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

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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 lot 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 bridged 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 $a = 20 \text{ dB}$ and a second preamplifier with $a = 42 \text{ dB}$. In the radio receiver the signal of the antenna with frequency $\nu_a$ is mixed with the oscillations of a local oscillator with frequency $\nu_{lo}$ in the mixer. The product has among others the frequency $\nu_{mix} = |\nu_a - \nu_{lo}|$. It’s easier to build a local oscillator with variable frequency and to hold $\nu_{mix}$ constant. All incoming signals are transformed on the constant frequency $\nu_{mix}$ by varying the frequency $\nu_{lo}$. 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

$$B(\lambda, T) = \frac{2k}{\lambda^2} T [W m^{-2} H z^{-1} s r^{-1}]$$

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

$$S = \int B(\theta, \phi) * P_n * d\Omega \ [W m^{-2} H z^{-1}], [Jy/fu]$$

$P_n$ 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 $10^{-26} W m^{-2} H z^{-1}$. If the flux is constant over the observed bandwidth the power that has been induced by the incoming radio waves is given by

$$P = \frac{1}{2} S A_e \Delta \nu \ [W]$$

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

$$A_e = A \cdot \eta \ [m^2]$$

$\eta$ is the dimensionless efficiency factor of the telescope and $0 \leq \eta \leq 1$. In $\eta$ 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)
\[ \lambda^2 = A_\epsilon \Omega_A \quad [m^2sr] \] (5)
\[ S = B \Omega_A \quad [Wm^{-2}Hz^{-1}] \] (6)
into Eq. (1) leads to a formula which brings flux density and temperature in relation. Here \( \Omega_A \) is the pattern solid angle of the antenna.

\[ T_a = \frac{SA_\epsilon}{2k} \quad [K] \] (7)

\( T_a \) is the so called antenna temperature which depends on the observing telescope through \( \eta \).

### 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 system temp. and sky temp.) and second measuring the flux of the sun (source temp. and systemp. 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.

\[ Y_{sun} = \frac{T_{sun} + T_{sys} + T_{sky}}{T_{sky} + T_{sys}} \]
\[ = 10^{\frac{T_{sys} + T_{sky} - T_{sky} + T_{sys} - T_{sys} - T_{sky}}{10}} \] (8)

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

\[ T_{sys} = \frac{S_{sun} \cdot A_\epsilon}{2k(1 - \frac{T_{sky}}{T_{sys}})} - T_{sky} \quad [K] \] (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 \( \sim 10K \) 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:

\[ G = \frac{4\pi}{\theta^2} \] (10)

Where \( \theta \) 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:

\[ A_\epsilon = G \ast \frac{\lambda^2}{4\pi} = \frac{\lambda^2}{\theta^2} \] (11)

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Adjustment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>1296 MHz</td>
</tr>
<tr>
<td>Bandwidth BW</td>
<td>6 kHz (IF2)</td>
</tr>
<tr>
<td>Receiving mode</td>
<td>USB</td>
</tr>
</tbody>
</table>

**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 \( \rho \) of about 0.065. So the fraction of the signal reaching the Earth again is given by:

\[ F = 0.065 \ast \frac{d^2\pi/4}{4\pi R^2} \ast \frac{1}{4\pi R^2} \ast \frac{\lambda^2}{4\pi} \ast G_R \] (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:

\[ P_R = P_T \ast G_T \ast 0.065 \ast \frac{d^2\pi/4}{4\pi R^2} \ast \frac{1}{4\pi R^2} \ast A_\epsilon \quad [W] \] (13)

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

\[ P = k \ast T_A \ast \Delta \nu \quad [W] \] (14)

### 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 \( a = 6.5 \text{ cm} \) 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 \( \lambda \) of 23 cm, which lies between \( \pm 2.5 \text{kHz} \). The beacon operates whenever the moon is above the transmitting station location.
3.1. Fast Fourier Transformation (FFT)

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 and not detect too much terrestrial background radiation. We used the program Spectrum Lab for the measurements. The data of the beacon we used in our measurements are listed in Table (3). Using Eq. (13) with $R \approx 2.5\times10^{19} km$ in the 5 days we measured, $d = 3475 km$ and $A_e = 11.58 m^2$ and considering the fact we just measure one polarization we get the power at the terminals of the antenna: $P_R = 4.9 \times 10^{-20} W = -193 dBW$. Putting in Eq. (9) $Y_{sun} = 18.2$, $A_e = 11.58 m^2$, $T_{sky} = 10 K$ and $S_{sun} = 50 \times 10^{-22} W m^{-2} Hz^{-2}$ one gets for the system temperature $T_{sys} = 112.0 K$. Using Eq. (14) to calculate the noise power $P_S = -207 dBW$ with the $\Delta \nu$ from Table (2) one gets then a potential signal to noise ratio (SNR) to $R = 14 dB$, which would guarantee good reception.

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 $R \approx 390000 km$ in the 5 days we measured, $d = 3475 km$ and $A_e = 11.58 m^2$ and considering the fact we just measure one polarization we get the power at the terminals of the antenna: $P_R = 4.9 \times 10^{-20} W = -193 dBW$. Putting in Eq. (9) $Y_{sun} = 18.2$, $A_e = 11.58 m^2$, $T_{sky} = 10 K$ and $S_{sun} = 50 \times 10^{-22} W m^{-2} Hz^{-2}$ one gets for the system temperature $T_{sys} = 112.0 K$. Using Eq. (14) to calculate the noise power $P_S = -207 dBW$ with the $\Delta \nu$ from Table (2) one gets then a potential signal to noise ratio (SNR) to $R = 14 dB$, 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 $-199 dBW$ 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 $-199 dBW$.

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

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![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.](image-url)
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 1296 MHz is not installed in the focuspoint leads to an effective aperture \( A_e \) of only 8m² (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 \( \nu = 1691 \text{MHz} \). 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 \( P_R = 4.1 \times 10^{-20} W = -194 \text{dBW} \). The signal strength is almost equal to that of APRAXOS, \( P_N = -206 \text{dBW} \) 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)

- 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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References