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Report of a simple 2-Element Solar Radio Interferometer at Bleien Observatory

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Abstract. A 2-element Michelson radio interferometer was installed at Bleien observatory. The main task of the experiment was on the one hand the demonstration of a solar interferometer with low cost components, on the other hand to compare different radio spectrometers as a backend for the interferometer. Furthermore, we tried to optimize the equipment to find the limits of the instrumental setup concerning radiometric sensitivity and angular resolution. Solar fringes were analyzed to determine these parameters. The sensitivity was found to be of the order of 0.3 Kelvin at a system temperature of 187 Kelvin while the angular resolution was found to be of the order of about 57″.

Key words. Interferometer, angular resolution, visibility, sensitivity, interference.

1. Introduction

In connection with a 'Praktikumsversuch' we (together with a student of the physics department) built up an East-West orientated 2-element Michelson radio interferometer at Bleien observatory RSG. The main task of the experiment was primarily the demonstration of a solar interferometer (Kraus, 1965; Swenson, 1980) with low cost components from the consumer market, secondarily the comparison of several different radio spectrometers as a measurement backend (frequency agile spectrometer Callisto, FFT-spectrometer Argos and single frequency receiver). The students experiment (Sant, 2006) has been finished and we wanted to take the opportunity to optimize the equipment to find the physical limitations of such an instrument concerning radiometric sensitivity and angular resolution. The main problem was to find an undisturbed frequency range to perform the observations. Eventually, we found a frequency (458.71MHz) which was undisturbed most of the time. The received signals will be analyzed and discussed in this paper.

2. Station description

The 2-element interferometer was built at the location of the solar radio spectrometer Phoenix-2 at Bleien observatory. The base line of the interferometer was orientated in East-West direction between the two main dishes (5m and 7m diameter) at a varying separation distance of 20m ...30m. The East-antenna, see figure 1 was temporarily mounted on a tripod in front of the spectrometer shack.

Fig. 1. Eastern side broadband TV-antenna of the solar interferometer at Bleien observatory. H. Meyer is carefully adjusting the antenna on a tripod to be pointed to Cygnus A.

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Fig. 2. Western side broadband TV-antenna of the solar interferometer at Bleien observatory. The other author, on top of the scaffold is checking the cable connection at the dipole.

Fig. 3. Two GaAs-FET low noise preamplifiers tuned to 458.71MHz. Each preamplifier was combined via a Bias-T to F-type cable adapters. According to their specifications, these LNA's have a noise figure NF in the order of 0.7dB (52Kelvin).

The West-antenna, see figure 2 was mounted on top of the maintenance scaffold to get the possibility to change the antenna separation (length of the base line). Both antennas were commercial TV antennas for UHF-TV band IV between channel 21 (470MHz) and channel 29 (534MHz). We used the antenna at the lower end (458.71MHz) of the band due to strong interference in the TV bands. Both antennas were connected via a short coaxial cable to low noise GaAs preamplifiers LNA435 from the HAM market, see figure 3 for hardware and figure 6 for stray parameter s21. These preamplifiers contain a single FET transistor stage and they can be adjusted to any frequency between about 400MHz and 460MHz. For gain versus frequency, see figure 6. Since the gain of these low noise preamplifiers was too low to compensate the attenuation (-8dB) of the coaxial cables, an additional cable amplifier (CONRAD) with 10dB gain was directly attached to the LNA435. Two identical coaxial cables (Jumbo) with a length of exactly 25m were prepared to feed the signal into the shack and also to supply the preamplifiers with dc current from the shack (12V/200mA in total). Both cables were connected via a quarter wave transformer (power combiner) to one single line of 50 Ohms, see figure 4. This combined signal was again amplified by a broad band rf amplifier (Kuhne) with 10dB gain to finally feed our communication receiver AR5000, see figure 5.

Acronyms used in labels and text are described in table 1.

3. Results

3.1. Spectrometer comparison

This is part of an extra paper created by a physics student (Sant, 2006) during his VP activities. The sweep frequency agile spectrometer Callisto is not sensitive enough for low active solar (see figure 7) or stellar observations due to the fact that only every 50msec an integration of 1msec is

Fig. 4. On top of the combiner a Bias-T was connected to a power supply to energize the preamplifiers with 12V dc. Eastern element cable (bottom left) and Western element cable (bottom right) were fed to a quarter wave power combiner.

Fig. 5. The radiometer (left) is a commercial communication receiver AR5000 fully programmable via a serial line from a PC. The digital multimeter (right) samples the analog voltage taken from the logarithmic detector AD8307 (middle top) and stores the data on a PC. In front of the multimeter we see a passive integrator (first order low pass filter) composed of a 1 Megohm resistor and a 1 microfarad capacitor.

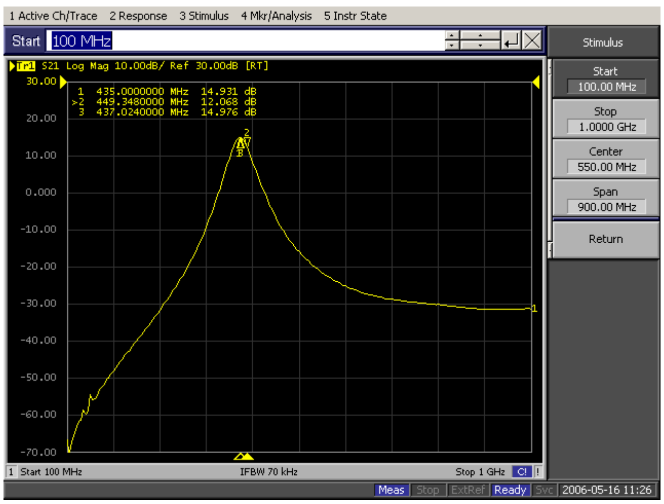

Fig. 6. This screen dump shows the gain (s21) of one of the two preamplifiers versus frequency. Maximum gain is about 15dB while the bandwidth (-3dB) is less than 50MHz.

being captured. Although, such kind of instruments were used in earlier years, see (Gaunt, 1976). On one hand the bandwidth is not large enough to get useful sensitivity. On the other hand it was not possible to observe with broader bandwidths due to heavy interference levels. But Callisto is almost ideal to observe satellite transitions through the main beam of the interferometer because satellite signals are quite strong compared to solar fringes, see satellite fringe pattern in figure 8.

The FFT spectrometer Argos was only on-line when people were around because of high risk of damage due to possible lightning strokes caused by local thunderstorms. Reason: the antenna system was not sufficiently grounded. In addition the data rate of the FFT spectrometer is extremely high thus, the instrument can only be used for short time observations. An example of solar interferometric fringes observed by the FFT spectrometer Argos can be seen in figure 9. The FFT has the big advantage that, within a rather disturbed spectral band one can always find undisturbed channels which then can be used for further analysis. Also the instrumental sensitivity can be improved by integrating several undisturbed channels into one single lightcurve. Thus, not to take too high risks we

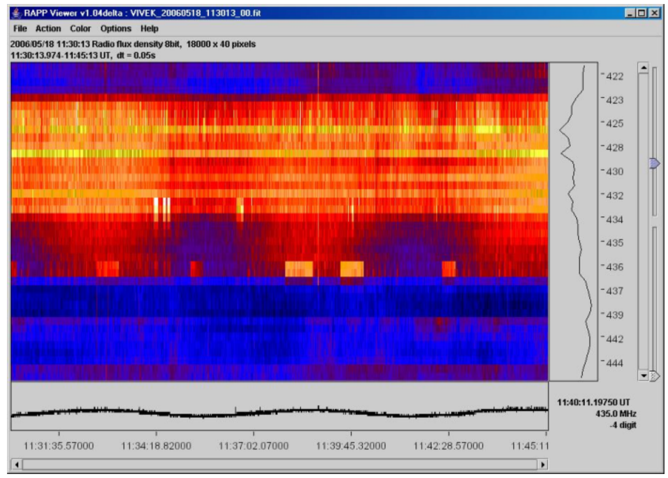

Fig. 7. Spectrum of a solar observation captured with our sweep frequency agile spectrometer Callisto within the amateur band at 435MHz (70cm wavelength). The cursor was set to a more or less undisturbed frequency, see lightcurve below the spectrum. One can see about two and a half fringes from the interferometer.

Abbreviation	description
AR5000	Commercial receiver
Argos	FFT spectrometer
Callisto	Radiospectrometer
CONRAD	Component supplier
dB	Deci Bel (in power)
ENR	Excess Noise Temperature
ETH	Eidgenössisch Technische Hochschule
FET	Field Effect Transistor
FFT	Fast Fourier Transform
FWMH	Full width half maximum
GaAs	Gallium Arsenide
Jumbo	Component supplier
Kuhne	Component supplier
LNA	Low Noise Amplifier
NF	Noise figure
Phoenix-2	Frequency agile spectrometer
RAPP	Radio astronomy and plasma physics
RSG	Building code of Bleien obs.
s21	Stray parameter for gain
SWR	Standing Wave Ratio
TV	Television
UHF	Ultra High Frequency

Table 1. Acronyms mentioned in labels and comments.

then decided to use our single frequency receiver AR5000 (figure 5) for our experiments because it also takes 100% of the captured energy at a given frequency and the cost for the receiver are not too high in case of an accident.

3.2. Non disturbed frequency, Allan time

The frequency agile spectrometer Callisto was used to determine quiet frequencies in the lower UHF band, see spectrum in figure 7. We had to find an acceptable compro-

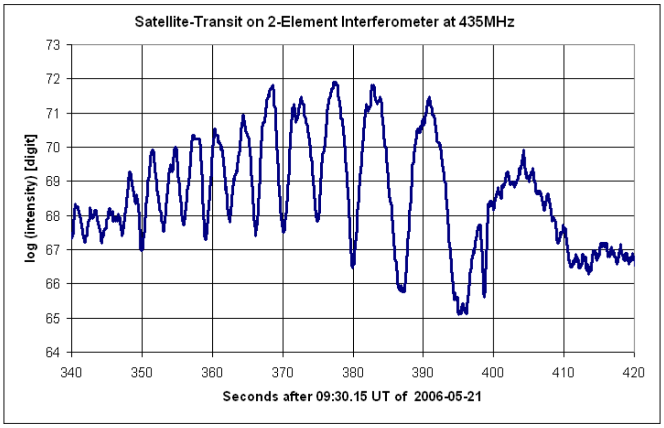

Fig. 8. Observation (using Callisto) of an amateur satellite at 70cm wavelength. The low orbit satellite takes only a few seconds to pass the main beam thus, the fringe frequency is high and the fringe period is in the range of a few seconds.

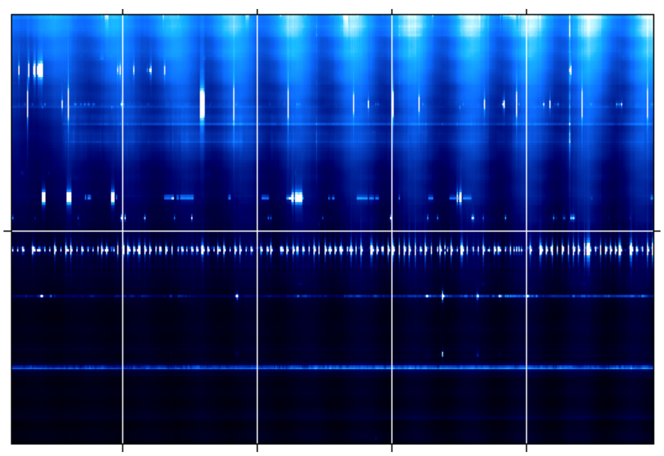

Fig. 9. Fourier transform spectrum of solar interferometer measured with ARGOS. One can easily see different fringe frequencies on the upper part (about 453MHz) with respect to the higher observing frequency (about 463MHz). The slope $\delta f/\delta t$ changes with time from < 0 to > 0.

mise between sensitivity of the antenna in the TV band (≥470MHz) and the sensitivity of the preamplifier in the amateur band between 430MHz ...440MHz. During the week we could make use of amateur frequencies in the 70cm wavelength band while during the weekends we had to avoid these frequencies due to high amateur activity. The final decision was then made to 458.71MHz. This frequency was all the time more or less quiet and was selected as the main observation channel. The useability of the selected frequency was checked by applying statistical methods (Allan variance, see Allan plot in figure 10) to the lightcurve at this frequency. To get this lightcurve a termination resistor was connected to each preamplifier input port. Both preamplifiers were strongly influenced by the outside, slowly varying temperature while receiver and detector were influenced by the fast varying air conditioning system. Due to several unwanted temperature influences only a few seconds of integration were useful. Even during

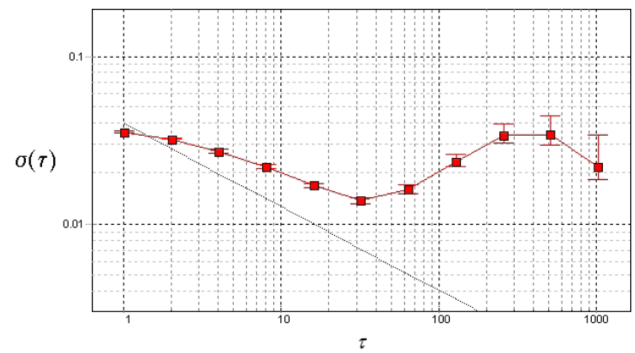

Fig. 10. Allan plot of the power-lightcurve between 14:30UT and 15:54UT of a termination resistor (300Kelvin) at the preamplifiers input. Sampling rate was 1 second, integration time also 1 second and radiometric bandwidth 220KHz. The gray line indicates the radiometer equation.

the first few seconds the radiometric equation was not fulfilled. It is essential to keep the temperature as constant as possible for all electronic components in the whole system.

3.3. Determination of separation

A known source (the sun, see figure 11) was used to determine the effective separation of the antennas. The fringe frequency was measured by applying Fast Fourier Transform to the light curve at 458.71MHz, see figure 12. By taking into account the actual declination δ of the sun on the day of observation, the separation distance D can be estimated assuming that the base line is East-West orientated and both antennas are at the same height.

$$D = \frac{\lambda}{cos(\delta)\ sin(\omega\ \Delta t)} = 22.7m\ (1\sigma = 0.3m) \quad (1)$$

where $\omega = 15°$ per hour and $\lambda = c/f$ where f is the receiving frequency of 458.71MHz. Δt is the result of the Fourier transform of the fringe function taken from figure 12. The statistical result does almost perfectly fit with manual measurements of 22.6m taken at the site.

3.4. Angular size of the sun

The angular size of the source can be determined by analyzing the fringe function. Since our detector is a logarithmic amplifier, several mathematical operations have to be applied to get the disc diameter ϕ. First operation is to convert the measured dc voltage into dB of electrical power.

$$Power_{dB}(t) = \frac{u(t)}{25.3mV} \quad (2)$$

$25.3mV/dB$ represents the given sensitivity of the logarithmic detector $AD8307$. Second operation is to convert these dB's into a linear power scale with arbitrary units.

$$P_{arbitraryunits}(t) = 10^{\frac{Power_{dB}(t)}{10}} \quad (3)$$

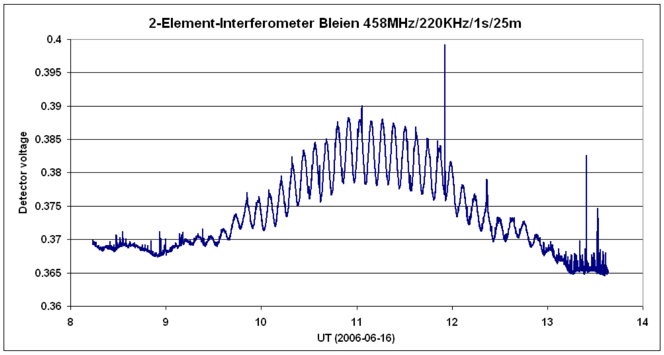

Fig. 11. Fringes of the sun produced by the interferometer with a spacing of about 25m at 458.71MHz. The minimum of the fringe function is above the baseline because the sun is not a point source but a disk with about 30" diameter. The visibility (Wohlleben/Mattes, 1973) can be used to determine either declination δ of the source or the disc diameter ϕ. Increasing noise around 13:30UT is due to lightning strokes from a nearby thunderstorm.

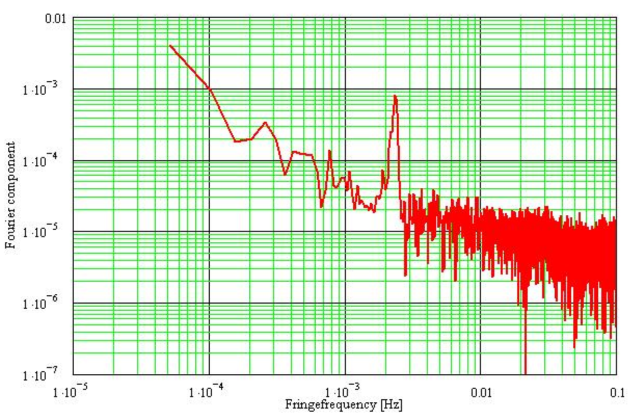

Fig. 12. Fourier transform of the solar fringe function from June 16th 2006. The spectral peak near 0.00233Hz fringe frequency corresponds to a fringe period Δt of about 428sec.

We can determine the maximum, Pmax, and the minimum, Pmin, of the fringe function with respect to the base line (background noise level). The visibility function v (Wohlleben/Mattes, 1973) can now be evaluated.

$$v = \frac{Pmax - Pmin}{Pmax + Pmin} \quad (4)$$

The visibility v, after (Wohlleben/Mattes, 1973) is also expressed by si(x) function

$$v = \frac{sin\left(2\pi \frac{D}{\lambda} \frac{\phi}{2}\right)}{2\pi \frac{D}{\lambda} \frac{\phi}{2}} \quad (5)$$

The solution of this pair of equation leads to the disc diameter ϕ of the sun. The equation can be solved either by mathematical spreadsheet or by taking a simplified approach.

$$\phi = \frac{\sqrt{6}}{\pi} \frac{\lambda}{D} \sqrt{1 - v} \quad (6)$$

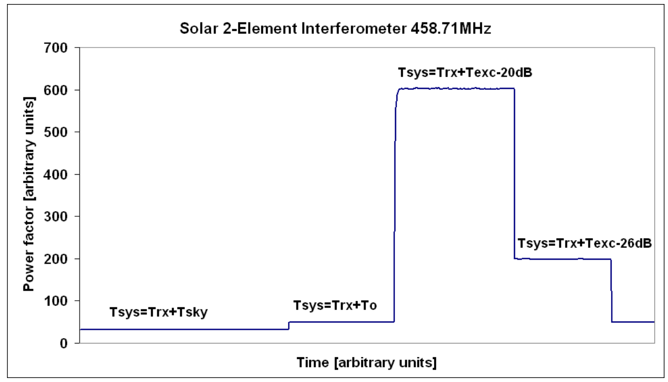

Fig. 13. Final lightcurve of calibration task of the East antenna by feeding in different noise levels into the preamplifier.

This simplified approach (Monstein, 1979) is sufficient for small disc diameters.

3.5. Calibration

A semiconductor noise source with different noise temperatures was connected to the antenna port of the preamplifier, for lightcurve see figure 13. Calibration of the East antenna was realized by feeding in several different noise levels into the preamplifier. Tsys denotes to system temperature and Tsky to the sky temperature while Trx means the receiver temperature measured at the input terminal of the preamplifier. To is a termination resistor at ambient temperature (To = 303Kelvin) while Texc denotes to the excess temperature of the noise source of 34.65dB ENR (883'980Kelvin). Remarkable is the fact, that Trx+Tsky is clearly below Trx+To. This is a good sign, it proofs the sensitivity of the GaAs-FET preamplifiers. By analyzing the lightcurve of figure 13 we may estimate the total noise figure F_{dB}.

$$F_{dB} = ENR - 10\ log(Y - 1) = 2.1dB \quad (7)$$

ENR denotes to the Excess Noise Ratio which, for the hot load was 34.65dB - 20.0dB = 14.65dB. Y denotes the the so called Y-factor, the output relation of hot load divided by the sky load. In our case Y=18.89. From that, total system temperature Tsys can now be derived.

$$Tsys = \left(10^{\frac{F_{dB}}{10}} - 1\right)\ To = 187Kelvin \quad (8)$$

Regarding the low noise figure of the preamplifiers this value is rather high. But it can be explained by the fact that the balloon- impedance-transformer at the antenna terminal converting 300 Ohms resistance of the dipoles into 75 ohms cable impedance are quite old, rusty and thus lossy. In addition, Tsys sees also in the order of 35Kelvin sky noise temperature which has also to be taken into account.

4. Numerical results

The results of two weeks of observation are listed in table 2. The quality of the data was extremely weather depen-

Date	$D[m]$	$\phi[°]$	SNR	$\frac{\sqrt{ln2}}{SNR}\frac{\lambda}{D}[\angle ``]$
16.06.2006	22.7	1.14	112	53
17.06.2006	23.0	0.93	83	71
18.06.2006	22.9	0.93	151	39
19.06.2006	22.6	0.66	170	35
20.06.2006	22.8	0.63	219	27
21.06.2006	22.7	0.54	347	17
22.06.2006	22.5	0.47	347	17
23.06.2006	22.8	0.60	186	32
24.06.2006	22.7	0.68	148	40
25.06.2006	21.8	0.85	78	80
26.06.2006	22.9	0.94	44	135
26.06.2006	23.1	0.94	44	134
Average	22.7	0.78	161	57
1σ	0.3	0.21	103	41

Table 2. Results from two weeks of observation at Bleien observatory. $D[m]$ denotes to calculated separation according to equation 1. $\phi[deg]$ denotes to the calculated solar disc diameter according to equation 6. SNR is the measured signal to noise ratio of the sampled solar fringes. The most right column is the relation of Gaussian adapted FWHM divided by SNR times wavelength divided by physical antenna separation.

dant. Heavy rain led to changes in cable impedance and even to short circuits in the connectors and cables. The extracted SNR is high during nice weather and rather low during wind and/or heavy rainfall. Only one measurement per day was done since the instrument was of type transit meridian with antenna fixed in azimuth and elevation. Declination of the sun was changing during measurement campaign from 23.36° up to 23.44° and again down to 23.30°.

5. Conclusions

From the present results one can conclude that this kind of interferometer is ideal for students experiments like 'VP' at Diavolezza. Only a few components are necessary to get a functional setup. Several sources can be detected, such as the sun, Cassiopeia A and Cygnus A. More sources may be identified by further optimizing the setup. Bigger antennas or groups of antennas would help. Most of the components were from the consumer or amateur (HAM) market and thus not too expensive. The initial total cost for all components for this 2-element interferometer were in the order of 8000.00 Swiss francs.

Acknowledgements. Both antennas, preamplifiers and the quarter wave transformer were provided by the author (HAM components). Mechanical parts, cables, tripod, receiver, power supplies, detector etc. were taken from RAPP- stock.

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