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Author(s):
Bernet, Martin

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Determination of Observation sensitivity limit of APRAXOS and PHOENIX-2 receivers using EME signals

Martin Bernet

Departement Physik, ETHZ, Switzerland, mbernet@student.ethz.ch

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Abstract. The aim of this work was to determine the sensitivity of the APRAXOS radio telescope in Zürich and the PHOENIX-2 observatory in Bleien. As a test beacon we used the SETI League EME Station located in New Jersey, USA. We couldn't detect the signal, although carefully checked the incoming signals.

Key words. receiver, system temperature, power flux density, APRAXOS

1. Introduction

APRAXOS is the name of the radio telescope of the Institute of Astronomy at the ETHZ located in the center of the city in Zürich. The location in a city is far from being optimal due to the fact there are a lof of man made noise such as mobile communication. Further problems are the buildings and trees around the antenna which contribute with their thermal radiation to the measured radiation. The APRAXOS system consists of a 5 m diameter parabolic dish, a feedhorn, the Focuspack (FOPA), the receiver AR 5000 and a computer to control the whole system and to collect the data. The parabolic dish is used to collect the electromagnetic waves and to focus them on the feedhorn. In the feedhorn the transition between free space propagation and guided wave propagation takes place. The incoming radiation induces a voltage in a dipole. Then the signal is preamplified in the FOPA. The FOPA contains also a noise generator and two switches. In order to get the highest possible sensitivity we briged the switch and connected the feedhorn directly with the preamplifiers. In our case we used first a narrow band preamplifier at 1296 MHz with an amplification of a = 20 dB and a second preamplifier with a = 42 dB. In the radio receiver the signal of the antenna with frequency υ_a is mixed with the oscillations of a local oscillator with frequency υ_{lo} in the mixer. The product has among others the frequency $\upsilon_{mix} = |\upsilon_a - \upsilon_{lo}|$. It's easier to build a local oscillator with variable frequency and to hold υ_{mix} constant. All incoming signals are transformed on the constant frequency υ_{mix} by varying the frequency υ_{lo}. Then the signal is filtered and is amplified again. Then the signal is converted into a DC voltage.

2. Radio technical terms and formulas

2.1. Flux density and antenna temperature

Here we introduce some important formulas which are used in the field of radio astronomy: To describe radio emissions from the sky one introduce a *brightness distribution function* B which is a function of the direction which one looks. From the Planck law in the Rayleigh-Jeans approximation there is a connection between the brightness B of a Black-body and its temperature T given by

$$B(\lambda, T) = \frac{2kT}{\lambda^2} \quad [Wm^{-2}Hz^{-1}sr^{-1}] \tag{1}$$

When you then look with your antenna in different directions on the sky you measure a *flux density* S

$$S = \int B(\theta, \phi) * P_n * d\Omega \quad [Wm^{-2}Hz^{-1}], [Jy/fu] \tag{2}$$

P_n is the normalized power pattern of the antenna. The unit normally used in radio astronomy to express flux density is Jansky or flux unit [Jy/fu]. 1 Jy or 1 fu is equal to $10^{-26}Wm^{-2}Hz^{-1}$. If the flux is constant over the observed bandwidth the power that has been induced by the incoming radio waves is given by

$$P = \frac{1}{2} S A_e \Delta\upsilon \quad [W] \tag{3}$$

$\Delta\upsilon$ is the observed bandwidth and A_e is the effective aperture of the telescope. A_e is smaller than the physical aperture A

$$A_e = A * \eta \quad [m^2] \tag{4}$$

η is the dimensionless *efficiency factor* of the telescope and $0 \leq \eta \leq 1$. In η are many parameters contained like surface condition of the telescope, parabola and focusing accuracy. In my calculations I used $\eta = 0.59$ for APRAXOS from (3). The factor $\frac{1}{2}$ considers the fact that just one polarization is measured and random polarization is assumed. Introducing the following relations (1)

$$\lambda^2 = A_e * \Omega_A \quad [m^2 sr] \tag{5}$$

$$S = B * \Omega_A \quad [Wm^{-2}Hz^{-1}] \tag{6}$$

into Eq. (1) leads to a formula which brings flux density and temperature in relation. Here Ω_A is the pattern solid angle of the antenna.

$$T_a = \frac{SA_e}{2k} \quad [K] \tag{7}$$

T_a is the so called antenna temperature which depends on the observing telescope through η.

2.2. System temperature and Y-Factor

When we measure with the antenna the flux density of a source, we don't only get the antenna temperature but we also measure the *system temperature* which results from the intrinsic noise from the radio receiver and the temperature of the cold sky. In order to know the system temperature a calibration has to be done. The calibration process consists of first measuring the flux of the cold sky (system temp. and sky temp.) and second measuring the flux of the sun (source temp. and system temp. and sky temp.). Then an attenuation of the sun in dB was done by known quantities until the level of the sun was reached. Through taking the dB-difference one can calculate the *Y-Factor* of the sun.

$$\begin{aligned} Y_{sun} &= \frac{T_{sun} + T_{sys} + T_{sky}}{T_{sys} + T_{sky}} \\ &= 10^{\frac{T_{sun+sys+sky}[dB] - T_{sys+sky}[dB]}{10}} \end{aligned} \tag{8}$$

Using Eq. (8) and Eq. (7) one gets to a formula for the system temperature

$$T_{sys} = \frac{S_{sun} * A_e}{2k(Y_{sun} - 1)} - T_{sky} \quad [K]. \tag{9}$$

where S_{sun} is the flux density of the sun which was taken online from The Space Environment Center (SEC)(2). For T_{sky} a value of $\sim 10\ K$ was assumed.

2.3. Antenna gain

To describe the characteristic of an antenna to transmit and receive radiation from a specific direction one use the *antenna gain* given by:

$$G = \frac{4\pi}{\theta^2} \tag{10}$$

Where θ is the beamwidth of the antenna, that means the FWHM of the transmitted power. An isotropic antenna (which doesn't exist) has a gain of 1. The relation of the antenna gain with the effective aperture is given by:

$$A_e = G * \frac{\lambda^2}{4\pi} = \frac{\lambda^2}{\theta^2} \tag{11}$$

in which Eq. (10) is used. Here λ is the wavelength of the transmitting or receiving radiation.

parameter	adjustment
Frequency	$1296MHz$
Bandwidth BW	$6kHz(IF2)$
Receiving mode	USB

Table 1. Major parameters of the APRAXOS AR-5000 receiver

2.4. Pathloss of Earth-Moon-Earth propagation

The transmitted power of an isotropic antenna is smeared over a sphere whose radius R is the distance from Earth to Moon. The Moon of diameter d with frontal area $d^2\pi/4$ only intercepts the fraction $\frac{d^2\pi/4}{4\pi * R^2}$ of the transmitted power. The Moon has an reflection coefficient ρ of about 0.065. So the fraction of the signal reaching the Earth again is given by:

$$F = 0.065 * \frac{d^2\pi/4}{4\pi * R^2} * \frac{1}{4\pi * R^2} * \frac{\lambda^2}{4\pi} * G_R \tag{12}$$

where G_R is the gain antenna of the receiver antenna. Using Eq. (11) and considering that the transmitting antenna has a gain yields G_T to an expression for the power on the terminals on the receiving antenna given by:

$$P_R = P_T * G_T * 0.065 * \frac{d^2\pi/4}{4\pi * R^2} * \frac{1}{4\pi * R^2} * A_e \quad [W] \tag{13}$$

P_T is the power at the terminals of the transmitting antenna and is connected with the antenna temperature T_a by

$$P = k * T_A * \Delta\nu \quad [W] \tag{14}$$

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3. Measurements

We optimized the APRAXOS adjustments to get a sensitivity as high as possible. We first varied the distance from the feedhorn to the parabolantenna to find the optimal place. Christian Thalmann (4) predicted a maximum for the most distant point from the parabolantenna for 1700 MHz. We found that the measured Y-Factor is almost constant over the observed distance from the most distant point. For our further measurements we took an offset of a=6.5 cm from the most distant point. In order to get a big signal to noise ratio we choose a bandwidth of the receiver of 6 kHz. In Table (1) the used parameters are listed:

When the monochromatic signal from the Earth reaches the moon an observer on the moon would see it dopplershifted due to the velocity of the Earth relative to the moon. An observer on Earth which wants to catch the signal has to consider that the signal is dopplershifted twice. In our measurements we used the NOVA Software to predict the doppler shift by a wavelength λ of $23cm$, which lies between $\pm 2.5kHz$. The beacon operates whenever the moon is above the transmitting station location.

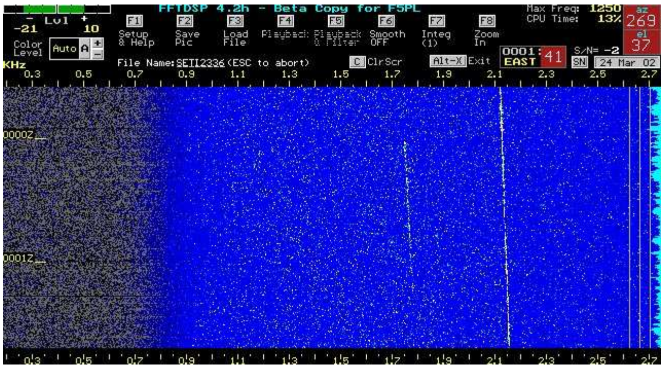

Fig. 1. EME-signal detected by a $7m$ mirror, displayed in a waterfall display, where one can see the signal strength in dependency of the wavelength.

It transmits a signal in a five minutes cycle, beginning exactly on the hour. The transmission sequence starts with a continuous signal for 60 seconds followed by a 5 words per minute (WPM) CW identifier for 30 seconds. Then there is no signal for 3.5 minutes. The reception time on Earth is delayed 2.5 seconds by round-trip EME propagation. In the measurements we considered, that the moon has to be at least 10 degrees above the horizon in Zürich an New Jersey to not detect too much terrestrial background radiation.

3.1. Fast Fourier Transformation (FFT)

In order to receive the weak signal we used the capability of Digital Signal Processing (DSP). For the measurements we used the program Spectrum Lab v2.4. Fast Fourier Transformation(FFT) is a way to verify weak narrowband signal. The incoming signal is split up into different channels with a smaller bandwidth and the intensity in such a channel is measured. The result is shown in a so called waterfall display, where one can see the signal strength in a certain frequency interval in dependency of the frequency for fixed moment in time. Figure (1) The waterfall display is useful for visual display of EME doppler shift. Spectrum Lab has also very useful function called FFT internal averaging. This system is similar to long-term integration for improving the apparent signal to noise ratio. The spectrum looks smoother. Other important parameters are the FFT Input size and the FFT sample rate. The sample rate υ determines the upper limit of the analyzed frequency. The sample rate has to be at least twice the analyzed frequency. The FFT input size N is the number of frequency intervals the signal is divided into. Both determine the resolution bandwidth ΔB which is given by

$$\Delta\nu = \upsilon/(2 * N) \qquad (15)$$

The parameters we mostly used in the measurements are shown in Table (2)

parameter	adjustment
FFT Input size	16384
FFT Sample rate	$22050Hz$
FFT resolution bandwidth	$1.3Hz$
FFT internal average	10
Filter	Hanning

Table 2. Parameters used in Spectrum Lab v2.4

Location	NJ,USA
Output	$200W = 33dBW$
Loss in feed line	$3dB = 0.5$
Frequency	$1296MHz$
Accuracy	$2Hz$
Antenna gain G_T	$24dBi = 251.2$

Table 3. Data of beacon used in the measurements

3.2. Predicted signal strength and measured system temperature for APRAXOS

The data of the beacon we used in our measurements are listed in Table (3). Using Eq. (13) with $R \approx 390000km$ in the 5 days we maesured, $d = 3475km$ and $A_e = 11.58m^2$ and considering the fact the we just measure one polarization we get the power at the terminals of the antenna: $P_R = 4.9 * 10^{-20}W = -193dBW$. Putting in Eq. (9) $Y_{sun} = 18.2$, $A_e = 11.58m^2$, $T_{sky} = 10K$ and $S_{sun} = 50 * 10^{-22}Wm^-2Hz^{-2}$ one gets for the system temperature $T_{sys} = 112.0K$. Using Eq. (14) to calculate the noise power $P_S = -207dBW$ with the $\Delta\nu$ from Table (2) one gets then a potential signal to noise ratio (SNR) to $R = 14dB$, which would guarantee good reception.

3.3. Test with a signal generator

In order to test the sensitivity of APRAXOS we used a signal generator (SG) as a calibrated source. We connected the SG with the feed line before the two preamplifiers to simulate the same conditions which signals from the antenna have. So we could prove a signal in the background up to $-199dBW$ at the terminal of the antenna with the same settings we used for the measurements. In the measurement with the signal generator we had to connect a lot of attenuation elements to reach a weak signal. So the attenuation we made was probably bigger than the sum of the elements and so the test signal was rather weaker than $-199dBW$.

3.4. Predicted signal strength and measured system temperature for PHOENIX-2

Our measurements took place from the 01.03.04 until 07.03.04. at APRAXOS in Zürich. In this time we didn't managed to prove a signal, so we decided to continue the measurements on the night from 09.03.04 to 10.03.04 in

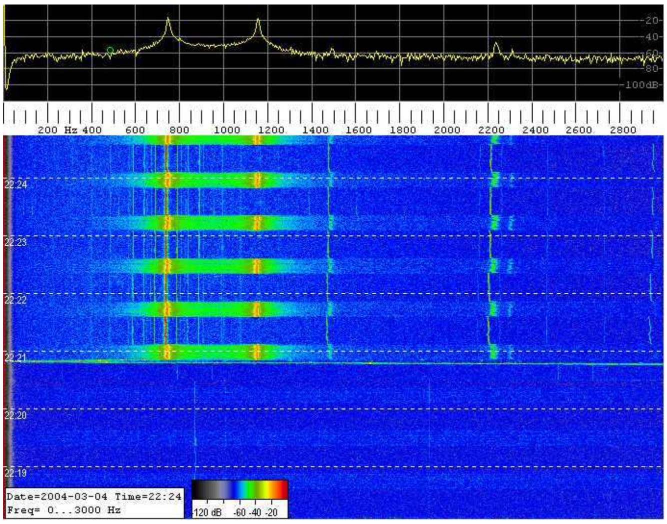

Fig. 2. Morse Signal on $1296.043000MHz$, used to control the settings.

Bleien, Argau, on the PHOENIX-2 system with a $7m$ mirror. Considering the physical area of the mirror, one expects to have a smaller signal at APRAXOS. But the fact that antenna for $1296MHz$ is not installed in the focuspoint leads to an effective aperture A_e of only $8m^2$ (6). Due to the fact we arrived too late in the evening to use the sun as a calibration source, we switched to METEOSAT-7 which is a strong source in a geostationary orbit. METEOSAT-7 sends on $\nu = 1691MHz$. Using again Eq. (9) with the integrated flux from METEOSAT-7 from [3]and a bandwidth of $220kHz$ and the measured Y-factor $Y_M = 80.3$ one gets for the system temperature $T_{sys} = 146K$. The calculated signal strength is $P_R = 4.1 * 10^{-20}W = -194dBW$. The signal strength is almost equal to that of APRAXOS the days before, although the effective aperture is smaller. This is because the distance between the Moon and the Earth had almost reached the minimum on 09.03.04 with $R = 3.72 * 10^8$. Using Eq. (14) again to transform the system temperature into system noise with $P_N = -206dBW$ leads to a value of $12dB$ for the signal to noise ratio, which would allow good reception.

4. Conclusion

Considering the calculated signal strength and the potential signal to noise ratio of $14dB$ in Zürich and $12dB$ in Bleien we should be able to detect the signal. There are several possibilities why we didn't detect the signal and I will discuss them below:

- We looked on the false frequency: This can be excluded, we made a test with the signal generator and the NOVA software always predicted the actual doppler shift. During the measurement we had a strong signal on $1296.043000MHz$ to control the settings. Figure (2)
- We looked on the false time or the beacon didn't send: On (5) one can see the current status of the beacon and to predict the possible observation time we used again the NOVA software.
- The parabolantenna didn't show on the moon in Zürich and Bleien: It was easy to control the orientation of the antenna with the calibration source.
- The beacon didn't show on the moon: This is our conjecture. On a meeting Christian Monstein talked with Paul Shuch, the executive director of the SETI League. He told that antenna control system is just precise to ± 1 and sometimes it doesn't operate at all.

To test this conjecture we recommend to repeat the measurements when the conditions are optimal. That means the distance Moon-Earth is small and the height of the moon trajectory (elevation) is big.

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