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Solar radius at sub-THz frequencies and its relation to solar activity

F. Menezes & A. Valio

[1] Center for Radio Astronomy and Astrophysics Mackenzie (CRAAM), Mackenzie Presbyterian University
e-mail: fabian.menezes@mackenzista.com.br, avalio@craam.mackenzie.br

Abstract. In the optical wavelengths, the solar radius is 695 700 km and this is what defines the photosphere. However, as the altitude increases, the electromagnetic radiation is produced at other frequencies, causing the solar radius to change as function of wavelength. The radius measurements and its dependence on the solar cycle enable a better understanding of the solar atmosphere. We measure the solar radius at the subterahertz frequencies of 0.212 and 0.405 THz – *i.e.*, the altitude where these emissions are primarily generated – and also analyse the radius variation over the 11-year solar activity cycle. For this, we used radio maps of the solar disk for the period between 1999 and 2017, reconstructed from daily scans made by the *Solar Submillimeter-wave Telescope* (SST), located at the Argentinean Andes. Our measurements yield radii of 966.5″ ± 2.8″ for 0.2 THz and 966.5″ ± 2.7″ for 0.4 THz. This implies a height of (5.0 ± 2.0) $\times 10^6$ m above the photosphere. Furthermore, we also observed strong anti-correlation between the radius variation and the solar activity at both frequencies.

Resumo. Em comprimentos de onda visíveis, o raio solar com um valor de 695 700 km define a fotosfera, a superfície visível do Sol. No entanto, à medida que a altitude aumenta, a radiação eletromagnética é produzida em outras frequências, fazendo com que o raio solar varie em função do comprimento de onda. As medidas do raio e sua dependência com ciclo solar permitem uma melhor compreensão da atmosfera solar. Medimos o raio solar nas frequências de subterahertz de 0,212 e 0,405 THz, isto é, a altitude onde essas emissões são geradas dominantemente - e analisamos a variação do raio ao longo do ciclo de atividade solar de 11 anos. Para isso, utilizamos mapas de rádio do disco solar para o período entre 1999 e 2017, reconstruídos a partir de exames diários realizados pelo *Telescópio Solar Submilimétrico* (SST), localizado nos Andes argentinos. Nossas medições revelaram raios de 966.5″ ± 2.8″ para 0,2 THz e 966.5″ ± 2.7″ para 0,4 THz. Isso implica uma altura de $(5,0 \pm 2,0) \times 10^6$ m acima da fotosfera. Além disso, observamos uma forte correlação entre a variação do raio e a atividade solar em ambas as frequências.

Keywords. Sun: atmosphere – Sun: chromosphere – Sun: fundamental parameters – Sun: radio radiation

1. Introduction

The solar radius is a very important parameter for the calibration of solar atmospheric models.

In this work, we measure the solar radius at subterahertz frequencies of 0.212 and 0.405 THz throughout 18 years, from 1999 to 2017, and its variations due to solar activity. More information on this work is available in Menezes & Valio (2017).

2. Observations and Data

The data used for this study are from the Solar Submillimeter-wave Telescope (SST) [Kaufmann et al. (2002)], installed at El Leoncito Astronomical Complex, Argentina. SST is a multi-beam radio telescope operating at 0.212 and 0.405 THz, with a HPBW [1] of 2′ and 4′, respectively.

To determine the solar radius, we used 67 000 maps of the whole Sun, which were created from azimuthal scans (Figure 1, *top-left*). First, we set the background and quiet-Sun values (respectively first and second highest peaks in Figure 1, *top-right*) so that the solar limb level is set as the mean value of them (*middle horizontal line* in Figure 1, *bottom-left*). Then, the coordinates corresponding to the solar limb level are fit by a circle yielding the circumference center (Figure 1, *bottom-right*) and the radius, that is the mean distance between limb coordinates and the center. After this procedure (for all the maps), the resulting radii values were corrected for the Earth's orbit eccentricity.

We used the Pearson correlation coefficient (PCC) to check for any correlation between solar activity and solar radius variations. The solar activity proxy used for this was the sunspot number (SSN; SILSO data, Royal Observatory of Belgium, Brussels).

[1] Half-Power Beam Width

Table 1: Values of mean sub-THz radii, optical radius [Mamajek et al. (2015)] and altitude above the photosphere.

Frequency	**R** (arcsec)	**R** ($R_\odot$)	**R** (10^8 m)	**Altitude** (Mm)
212 GHz	966.5 ± 2.8	1.007 ± 0.003	7.01 ± 0.02	5.0 ± 2.0
405 GHz	966.5 ± 2.7	1.007 ± 0.003	7.01 ± 0.02	5.0 ± 2.0
Optical	959.63	1	6.957	0

3. Results and discussion

The mean radius obtained for both 0.212 and 0.405 THz was 966.5″ with rms of 2.8″ and 2.7″, respectively (Figure 2). These results are also summarised in Table 1.

To check for consistency, we ploted our results with those from other authors in Figure 3. As can be seen from the figure, the emission altitude decreases exponentially with frequency. Our results, shown as stars in the plot, are in good agreement with previous ones.

We also compared our results to a simple model of the Sun – *i.e.* a solar disk with constant intensity over the disk and a radius of 966″. Then this model was convolved with SST's reconstructed beams. Lastly, we also calculated the solar radius from ALMA's 0.239 THz solar map that resulted in a radius of 964.9″ ± 2.8″, *i.e.* a difference of 1.6″.

In addition to the solar average radius, we investigated the dependence of the solar radius on solar activity (or sunspot number). The temporal series are shown in Figure 4, where the PCC yield correlation coefficients of $\rho_{0.212\text{THz}} = -0.755$

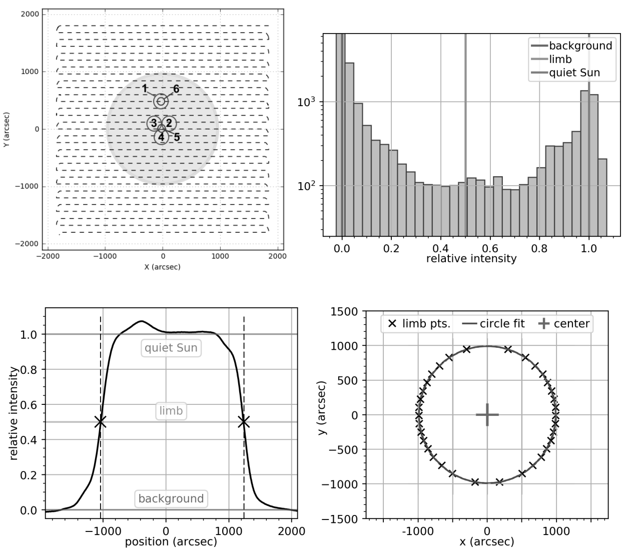

FIGURE 1: *Top-left*: Scans over the solar disk made by SST. *Top-right*: Histogram of the temperature values from the scans. *Bottom-left*: Definition of the solar limb points of a single scan. *Bottom-right*: Limb coordinates with circle fit.

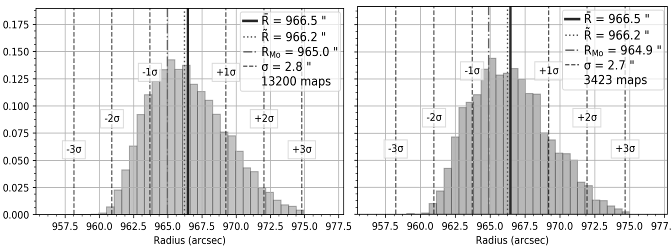

FIGURE 2: Histogram of the solar radius values at 0.212 THz (*left*) and at 0.405 THz (*right*).

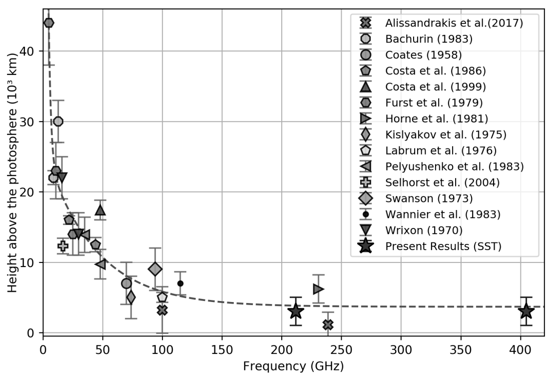

FIGURE 3: Previous altitude values as a function of the frequency from other authors and including our present results. The dashed line represents a double exponential curve fit to the points.

and $\rho_{0.405\mathrm{THz}} = -0.853$. These values indicate a strong anti-correlation between the 11-year solar activity cycle and the temporal variation of sub-THz radii.

4. Conclusions

The mean sub-THz radii estimated in this work implies that most of the emission originates in the chromospheric layer of the solar atmosphere considering the measurements uncertainty. On

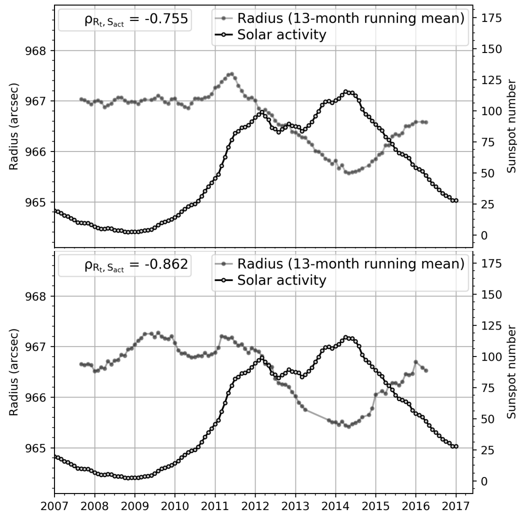

FIGURE 4: Radius temporal variations (*gray lines*) and sunspot number (*black lines*) from 2007 to 2017. *Top*: 212 GHz. *Bottom*: 405 GHz.

the other hand, the anti-correlation between the radius and solar activity may be related to the existence of polar brightenings that are anticorrelated to the solar magnetic cycle.

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