A.1 FFT with CALLISTO

```matlab
function K = fourier(k,x,y,N)
% Fourier of the FFT of the measurements with CALLISTO -> Frequency ogile
% x: intensity vector
% y: time vector
% N: amount of interpolation points

% Ploting the signal in its original state in digits
subplot(2,1,1)
title('2 Element Interferometers, Eisele, Callisto, mm. , MHz, 2006/07., between ...1., ...2., UT', 'FontSize',12)
grid on
xlabel('Time t / hours'), ylabel('Digits'), legend('Signal')

% Ploting the signal in its original state in dB
subplot(2,1,2)
x=5000000/(256^500); % converting the digits to dB
plot(x,10
grid on
xlabel('Time t / hours'), ylabel('dB'), legend('Signal')

% Ploting FFT of the Signal with N interpolation points
subplot(2,1,3)
N=1000; % N
x=log10(abs(w)); % logaritmizing the signal, from dB to a power factor
FFT(w), x
real(log10(w), x); % ploting the FFT on a graph with a logaritimic x-axis
grid on
xlabel('Frequency f / Hz'), ylabel('Counts'), legend('FFT, N = 1000'), int2str(N))
```

**Figure 19:** M-File of the FFT with CALLISTO

A.2 FFT with Argos

Since the Argos FFT Spectrometer works with a linear detector, the signal does not have to be converted and entlogarithmized, so that the signal can be FFT directly.

```matlab
function g = argosfft(x,y,N)
% argosfft(x,y,N)
% x: time vector
% y: intensity vector in digits
% N: number of interpolation points

% Ploting the signal in its original state in digits
subplot(2,1,1)
title('2 Element Interferometers, Eisele, Argos FFT Spectrometer, mm. , MHz, 2006/07., between ...1., ...2., UT', 'FontSize',12)
grid on
xlabel('Time t / hours'), ylabel('Digits'), legend('Signal')

% Ploting the signal in its original state in dB
subplot(2,1,2)
x=5000000/(256^500); % FFT of the signal with the N interpolation points
F(x), x
real(log10(w), x); % ploting the FFT on a graph with a logaritimic x-axis
grid on
xlabel('Frequency f / Hz'), ylabel('Counts'), legend('FFT, N = 1000'), int2str(N))
```

**Figure 20:** M-File of the FFT with Argos
A.3 FFT with AR5000

```matlab
function k = soustita(x,y,D)
% Function for the FFT of the measurements with AR5000 -> Single Frequency
% x: log detector
% y: intensity vector in volts
% D: number of interpolation points
% Plot the signal in its original state in V
plot(x,y)
% Title the soustita Figure
title('Two Element Interferometer Elektron, AR5000, mm, kHz, 2006/66. between ... and ... UT', 'FontSize',12)
grid on
xlabel('Time / hours','FontSize',20),ylabel('Voltage / V'),legend('Signal')

% Plotting the signal in its original state in dB
subplot(3,1,2)

% Converting the volts to dB
plot(20*log10(x)),
grid on
xlabel('Time / hours','FontSize',20),ylabel('dB'),legend('Signal')

% Plotting FFT of the signal with 5 interpolation points
subplot(3,1,3)

% Normalizing the signal, from dB to a power vector
M=abs(FFT(x,D));
% FFT of the signal with the M interpolation points

% Plotting the FFT on a graph with a logarithmic x-axis
grid on
xlabel('Frequency f / Hz','FontSize',20),ylabel('Counts'),legend('FFT, k = ', 'int2str(D)')
```

Figure 21: M-File of the FFT with AR5000

A.4 The baseline

```matlab
function b=basline(f,L,D)
% Calculating the baseline length
% f: Frequency of signal
% L: Frequency at which measurements were done [Hz]
% D: Amplitude of the sun [degrees]
% T=1/f; % Period of frame
% lambda=300/F; % Wavelength of measured radiowaves [nm] / [lambda = f / T]
% w=sin(pi*(f0*10)^2); % Angular magnitude of the earth [radians]
% dcos=1/10; % Detection of the sun [radians]
% l=lambda*(cos(2*pi*dim*WT)); % Length of baseline [m]
```

Figure 22: M-File of the calculation of the baseline

A.5 Visibility function and angular size

To determine the visibility $V$, one has to determine $S_{\text{max}}$ and $S_{\text{min}}$, which are the maximum and minimum values of the fringes at the peak respectively, and then subtract the background $S_B$, such that $S_{\text{max}}$ and $S_{\text{min}}$ are normalized. The visibility is defined by:

$$V = \frac{\tilde{S}_{\text{max}} - \tilde{S}_{\text{min}}}{\tilde{S}_{\text{max}} + \tilde{S}_{\text{min}}}.$$  

where $\tilde{S}_{\text{max}}$ and $\tilde{S}_{\text{min}}$ are the normalized values.

For the angular size of the sun $\phi$ the formula was somewhat simplified, such that it is an approximation. To calculate $\phi$ one needs the wavelength $\lambda$ at which the measurement took place, the length of the baseline $L$ and the visibility $V$. The approximated equation is then:

$$\phi = \frac{\sqrt{6}}{\pi} \cdot \frac{\lambda}{L} \cdot \sqrt{1-V},$$

where $\phi$ is in radians. To get a value in degrees one has to multiply $\phi$ by $\frac{180}{\pi}$. 

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