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VHF antenna calibration for RFI monitoring using sky signal

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Abstract

As part of the radio frequency interference surveillance system of Nançay radio astronomy station, an inverted V dipole with dedicated front-end electronics is used for monitoring of the 15 MHz - 80MHz frequency range. Within this framework, a calibration method is required for RFI noise temperature estimation in Kelvins. Calibration on external artificial sources are a challenge at such low frequencies and on a single antenna system. On the other hand, another specificity of this frequency band is the domination of sky power over instrumental noise, which may serve as the reference external signal.

The influence of sky signal on acquired data is investigated. It is easily detected as a dB scale power modulation with a sidereal day period on the whole frequency range. The frequency dependence of this observed signal is set by the physical parameters of the sky, antenna, and following instrumentation.

We show that using a sky model integrated through the large simulated beam of the dipole, this modulation is well reproduced and excised, which is verified by measuring the residual baseline variation in time after excision.. Since the modeling gives access to frequency dependence of the incoming signal, it is used to estimate calibration parameters by fitting this model in a sidereal time/frequency plan.

As a result, a normalization gain from arbitrary power units to Kelvins is obtained, together with an estimation of the noise temperature due to electronics. A residual time variability after calibration is observed in the lowest frequencies and on months timescale, possible origins and further studies on this subject are discussed

Index Terms— One, two, three, four, five

1 Introduction

Nançay radioastronomy station is a 150 ha site in a radio quiet zone situated in the french Sologne forest, about 200 km south of Paris. The numerous instruments installed on this site are covering a large frequency range from 10 MHz up to 4 GHz. In order to monitor the RFI environment, the Nançay Surveillance Antenna (NSA) has been set up. The total 10 MHz – 4 GHz band is splitted and observed by 3 differents antennas for the 10-100 MHz, 100 MHz – 1GHz and 1 GHz – 4GHz band.
This article deals with the lowest 10-100 MHz part, observed through a LWA-like horizontal dipole. That dipole is coming from the Nenufar collaboration [1] and is fitted with its original front end electronics. This low frequency band has different constraints compared to higher frequencies, namely no directionality, a sky dominated noise in the major part of the frequency range, and an antenna lying on the ground (contrary to other NSA antennas installed on a tower at a given height). In those conditions and without any internal calibration source, the transform from arbitrary power units to Kelvins is not straightforward. One can nevertheless note that one of the specificity, namely the sky dominated noise, can be seen as an opportunity for calibration. Provided one has a good model to describe the sky signal, it can be ween as a succession of source temperatures evolving in time and covering the whole large beam of the dipole. One could thus apply the traditional calibration techniques with hot and cold load, but using the sky as the blackbody source, and the evolution of that signal in time to emulate a succession of different source temperatures.
The latter work is described here, restrained to 20 – 80 MHz frequencies due to instrumentation limitations.

2 Sky temperature below 100 MHz

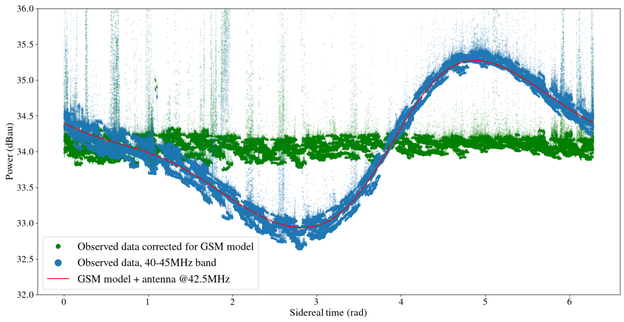

Figure 1: Observed power over several months vs. sidereal time in the 40-45MHz band (blue), simulated power profile adjusted by a dB offset (red), and correponding residuals after substraction (green)

The power signal acquired in a given band below 100 MHz can be seen to fluctuate periodically in time. That fluctuation can clearly be identified by simply plotting data with respect to sidereal time. An example is shown in Figure 1, where the blue markers are the raw signal integrated in the 40-45MHz band, the red line is a model, and the green markers are data after substraction of the model. The signal being periodic in sidereal time, this method naturally allows to accumulate data to refine the model (the plot above is based on about 6 months of data). The shape of the fluctuation being rather smooth, it is rather easy to fit a model on raw data without any prior hypothesis. We are using a homemade method based on both spline interpolation and iterative rejection of outliers, but a simple median filter may also do the job.
The excision of the sky signal in time is thus rather straightforward. From a ~2.5 dB variation, this allow to bring the residual fluctuations down to 0.1dB or less, which is compatible with the noise level in each subband.
Neverthess, while this behaviour in time can be easily deduced from the data, the dependence in frequency is harder to catch : the sky signal frequency dependence is mixed with unknown instrumental frequency dependent features (antenna, frontend..).
In order to calibrate the data in Kelvins unit, we thus have to get a valid model of the frequency dependence of the sky signal.

3 Sky signal modeling

The sky signal is basically the results of the sky above the antenna at a given moment, seen through the radiation pattern of the dipole antenna. Mathematically we need to convolve a sky map in Kelvins with the antenna's radiation pattern.

3.1 Antenna radiation pattern

The antenna radiation pattern is obtained through simulations using the momentum method (NEC2 software). While this method may have a limited accuracy especially for low incidence, the details of the radiation pattern are of negligible consequence on the final results. The convolved skymap will essentially be a very low resolution version of the sky with one single large pixel. Further iterations could nevertheless refine the modeling taking better into account more subtle characteristics of the radiation pattern (near horizon gain, environment modeling…). There was no ground plane for this study, which is another way the system could be improve. The soil surrounding the antenna is modelled as an imperfect conductor using the Sommerfeld/Norton method with average parameters for typical wet/dry soil.

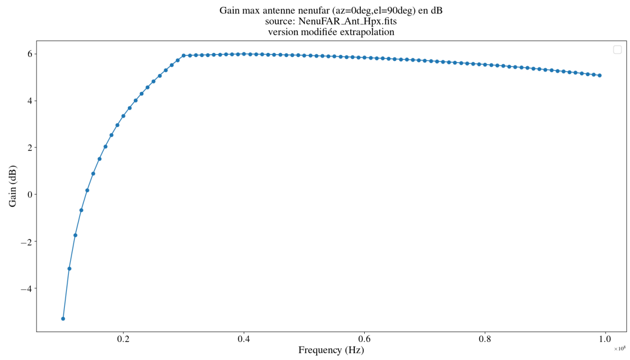

Figure 2: Antenna maximum gain vs. frequency as simulated by NEC2

The results are shown on Figure 2, with maximum gain towards zenith being at maximum around 30 MHz, with a slow decay towards high frequencies and a steep loss of gain at lower ones.

3.2 Brightness temperature skymap

The sky model is computed from the Global Sky Model (GSM) [2], gathering data from 10 MHz to 100 GHz. The brightness temperature for each point of the skymap is computed for a given sidereal time and a given observer position, as a function of frequency (see Figure 3).

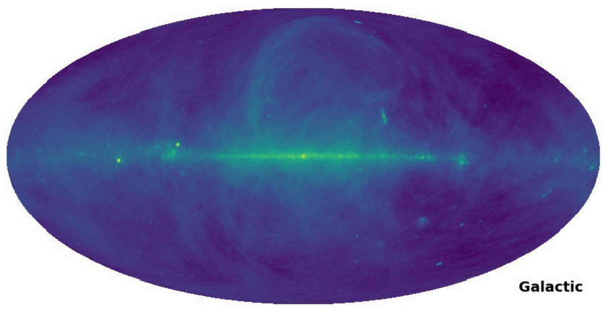

Figure 3: example of GSM map

Let $T_B(\theta,\varphi,ts,F)$ be the brightness temperature in (azimuth, altitude) direction (θ,φ), at sidereal time ts and at frequency F, and $G(\theta,\varphi,F)$ the gain pattern of the antenna.
The antenna temperature due to sky signal $T_B(ts,F)$ is expressed as:

$$T_A(ts,F) = \frac{1}{4\pi} \iint_{\theta,\varphi} G(\theta,\phi,F)\, T_B(\theta,\phi,t_s,I \quad (1)$$

The resulting map of antenna temperature with respect to sidereal time and frequency is shown in Figure 4.

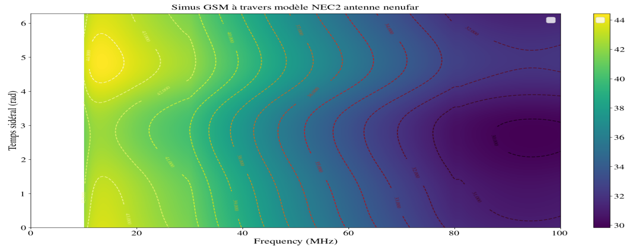

Figure 4: Modeled antenna temperature (dB scale) in the sidereal time/frequency plane

5 Sky signal excision and calibration

5.1 1st approximation : gain only

Our calibration model is a classic linear one with 2 parameters, namely a gain term and an temperature offset term.

$$T_{receiver}(F) = G(F).T_{sky}(F) + T_{noise}(F) \qquad (2)$$

Where $T_{receiver}$ is the measured temperature, G is the gain term and T_{noise} the offset term to be determined, Tsky is the sky temperature model, and F is the frequency.
We expect T_{noise} to have a large contribution from electronic noise. Since the frontend noise temperature is on the order of 100K, while the sky temperature is of the order of 1000K or more in most of the band, we make a first evaluation neglecting the offset term.
The only parameter left to be determined is the gain term, that is estimated by forming the $T_{receiver}/T_{sky}$ ratio, i.e. observed data over modeled ones.

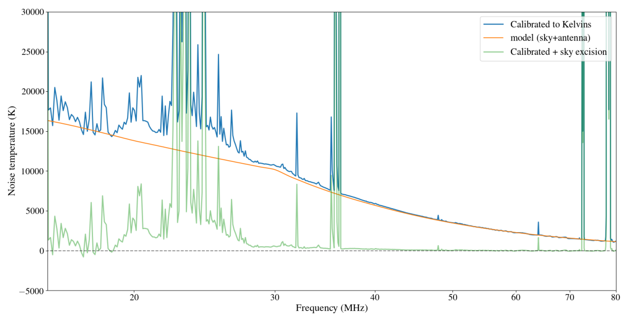

Figure 5: blue: Observed power spectrum converted to Kelvins using the computed gain (see text, to be compared to raw spectrum shown in figure 3), orange: Noise temperature model as simulated with GSM and antenna radiation pattern, green: Residual power spectrum in Kelvins after sky model substraction.

The resulting ratio is smoothed in frequency by the iterative spline based method already mentioned above in order to reject outliers (here mainly the emission lines in the spectrum). Once the gain term is estimated, the raw data can be translated to K and the sky signal may be excised. An example result is shown in figure 5

5.2 Full model fit

In order to refine the modeling, we take the offset term into account together with the gain term. They are both determined by a linear fit of the modeled sky signal in sidereal time on the data in each subband, once gain using iterative spline interpolation. One may see the good match between the model and data shape vs. time on Figure 1.

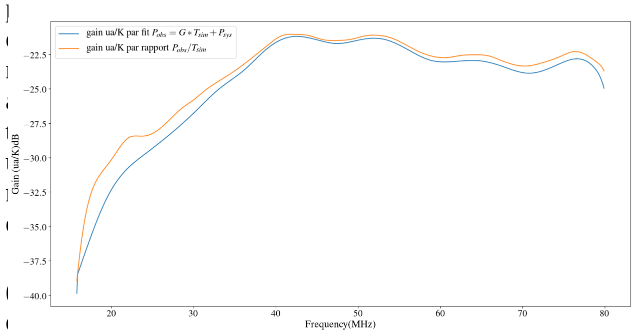

Figure 7: orange : gain term computed without offset term (ratio). blue: gain term computed with full fit on data

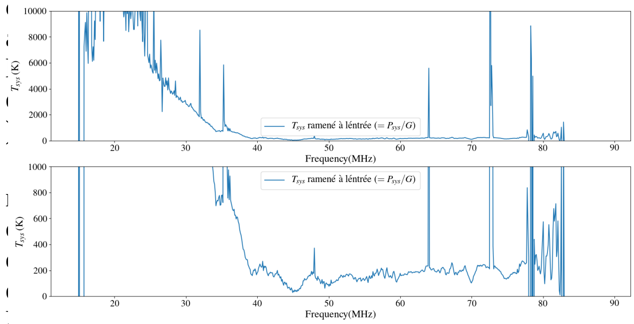

Figure 8: Offset term (Tnoise) computed by full fit on the data (bottom is a close up of top graph)

The results are presented in Figure 7 and 8. One may note the influence of the offset term introduction on the gain, especially at low frequencies.
The estimated T_{noise} has the right order of magnitude, with a steep rise below 40 MHz that may be due to electronic noise/antenna electrical efficiency drop.

Conclusion

It has been shown that sky signal below 100 MHz on a dipole antenna can be used for data calibration through the use of antenna modeling and skymap simulation.

As a result the raw data may be translated into Kelvins unit, sky signal may be excised, and we gained insight on our instrumentation chain.
The offset term is determined with a dispersion of the order of 100s of Kelvins, which is limited though largely sufficient for strong RFI work.
Several points could be investigated for further improvement, namely ground screen for the antenna, modeling of close environment, and independent modeling/measurement of the frontend electronics.
One possible path that we began to explore is using polynomials to allow smooth gain variation in addition to the presented skymap based modeling. This effective model on the data is improving the quality of the fit. Interestingly, the day by day polynomials determined on data are showing a recurring behaviour from day to day, which seems to indicate this method does correct for some systematic errors in the skymap based model, which we will study further.
Also the lowest frequency part (< 30 MHz) is challenging, since it is crowded with RFI lines, fluctuating and in a region of low efficieny for the instrumentation chain. We plan to get insight on that thanks to long term monitoring of the spectrum features.

References

[1] P. Zarka et al., “The low-frequency radio telescope NenuFAR”, URSI GASS 2020, Rome, Italy, 29 August - 5 September 2020.

[2] A. De Oliveira-Costa et al., “A model of diffuse Galactic radio emission from 10 MHz to 100 GHz”, Monthly Notices of the Royal Astronomical Society, Volume 388, Issue 1, pp. 247-260.