

# A calibration of the small solar radiotelescope using a new moon

## Abstract

Background: Defining the solar brightness temperature at centimetre wavelengths has always been challenging. One of the main reasons has been the lack of a proper calibration source. We carried out observations at 2.7 cm (11.2 GHz) by using the New Moon for the solar brightness temperature calibration. The solar and Moon observations were made using the 1.8-meter radiotelescope operated by the Aalto University Metsähovi Radio Observatory in Finland. In this article, we present our method for defining the brightness temperature of the quiet-Sun level (QSL). Based on these observations, we found  $11\,500\text{ K} \pm 1500\text{ K}$  to be the mean value for the QSL temperature. This value is quite similar which was reported earlier.

**Keywords:** radiotelescope, radio observations, solar brightness temperature, quiet-Sun level (QSL), lunar brightness temperature

Volume 3 Issue 3 - 2019

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**Received:** February 13, 2019 | **Published:** May 10, 2019

## Introduction

Defining the solar brightness temperature at centimetre has always been difficult. One of the main reasons has been the lack of a proper calibration source. The New Moon has discovered to be a stable and a sufficient powerful calibration source. The most recent studies are made by.<sup>1-3</sup> The solar brightness temperature calibration makes possible that all the other detected solar radio burst can be scaled more reliable to the quiet-Sun level (QSL) temperature. The emission at 11.2 GHz originates either in the upper chromosphere or in the transition region. More accurately defined brightness temperature value of the QSL could also explain the origin of the emission more carefully. The main purpose of this work is to find calibrated solar brightness temperature at 11.2 GHz. In addition, we want to study the beam shape of the radiotelescope. For proper radiotelescope calibration, it is useful to know the beam width, shape and possible beam side lobes as well. This work is continuation to study done by<sup>1</sup> and the methods used in this study are consistent with them.

## Instrumentation

Metsähovi MRO-1.8, located at Metsähovi Radio Observatory (MRO), Aalto University (Helsinki Region, Finland, GPS coordinates: N60°13.04', E24°23.35'), is a radio telescope with a 1.8 m dish diameter dedicated for continuous solar observations. The operation frequency range of the radiotelescope is between 10.7 and 11.7 GHz. The front-end of the receiving unit is a low-cost commercial component, a low-noise block down converter (LNB), which converts radio frequency to the intermediate frequency (950-1950 MHz). And finally, the total power of the intermediate frequency band will be sampled and recorded. The telescope's system temperature is higher than 300 K. The full documentation of MRO-1.8 radiotelescope can be found from.<sup>4-6</sup> In Figure 1, MRO-1.8 radiotelescope is shown. MRO-1.8 radiotelescope has been operational since 2001 and it has detected more than a hundred solar radio bursts.<sup>5</sup> Besides studying versatility solar radio burst properties,<sup>5,7</sup> for instance oscillation features have been studied using MRO-1.8<sup>8</sup>.



**Figure 1** A photograph of MRO-1.8 radiotelescope. Two log-periodic antennae attached to both sides of the dish observe the Sun at the decimeter wavelengths.

## Observations

The calibration observations were made between winter 2018 and spring 2019. Totally six consecutive Sun-Moon-observations were made; the lunar map was observed at first and immediately after this, solar map was made. The observations were raster scan maps (30 sweeps) over the Sun (Figure 2) and the Moon (Figure 3) disks. The radiotelescope is not designed for scanning observations, thus it took ca. 30 minutes to make one raster map. The radiotelescope is designed to track Sun continuously. The full raster scan map was made with the size of 3 degrees x 3 degrees. A single step in the raster scan map was 300 millidegree, thus one raster map consists on 441 measurement points. The step size is roughly one third of the full beam size. In Table 1, a summary of all observations is presented. The consecutive Sun-Moon-map combinations are made similar elevation ranges ( $\pm 5$  degrees). Observation days were selected so that the activity of the Sun at 11.2 GHz was low. A cosine correction is applied to the results to eliminate the effect of the changing elevation during each raster scan map. The previous study<sup>1</sup> was made at 37 GHz. That frequency

is more sensitive for the prevailing atmospheric (weather) conditions than 11.2 GHz. MRO-1.8 radiotelescope has no protective radome.

**Table 1** Summary of Sun-Moon observations: date, offset (in days) from the New Moon, the calculated Moon brightness temperature, the Sun brightness temperature and the activity status of the Sun

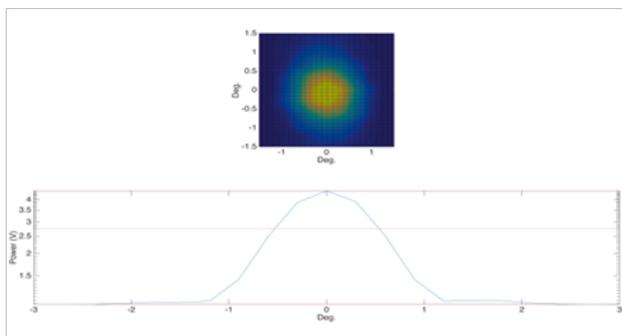
Date	Offset (day)	$T_{moon}$	$T_{sun}$	Status of the Sun
12/13/2018	6	232.8	11 347	Very minor activity
2/4/2019	0	232.3	11 882	Small activity
2/5/2019	1	231	10 831	Small activity
2019-02-06 (1)	2	230.2	12 863	Small activity
2019-02-06 (2)	2	230.2	10 032	Small activity
2/8/2019	4	230.4	12 272	Small activity

### Defining the solar brightness temperature at 11.2 GHz

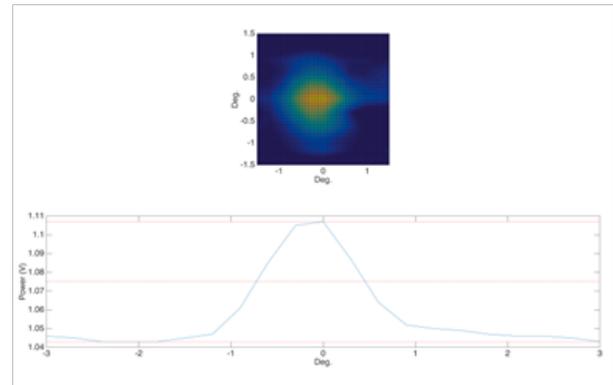
In Figure 2, the most upper read line indicates the solar maximum intensity. Actually, this intensity is a sum of solar and background (sky) intensities ( $I_{sun} + I_{background}$ ). The lowest read line indicates only the background (sky) intensity ( $I_{background}$ ), thus the difference between these values is a real solar intensity ( $I_{sun}$ ). Similar deduction is applying for the Moon, Figure 2 ( $I_{moon}$ ). The maximum and minimum intensities were also verified from the raster maps (upper plots in Figure 2 & Figure 3). The maximum intensity was typically found from the middle sweep (lower plots in Figure 2 & Figure 3) of the raster scan map. If the pointing of the telescope is not perfect, then the middle sweep will not be fully reliable. That is why the raster scan maps were made.

After that, the Sun-Moon-ratio ( $r_{sun\_moon}$ ) can be calculated as  $I_{sun} / I_{moon}$ . The Moon brightness temperature  $T_{moon}(v)$  is described as<sup>2</sup>

$$T_{moon}(v) = T_0(v) + T_1(v) \cos(\omega t - \xi(v))$$



**Figure 2** In upper plot, a raster scan map of the Sun and in lower plot, the middle sweep (15 out of 30) over the solar disk. In upper plot, the yellow colour indicates high intensity and the blue colour indicates low intensity (=sky intensity).



**Figure 3** In upper plot, a raster scan map of the Moon and in lower plot, the middle sweep (15 out of 30) over the lunar disk. In upper plot, the yellow colour indicates high intensity and the blue colour indicates low intensity (=sky intensity).

where the mean brightness ( $T_0(v)$ ) temperature over a lunation at 11,2 GHz is 218 K. The amplitude of the 29.3-d first harmonic ( $T_1(v)$ ) is 12 K. And the phase shift ( $v$ ) of this harmonic as measured from the time of the New Moon is  $35^\circ$ .  $\omega$  is the angular frequency of the lunar cycle ( $12.26^\circ$  per day). The Moon brightness temperatures ( $T_{moon}$ ) during the observations are summarized in Table 1. Finally, the solar brightness temperature ( $T_{sun}$ ) can be defined as  $T_{moon} \times r_{sun\_moon}$ . This value is the quiet Sun level (QSL) at 11.2 GHz. The observed solar brightness temperatures are also presented in Table 1. The values for all the observing sessions are the mean QSL brightness temperature 11538 K, the minimum QSL temperature 10032 K and the maximum QSL temperature 12863 K. From our measurements, we conclude that the solar brightness temperature at 8 mm is 11500 K $\pm$ 1500 K.

### Beam pattern

The full width half power (FWHP) on the radiotelescope is defined as  $1.02 \times \lambda/D$ , where  $\lambda$  is the used wavelength and  $D$  is the diameter of the radiotelescope's main reflector<sup>9</sup>. Thus at 11.2 GHz FWHP is 0.87 degree. This is an ideal, the theoretical beam width. Our measurement, on the basis on solar scans over the solar equator, showed that the beam width is  $1.09^\circ$ . The difference between these values is clear; the radiotelescope's design is not ideal. The middle red line in Figure 2 and Figure 3 indicates FWHP. In addition, small side lobes are detected distance of 1.5 degree from the top of the telescope's main lobe. However, the side lobes are only 2 % higher than the sky intensity, which can be seen in Figure 1 (position of the weak side lobe is marked as a blue arrow). The Moon is too weak source to study side lobe effect. We cannot see any clear indication on side lobes in Figure 3 (lower plot). We can conclude that the feed and other telescope mechanics are designed properly. The raster scan map was made with size of 3 degrees x 3 degrees, thus if there are side lobes with the distance more than 3 degrees from the main lobe, we did not notice those.

### Conclusion

Our observations showed that the QSL temperature value at 11.2 GHz is 11 500 K $\pm$ 1500 K. This value matches the values that have mostly been used in the literature so far, 12 000<sup>5</sup> K and 12 200 K<sup>2</sup>. The

defined QSL temperature is so low that we can assume that the emission originates from the upper chromosphere more than the lower part of the transition region. MRO-1 radiotelescope has been previously used only for the solar observations. This was the first attempt to observe other source than the Sun. The telescope's system sensitivity was also sufficient for the lunar observations. Maybe other stable radio sources could also be used for the calibration purposes *e.g.* Jupiter. This should also be tested in the nearest future. The possible error sources are the fact that observations are made at relatively low elevations (<20 degrees) angles. The radiotelescope is not designed for raster scan mapping and single map observations took more than 30 minutes. On that period of time, atmospheric condition may vary. In the future, we have to study if the single sweeps (middle sweep) could be decent for the calibration analysis. We will start the calibration observations on a regular basis (monthly) near the occasions of New Moon. The telescope is dedicated only for solar observations, thus the time for the calibration observation can be arranged easily. The calibration should be made times when Sun's activity status is low; high solar activity may distort the observation results. In addition, the weather conditions should be reasonable during the calibration observation sessions. The MRO-1.8 radiotelescope has also calibration (noise) diode injection possibility. The noise source can be controlled remotely. We will try to find a solution to use more effectively noise source, and could we use it also in calibration purposes (brightness temperature definition). One of the main results is that we got a confirmation that the calibration method for defining QSL brightness temperature is functional even if the radiotelescope is smaller than in the previous study,<sup>1</sup> sensitivity is lower and the observation frequency range is different.

## Acknowledgments

None.

## Conflicts of interests

Authors declare that there is no conflict of interest.

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