2-Element adding radio-interferometer with CALLISTO determination of the diameter of the sun

Report

Author(s):
Blülle, Balthasar; Grädel, N.N.; Guglielmetti, M.; Steger, P.S.P.; Monstein, Christian

Publication date:
2008

Permanent link:
https://doi.org/10.3929/ethz-a-005561266

Report for VP-Astro-Week 2008 in Diavolezza
March 9, 2008

2-Element adding Radio-Interferometer with CALLISTO

Determination of the Diameter of the Sun.

B. Blülle.[1], N.N. Grädel[1], M. Guglielmetti[1], P.S.P. Steger[1] and C. Monstein[2]

[1] Swiss Federal Institute of Technology, CH-8092 Zurich, Switzerland
e-mail: bbluelle@student.ethz.ch,
e-mail: ngraedel@student.ethz.ch,
e-mail: marcog@student.ethz.ch,
e-mail: psteger@student.phys.ethz.ch
[2] Institute of Astronomy, Swiss Federal Institute of Technology, CH-8092 Zurich, Switzerland
e-mail: monstein@astro.phys.ethz.ch

Received: March 9, 2008

ABSTRACT

Aims. The angular diameter Φ of the Sun was measured by means of radio interferometry.
Methods. We used a two-element adding interferometer in connection with the spectrometer CALLISTO. The Allan variance and Allan time were measured. Quiet frequencies had to be found. During week 2 in 2008 we measured the Sun seven times, at night we looked at the background. The fringe pattern of an interferogram was normalized, processed and fourier-analysed, the peak frequency identified and the diameter Φ of the Sun inferred from the visibility function.
Results. We verified a value of $\Phi \approx 34.8' \pm 2.2'$.

Key words. radio interferometry – CALLISTO

1. Scientific Background

Interference can be achieved by superimposing signals from two or more telescopes. Such an interferometer gives a higher resolution than a one single telescope. Interferometry is particularly useful in radio astronomy, where we deal with large wavelengths in the range of 10^{-3}m to tenths of meters.
For our observations we used a simple two-element adding interferometer. See figure 1 for a scheme.
Δs is the difference in path length which gives rise to the phase difference Ψ between the signals $V_A(t)$ and $V_B(t)$, reaching the antenna A and B, respectively. Since the Sun is an extended object we expect to see a pattern that qualitatively looks like figure 2.
We now refer to equations from [MoMe06]. With geometrical arguments one sees that the baseline distance D can be calculated using equation (1), where δ is the actual declination and Δt is the fringe period which we receive by taking the fourier transform of the fringe function. ω denotes the angular frequency of earth rotation, $\omega = 15°/$ h. We can then compare the result for the baseline to a manual measurement and use this as a check for the accuracy of the interferometer.

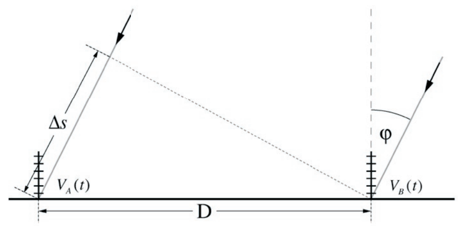


Fig. 1. Geometry of a two-element adding interferometer.

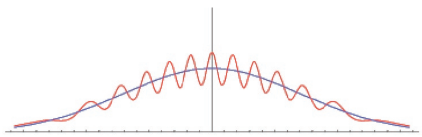


Fig. 2. Expected interference pattern.

$$D = \frac{\lambda}{\cos(\delta)\sin(\omega\Delta t)}. \qquad (1)$$

We expect the interferometer pattern to look like figure 2. From this figure we can calculate the visibility function v given by:

$$v = \frac{P_{max} - P_{min}}{P_{max} + P_{min}} = \frac{\sin 2\pi \frac{D}{\lambda}\frac{\Phi}{2}}{2\pi \frac{D}{\lambda}\frac{\Phi}{2}}, \qquad (2)$$

where Φ denotes the angular diameter of the Sun. We rewrite this equation with a Taylor-expansion:

$$v = \frac{\sin(x)}{x} \approx \frac{x - x^3/6}{x} = 1 - \frac{x^2}{6} \qquad (3)$$

with $x = 2\pi(D \cdot \Phi/2\lambda)$. When we insert x and solve for Φ we get

$$\Phi = \frac{\sqrt{6}}{\pi}\frac{\lambda}{D}\sqrt{1-v}, \qquad (4)$$

from which we can calculate the angular diameter of the Sun.

2. Observations

2.1. Observation Plan

Diavolezza lies at latitude 46°24′44“, longitude 9°57′55″ and an altitude of 2978 m. This position is needed for calculating the location of the measured objects. In this section we outline the roadmap for our observations. On the day of arrival we were busy with the mounting and setup of the antennas. Then we tested the functionality of the two antennas seperately. We compared the signal of the antennas to a signal from a 50 Ω termination resistor which gives a countinuous spectrum at the background temperature (~ 270 K).
We then connected the two antennas and looked at the combined signal. The results of our testing looked qualitatively good so we started a background measurement during the night in order to find frequencies which have minimum disturbancies. From this we chose a frequency range we wanted to measure on. In the next days we did the measurements as planned in table 1. By generating a spectral overview we then again chose several undisturbed frequencies for a suited frequency program (see fig. 3).

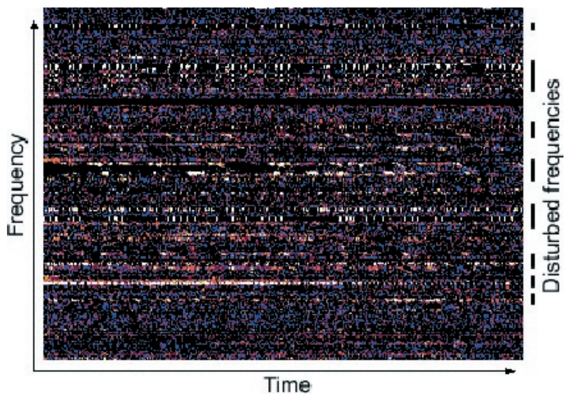


Fig. 3. Spectral Overview indicating disturbed and undisturbed frequencies

Table 1. Measurements

Date	No.	Time(UTC)	Az.	El.	Frequency range
8-1-2008	1.1	09:40-14:00	180.06°	21.33°	450 - 700 MHz
9-1-2008	2.1	07:05-10:00	139.24°	10.86°	450 - 550 MHz
	2.2	10:00-13:00	180.10°	21.46°	450 - 550 MHz
	2.3	13:00-16:00	220.95°	10.79°	450 - 550 MHz
10-1-2008	3.1	07:00-10:25	139.09°	10.94°	450 - 550 MHz
	3.2	10:40-16:00	200.65°	16.23°	450 - 550 MHz

2.2. Allan Time

The Allan Time is a statistical measure. It determines the time over which an integration still improves the signal to noise ratio of the result. During night, we measured on a quiet frequency of 470.125 MHz. We then using *AlaVar 5.2* found an Allan time for the whole system of 100 s as shown in figure 4. A repetition of the measurement with 50 Ω termination resulted as expected in a longer Allan Time (figure 5).

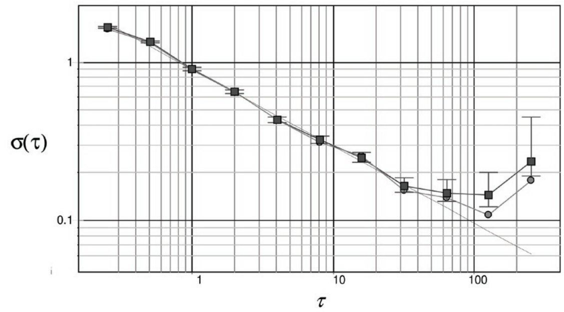


Fig. 4. Allan variance of Sky Radiation at 470.125 MHz after Sunset

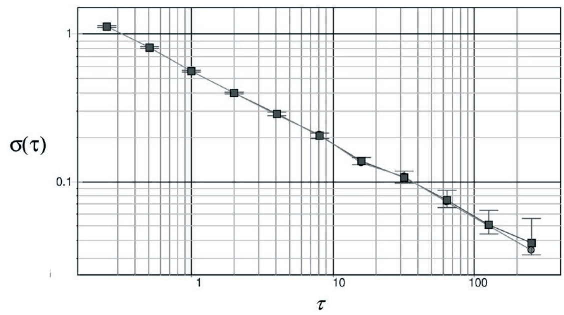


Fig. 5. Allan variance of Measurements at 470.125 MHz using 50 Ω termination

3. Experimental Setup of the 2-Element Interferometer

3.1. Adjustment of the Antennas

The two antennas were placed on an east-west orientated baseline at a distance of 22 m. We chose both antennas to be installed at the same base height on top of the roof of the restaurant. In order to find the east-west line we located the Piz Tschierva, which is situated exactly to the west of Diavolezza (see fig. 6 and 7).

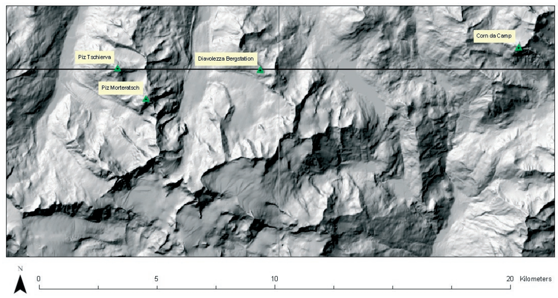


Fig. 6. Piz Tschierva and Diavolezza top station are located on an east-west line.

3.2. Hardware Setup

We used two standard TV antennas (UHF), originally designed for a frequency range between 470 MHz and 530 MHz, but also quite responsive in higher frequencies. The received signal was amplified by a preamplifier *Kuhne 0515B* at both antenna outputs to compensate for the signal loss in the cables. Two coaxial cables of the same length (15 m) were installed to feed the signal into a *Wilkinson* broadband power-combiner and were again routed through another coax-cable to a signal

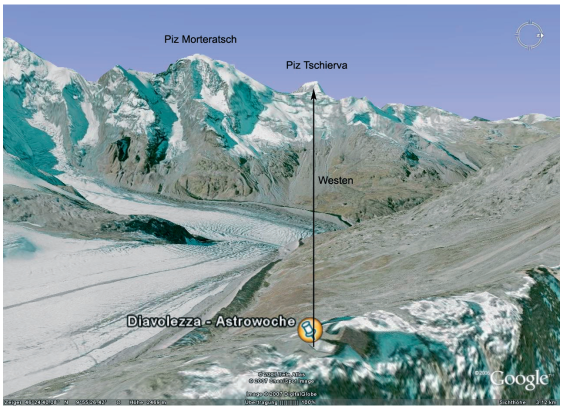


Fig. 7. View of Piz Tschierva from Diavolezza top station, located directly to the west.

Table 2. Used devices and material

device / material	quantity
TV antennas of type EB 66 UHF	2
adjustable tripod	2
amplifiers Kuhne 0515B	2
coax cables 25 m	2
coax cable 50 m	1
power combiner	1
12V power supply unit	1
attenuator (10 dB)	1
spectrometer CALLISTO	1
connection cable CALLISTO → laptop	1
boxes for snow protection of connections and amplifiers	3
termination resistors / sample noise	2

attenuator and then to the CALLISTO-spectrometer placed inside the restaurant building. CALLISTO was then connected to a computer through a serial interface and the measurement was controlled by a controller-software written for CALLISTO. The two preamplifiers were fed by a 12 V power supply unit out of the restaurant building. All cable connections, amplifiers and the power combiner were put into plastic boxes to protect them from snow, humidity and strong variations in temperature. See hardware setup scheme in fig. 3.2.

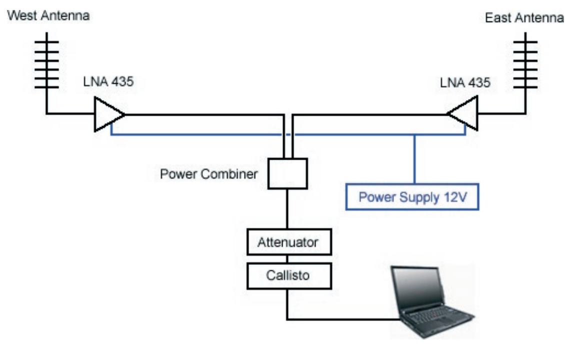


Fig. 8. Instrumental setup

4. Data Reduction

The measurements were saved as *.fits* files by the control software of Callisto (see fig. 9 for an example). A program *FitsToAscii* was used to cut out lightcurves at certain wavelengths. It was modified to automatically write out the lightcurves of a subsequent list of frequency channels as a CSV-formated file. The CSV-file was imported in *Mathematica* and converted into lists, one for each frequency. Having normalized the data for conversion from char to voltages and for delogarithmizing it using the formula

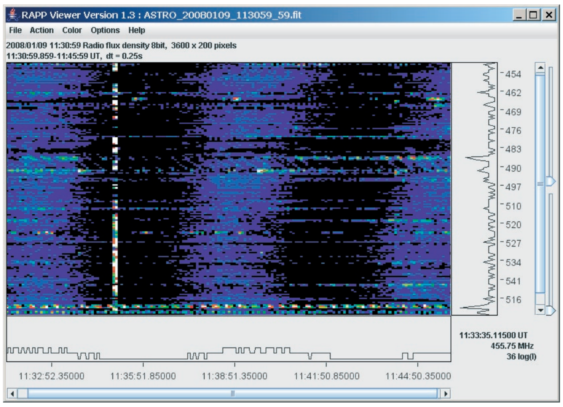


Fig. 9. Fits-file visualized by JavaViewer: The vertical fringes show that this was a measurement taken at about noon (meas. No. 2.2). The pattern is almost completely undisturbed – one of our best measurements.

$$\log_{10} A' = \frac{A}{255} \cdot V_{max}/\Delta V \tag{5}$$

we manually checked the different channels, neglected disturbed ones and summed up the others. The next step was to remove apparent outliers and cut out the disturbed data at the beginning and the end of the measurement. The resulting fringe pattern was smoothed twice over a timescale determined by the Allan time of the measurement system. The visibility function was then calculated from the maximum and the mean of two local minima in the middle of the Gaussian (see fig. 2). Using this result in 4 gave a value for the disc diameter of the Sun in radians, later converted into arc minutes.
A FFT of the fringe pattern showed a peak at the frequency corresponding to the fringe period Δt. From this and with known declination δ we calculated the baseline distance between the two antennas with

$$D = \frac{\lambda}{\cos\delta\ \sin(\omega \cdot \Delta t)}, \tag{6}$$

and compared it with the measured one. The *Mathematica* code with the detailed calculation as well as an error calculation can be found in the annex.

5. Results

The only useful results were obtained from the run on the second day. The other fringe patterns were either disturbed periodically by human radio emissions or gave no qualitatively good fringes because of temperature shifts. On the last day a blizzard turned the antennas and caused a jump in the sensitivity range of CALLISTO.
We got a value of 21.9±0.6 m for the baseline and 34.8′±2.2′ for the solar diameter. The measured distance of 22 m was actually very close to the calculated one. The error mostly arose from the uncertainty of the integer value of the fringe period with FFT. The literature value for the Sun diameter of 32.7′ is slightly underestimated, since we measured in the radio range where the

outer layers of the photosphere are emitting. Our error is as big as 2.1′ due to uncertainties in the integrated lightcurve which could not be smoothed out to the full Allan time, since this procedure would have caused raiser the value for p_{min} and lowered the one for p_{max} too much.

References

Monstein, C., & Meyer, H. 2006, Report of a simple 2-Element Solar Radio Interferometer at Bleien Observatory, Physics, Astronomy and Electronics Work Bench (Zurich)

Sant, V. 2006, Two Element Interferometer with TV-antennas observing the Sun at 425MHz, (D-PHYS-VP2006, Zurich)

Wohlleben, R., & Mattes, H. 1973, Interferometrie in Radioastronomie und Radartechnik, (Vogel Verlag, Bonn)

Acknowledgements. We would like to thank C. Monstein for his helpful advice and support and the Institute of Astronomy ETHZ for enabling us this interesting experience. Furthermore we vere happy to count on the technical support of S. Zihlmann who prepared the instruments for us.

6. Annex - Mathematica Code of Data Reduction

Determination of Sun Diameter

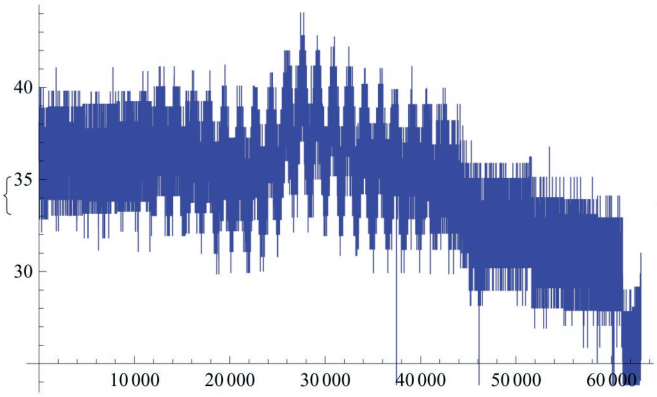
Definitions

```
In[18]:= f = 497.5*^6;
         λ = 2.99792485*^8 / f;
         detectorCoeff = 0.1;
         maxVolt = 5;
         timePerSweep = 1 / 4.;
         filename = "/home/psteger/diavolezza_tag2/LC042_046.dat";
         channelcount = 5;
         dMeas = 22;
         δ = 20 Degree;
```

```
In[27]:= A = Import[filename, "Table"];
         B = Table[0, {channelcount}];
         For[i = 1, i < Length[A], ++i,
           If[Length[A[[i]]] ≠ channelcount,
            A[[i]] = Table[0, {channelcount}],
            True
           ]
          ];
         lightcurve = Transpose[A];
```

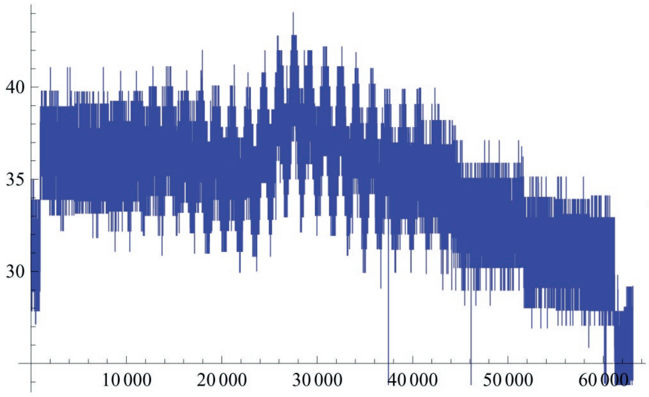
```
In[31]:= For[i = 1, i <= channelcount, ++i,
           B[[i]] = ListLinePlot[lightcurve[[i]]]];
         B
```

Out[32]= {



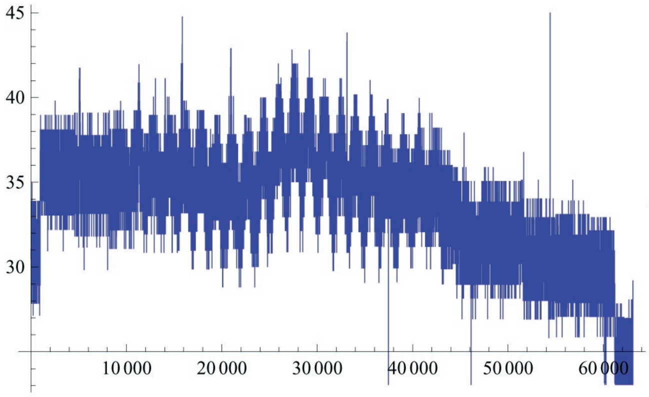
40
35
30
10 000
20 000
30 000
40 000
50 000
60 000

,



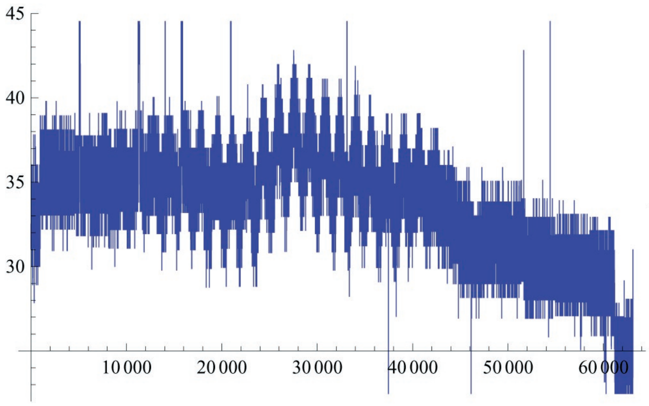
40
35
30
10 000
20 000
30 000
40 000
50 000
60 000

,



45
40
35
30
10 000
20 000
30 000
40 000
50 000
60 000

,



45
40
35
30
10 000
20 000
30 000
40 000
50 000
60 000

,

```
In[33]:= exclude = {4, 5};
```

Normalization

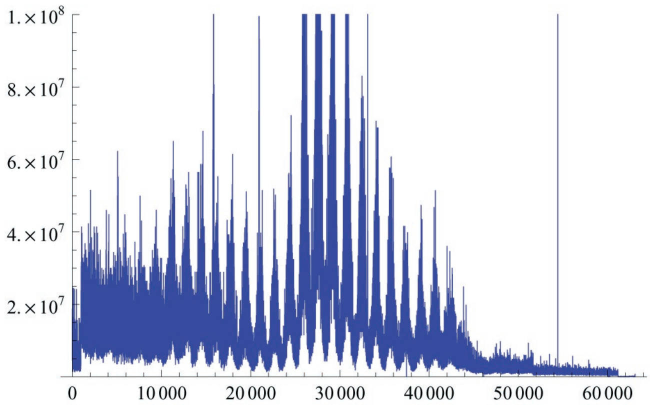
```
In[34]:= lightcurve = 10^(((lightcurve/255)*maxVolt)/detectorCoeff);

In[35]:= lightcurveOpt = Table[0, {Dimensions[lightcurve][[2]]}];
         For[i = 1, i ≤ channelcount, ++i,
           If[! MemberQ[exclude, i],
             lightcurveOpt = lightcurveOpt + lightcurve[[i]],
             Print[i]
            ];
          ];
         lightcurveOpt = lightcurveOpt / (channelcount - Dimensions[exclude][[1]]);
         ListLinePlot[lightcurveOpt, PlotRange → {0, 10^8}]
```

4

5

Out[38]=

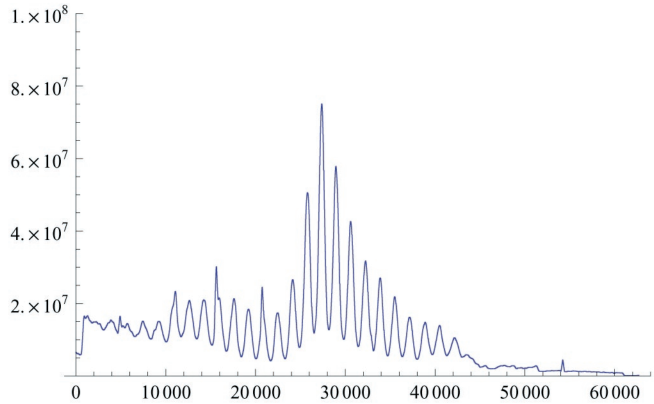


Average in time

```
In[39]:= intTime = 199;
         lcMA = MovingAverage[lightcurveOpt, intTime / 20 // Floor];
         lcMB = MovingAverage[lcMA, intTime];
         lcMC = MovingAverage[lcMB, intTime];
```

In[43]:=
```
ListLinePlot[lcMC, PlotRange → {0, 10^8}]
```

Out[43]=



In[44]:=
```
range = {1, Length[lcMC]};
lcMA = Take[lcMA, range];
lcMB = Take[lcMB, range];
lcMC = Take[lcMC, range];
```

Pmax and Pmin

In[48]:=
```
PPmax = Floor[Median[Flatten[Position[lcMC, Max[lcMC]]]]]
Pmax = lcMA[[PPmax + intTime]]
```

Out[48]= 27381

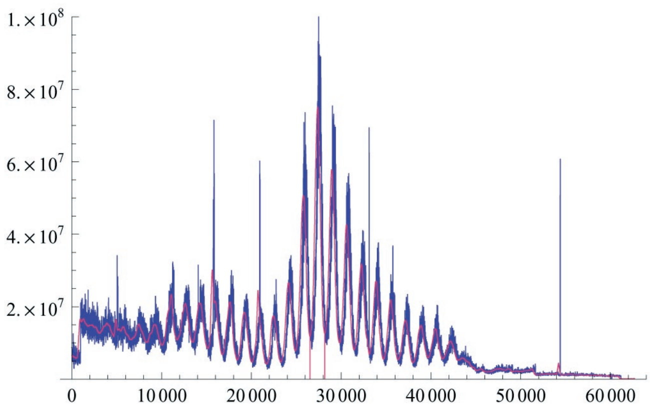
Out[49]= 8.13588×10^{7}

In[50]:=
```
For[i = PPmax, i > 1, --i,
  If[lcMC[[i - 1]] > lcMC[[i]],
   PPminLeft = i; Break[],
   False
  ];
 ];
PPminLeft
For[i = PPmax, i < Length[lcMC], ++i,
  If[lcMC[[i + 1]] > lcMC[[i]],
   PPminRight = i; Break[],
   False
  ];
 ];
PPminRight
lcMCCheck = lcMC;
lcMCCheck[[PPminLeft]] = 0; lcMCCheck[[PPminRight]] = 0;
ListLinePlot[{lcMA, lcMCCheck}, PlotRange → 1*^8]
```

Out[51]= 26 526

Out[53]= 28 171

Out[56]=



In[57]:=
```
Pmin = Mean[{lcMA[[PPminLeft + intTime]], lcMA[[PPminRight + intTime]]}]
```

Out[57]= 1.0322×10^{7}

Diameter

In[58]:=

$$\nu = \frac{\text{Pmax} - \text{Pmin}}{\text{Pmax} + \text{Pmin}}$$

$$\lambda = \frac{2.99792485*\hat{}8}{f};$$

$$\Phi = \frac{\sqrt{6}}{\pi}\,\frac{\lambda}{\text{dMeas}}\,\sqrt{1-\nu};$$

$$\Phi\text{Minute} = \Phi * \frac{180}{\pi} * 60$$

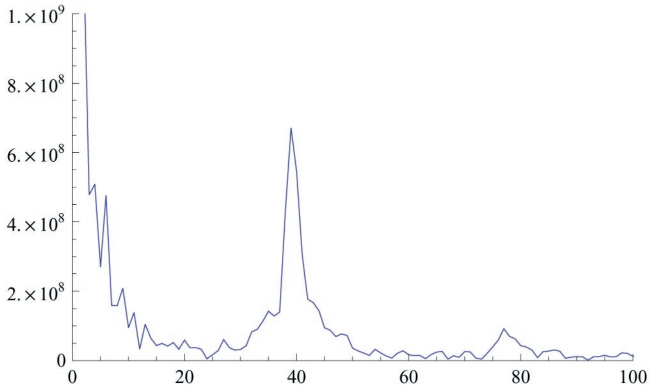
Out[58]= 0.774828

Out[61]= 34.8387

Fringe Period, Baseline

In[62]:=
```
lcFFT = Abs[Fourier[lcMC]];
ListLinePlot[lcFFT, PlotRange → {{0, 100}, {0, 1*^9}}]
```

Out[63]=



In[64]:=
```
offset = 10;
fringeFreq = Flatten[Position[Take[lcFFT, {offset, Length[lcFFT]}],
     Max[Take[lcFFT, {offset, Length[lcFFT] / 2 // Floor}]]]][[1]] + offset - 1
```

$$\text{fringeTime} = \frac{1}{\text{fringeFreq} * 1 / (\text{Length[lcFFT]} * \text{timePerSweep})}$$

Out[65]= 39

Out[66]= 401.885

In[67]:= ω = 360 Degree / (24 * 3600);

$$\text{dCalc} = \frac{\lambda}{\text{Cos}[\delta]\ \text{Sin}[\omega * \text{fringeTime}]}$$

Out[68]= 21.945

Results

In[69]:=
```
dMeas
δ
dCalc
ΦMinute
```

Out[69]= 22

Out[70]= 20 °

Out[71]= 21.945

Out[72]= 34.8387

Errors

```
Φn[ff_, dmeas_, pmax_, pmin_] := (√6/π) ((2.99792485*^8/ff)/dmeas) Sqrt[1 - (pmax - pmin)/(pmax + pmin)];

180/π * 60 * (D[Φn[ff, dm, pmax, pmin], ff]^2 (Δff)^2 + D[Φn[ff, dm, pmax, pmin], dm]^2 (Δdm)^2 +
    D[Φn[ff, dm, pmax, pmin], pmax]^2 (Δpmax)^2 + D[Φn[ff, dm, pmax, pmin], pmin]^2 (Δpmin)^2)^(1/2) /.
  {ff → f, dm → dMeas, pmax → Pmax, pmin → Pmin, Δff → 0.5*^6, Δdm → 0.05,
   Δpmax → 5*^6, Δpmin → 5*^6 / √2}
```

Out[96]= 5.37994

This is the error for Φ in arc minutes.

```
In[101]:= dCalcn[ff_, d_, w_, fr_, ts_] := (2.99792485*^8/ff) / (Cos[d] Sin[w * 1/(fr/(Length[lcFFT]*ts))]);

(D[dCalcn[ff, d, w, fr, ts], ff]^2 (Δff)^2 +
    D[dCalcn[ff, d, w, fr, ts], d]^2 (Δd)^2 + D[dCalcn[ff, d, w, fr, ts], w]^2 (Δw)^2 +
    D[dCalcn[ff, d, w, fr, ts], fr]^2 (Δfr)^2 + D[dCalcn[ff, d, w, fr, ts], ts]^2 (Δts)^2)^(1/2) /.
  {ff → f, d → δ, w → ω, fr → fringeFreq, ts → timePerSweep, Δff → 0.5*^6, Δd → 2 Degree,
   Δw -> 360 Degree / (24 * 3600) - 360 Degree / (24 * 3600 + 1), Δfr → 2, Δts → (1 / 4 - 1 / 4.001)}
```

Out[102]= 1.15932

Error for dCalc in meters.