Monitoring the brightness temperature of the Moon throughout the lunar cycle from radio observations in the Ku band

David Galeano¹ and Edwin A. Quintero²
Alfa Orion Astronomy Research Group. Astronomical Observatory, Faculty of Basic Sciences, Universidad Tecnológica de Pereira, Complejo Educativo La Julita, Risaralda, Colombia.
E-mail: ¹david.galeano@utp.edu.co, ²equintero@utp.edu.co

Abstract. Within the spectrum of radio waves, the Ku band (12 - 18 GHz) stands out for the wide range of instruments available and for its relative ease of acquisition, given that satellite television operates in this band. This situation offers a great opportunity for the development of radio astronomy in countries with unfavorable climatic conditions for optical astronomy, since this band is only affected by dense masses of water vapor. In this article we present a methodology for the calibration of the receiver system of compact Ku-band radio telescopes, and its application in the determination of the brightness temperature of the Moon. Our methodology involves modeling the influence of the atmosphere of the Earth on the response of the radioreceptor, which minimizes the error in the calculation of the brightness temperature of the observed object. We applied the proposed methodology in the monitoring of the Lunar cycle using the Ku-band radio telescope of the Observatorio Astronómico de Universidad Tecnológica de Pereira, Colombia (OAUTP). After observing during May, June, and July of 2021, we obtained an average temperature of 213.15 K, with maximum and minimum values of 275.55 K and 150.75 K, respectively. In addition, we evidenced a delay of 5.75 days between the phase in which the maximum temperature is presented and the phase of the full Moon, which is consistent with the frequency of observation. The results show that our methodology is useful to optimize the calibration of compact Ku-band radio telescopes, and expand the potential of this type of instrument for the scientific study of radio sources other than the Sun, in this case the Moon.

1. Introduction
The observation of the Moon on radio waves dates back to the early 60s, shortly before the first moon landing of the Apollo missions. The success of the Apollo 13 mission made it possible to extract material from the lunar surface [1], thus stimulating the study of the thermal properties of regolith [2]. This motivated radio wave lunar observation in the mid-70s [3]. Since then, baseline radio astronomy has been a key tool in the development of the thermal profile of the Moon, which has made it possible to determine its temperature in the range of microwave spectrum [4], [5], [6], and its use as a reference for the calibration of radio telescopes [5], [8]. At present, the development of satellite technology has benefited the sending of probes into the lunar orbit, strengthening studies of the Earth’s natural satellite using radio astronomy [10].

Centimeter wavelength radio astronomy, specifically in the Ku band, does not require exceptional observation conditions to obtain useful scientific data from the celestial bodies under

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
This makes it an alternative for monitoring the brightness temperature of the Moon in countries with unfavorable climatic conditions, having as the only obstacle dense masses of water vapor. In addition, the apogee of satellite communication in the 1990s put to the market a wide range of low cost, readily available Ku-band centered and easy to acquire radio receivers. Thanks to this, amateur astronomers and small-scale observatories have managed to dabble in radio astronomy, through radio telescopes developed with elements typical of satellite television. These devices, consisting of parabolic antennas of around 1 m in diameter, have been used successfully in solar and lunar observation. In 2018, at the Observatorio Astronómico of Universidad Tecnológica de Pereira, Colombia (OAUTP), we developed a radio telescope focused on the observation of radio sources in the Ku band. This equipment is composed of a 1.2 m parabolic mesh type antenna, which is supported on a motorized altazimuth mount with a maximum resolution of 0.2 °. As presented in [20], the instrument has been successfully used in the observation of the Sun, the Moon, and the Milky Way. Although the methodology presented in [20] for the calibration of the receiver system allowed to calculating the brightness temperature of the Sun and the Moon, yielding values of 10441 K and 264 K respectively, this methodology does not consider the influence of atmospheric noise at different altitudes, a determining factor in calculating the brightness temperature of the Moon.

In this paper, we present a methodology for the calibration of the positioning system (Section 2.1) and the receiver system (Section 2.2) of compact radio telescopes. Given the need to reduce noise sources, we developed an atmospheric model from the change in the output in the radio receiver when observing different altitudes. This model makes it possible to identify the magnitude of the noise generated by the receiving system, the atmosphere, and the cosmic microwave background, and then remove them from the signal thrown by the radio telescope when aiming at the object of interest. In addition, we expose the technique used for observing the Moon (Section 2.3) and calculating its brightness temperature at 11 GHz (Section 2.4). To optimize the process, we introduced the “Lunar Cycle” utility, which we included in the Compact Radio Telescope software (Section 2.5) [20]. The methodology was validated by recording the brightness temperature of the Moon during its translation cycle in the months of May, June, and July 2021 with the Ku-band radio telescope of the OAUTP (Section 3).

2. Methodology
We present a methodology for the calibration of the reception system of compact radio telescopes, focused on the calculation of the brightness temperature of the Moon. This methodology is included in a window of the software Compact Radio Telescope (CRT) [20] available at: https://observatorioastronomico.utp.edu.co/radioastronomia/compact-radio-telescope-crt-software.html. This tool facilitates the observation of the Moon, the calculation of its brightness temperature and the storage and processing of the recorded data. The methodology is made up of the following stages.

2.1. Calibration of the positioning system
The correction of the error in the positioning is carried out following the methodology presented in Section 2.1 of [20]. The procedure consists of carrying out the solar observation through a square matrix. In the resulting matrix, each node represents the intensity of the signal at a given coordinate. This allows quantifying the difference between the central node, where the radio telescope is aiming at, and the node with greater intensity, that is to say, the actual position of the object. Figure 1 shows the result obtained after executing the observation of the Sun through a 2 x 2 matrix with 0.2 ° resolution. There it can be observed that the Sun is located in the center of the grid, which indicates that the antenna is calibrated correctly in terms of its positioning.
2.2. Calibration of the receiver system

The calibration of the receiver system focuses on identifying the noise sources that alter the output signal emitted by the radio telescope. Among these sources is the temperature of the system \( T_{\text{sys}} \), which is defined as the thermal noise provided by the electronic system of the radio receiver \[15\]. Although in \[20\] we present a method for calculating \( T_{\text{sys}} \), it does not take into account the influence of factors external to the reception system such as atmospheric noise and the cosmic microwave background. Since the response signal from the instrument represents an indirect measurement of temperature, changes in the density of the atmosphere at different altitudes result in an increase in the noise present in the detected signal \[21\]. According to \[22\], to determine the influence of the atmosphere, it is necessary to record the response of the radio telescope when observing different altitudes. Table 1 shows the voltage value that was obtained when aiming the antenna of the Ku-band radio telescope of the OAUTP at altitudes from 90 ° to 10 °, in steps of 10 °.
Table 1. Voltage response of the Ku-band radio telescope of the OAUTP when observing altitudes from $90^\circ$ to $10^\circ$.

| Altitude ($^\circ$) | $1/\sin(\text{Altitude})$ | Output (V) |
|--------------------|---------------------------|------------|
| 90                 | 1                         | 0.0373     |
| 80                 | 1.015                     | 0.0375     |
| 70                 | 1.06                      | 0.0374     |
| 60                 | 1.15                      | 0.0411     |
| 50                 | 1.3                       | 0.0412     |
| 40                 | 1.55                      | 0.0395     |
| 30                 | 1.99                      | 0.0406     |
| 20                 | 2.92                      | 0.0448     |
| 10                 | 5.75                      | 0.0747     |

As shown in Figure 2 [22], the response given by the radio receiver when aiming at an altitude of $90^\circ$ represents the reading of the system temperature ($T_{sys}$), the cosmic background noise ($2.7 K$) and the atmospheric emissions ($T_{zen}$), which increase at low altitudes. By constructing a linear regression of the form $y = mx + b$ for the voltage signal as a function of the inverse of the sine of the altitude, it is possible to quantify the magnitude of each noise source. Figure 3 represents the trend curve of the results obtained in Table 1 and the constants “$m$” and “$b$” of the calculated linear regression.

Once the linear regression has been constructed, as shown in Figure 3, it is necessary to direct the radio telescope to an object whose temperature is known ($T_{ref}$), recording the voltage response generated by this object at the radio receiver output ($V_{ref}$). At this point, the contributions of the atmosphere are negligible. Consequently, $V_{ref}$ represents the noise of the electronic system $b$ plus the stimulus in voltage generated by $T_{ref}$. Although atmospheric noise is minimal at this point in the calibration process, it is necessary to take into account the cosmic microwave background, reason why its magnitude ($2.7 K$) must be subtracted from $T_{ref}$. This interpretation makes it possible to define the constant of proportionality $a$, as presented in equation 1.
\[ a = \frac{V_{\text{ref}} - b}{T_{\text{ref}} - 2.7} \]  

(1)

The intersection with the vertical axis \((b)\) of the projection to the left of the linear regression in Figure 2 is determined by equation 2 taken from [22].

\[ b = a(T_{\text{sys}} + 2.7K) \]  

(2)

After replacing the value of \(a\) in equation 2 and carrying out the necessary clearance, equation 3 is obtained. This shows the direct relationship of \(T_{\text{sys}}\) with the values obtained for \(b\), \(T_{\text{ref}}\) and \(V_{\text{ref}}\). In addition, the reduction of noise generated by the cosmic microwave background of 2.7 \(K\) is shown, which is present in all the observations, regardless of the direction observed.

\[ T_{\text{sys}} = b\frac{T_{\text{ref}} - 2.7}{V_{\text{ref}} - b} - 2.7 \]  

(3)

Returning to Figure 2, it should be noted that the zenith temperature is obtained by evaluating the linear regression at \(1/sin(\text{Altitud}) = 1\), subtracting \(b\) from the value obtained. Since this result presents units of tension \((V_{\text{zen}})\), it is necessary to divide it by \(a\), thus arriving at equation 4. This equation defines the zenith temperature \((T_{\text{zen}})\) as the ratio between \(m\) and constant \(a\), obtained in the previous procedure.

\[ T_{\text{zen}} = \frac{m}{a} \]  

(4)

By aiming the radio telescope at the dome of the OAUTP when it was at 292.15 \(K\), we recorded a voltage value of 0.0817 \(V\). The quantities \(T_{\text{sys}}, a \) and \(T_{\text{zen}}\) presented in Table 2 were obtained from this value. Another important parameter presented in Table 2 is the full width of the antenna beam \((FPBW)\). This represents the resolution of the parabolic dish and defines the radiation zone of the antenna where the reception of the signal is adequate. The calculation of this variable for the Ku-band radio telescope of the OAUTP is explained in detail in [20].

### Table 2. Operation parameters of the Ku-band radio telescope of the OAUTP obtained after the calibration of the receiver system.

| \(m\) | \(b\) | \(T_{\text{sys}}\) | \(T_{\text{zen}}\) | \(a\) | \(FPBW\) |
|-------|------|-----------------|-----------------|------|---------|
| Units | \(V\) | \(V\)           | \(K\)           | \(K\) | \(\frac{mV}{K}\) | \(^{{}^\circ}\) |
| Value | 0.0074 | 0.029           | 158.6           | 40.7  | 0.1813  | 2.2        |

### 2.3. Data acquisition

As indicated in [11], the transit method is based on aiming the radio telescope towards a coordinate through which the celestial body is going to cross. The objective of this method is to capture the radiation pattern registered by the antenna while the object in question crosses its field of view at sidereal speed. For the observation of the Moon, clouds represent a considerable source of interference. Consequently, we executed the transit method by aiming at the coordinates of the Moon 2 minutes in advance, recording the transit for 15 minutes, which allows avoiding long sessions. The radiation pattern recorded when executing the transit method is presented in Figure 4. After processing the data with a second-order Butterworth digital low-pass filter, with a cut frequency of 0.02 \(Hz\), we obtained the result shown in Figure 5.
Figure 4. Lunar Transit recorded on June 21, 2021 at 11:13 through the Ku-band radio telescope of the OAUTP.

Figure 5. Lunar transit of Figure 4 after the application of a Butterworth digital low pass filter with cut-off frequency of 0.02 Hz.

When calculating the Gaussian approximation of the form \( f(x) = H + Ae^{\frac{(x-x_0)^2}{2\sigma^2}} \), we obtained the values for the constants \( H \), \( A \), \( x_0 \) and \( \sigma \) shown in Table 3. This approach allows interpolating the change in voltage generated by the Moon at the output of the radio receiver (Figure 5), which has a magnitude of 0.919 mV with respect to the background sky and a signal-noise ratio of 1.024 dB.

Table 3. Constants calculated for the Gaussian adjustment \( (f(x) = H + Ae^{\frac{(x-x_0)^2}{2\sigma^2}}) \) of the transit recorded in Figure 5.

| \( H \) | \( A \) | \( x_0 \) | \( \sigma \) |
|-------|-------|-------|-------|
| Units | mV    | mV    | s     | s     |
| Value | 37.334| 0.919 | 337.422| 139.289|


2.4. Brightness temperature

According to [23], the brightness temperature of a body represents the temperature at which a black body would radiate a radiation intensity similar to that of the object for a specific frequency. This temperature is similar to the physical temperature if the object observed behaves like a black body [3]. Before carrying out the calculation of the brightness temperature of the Moon, it is necessary to determine the temperature observed by the antenna when it is detected by the radio receiver \( (T_a) \). According to [21], the voltage at the radio telescope output when aiming at a hot body \( (V_{out}) \) represents the voltage generated by the object \( (V_a) \) plus the noise of the system \( (V_{sys}) \), the atmosphere \( (V_{zen}) \) and the cosmic microwave background noise \( (V_{fc}) \), as shown in equation 5.

\[
V_{out} = V_a + V_{sys} + V_{zen} + V_{fc} \tag{5}
\]

After multiplying equation 5 by the inverse of the proportionality constant between the output voltage and the observed temperature \( (a) \), and carrying out the relevant clearance, equation 6 is obtained. This equation relates the operating parameters of the radio telescope and the response in radio receiver voltage generated by the Moon \( (V_{out}) \), eliminating the noise contributed by \( T_{zen}, T_{sys} \) and the cosmic microwave background \( (2.7 K) \).
\[ T_a = \frac{V_{out}}{a} - T_{sys} - T_{zen} - 2.7K \] (6)

For the maximum voltage output shown in Figure 5 (38.254 mV) and the parameters obtained in Table 2, we calculated a \( T_a \) of 8.91 K. This magnitude does not represent the brightness temperature because the FPBW of the antenna is greater than the angular width of the Moon (\( \theta \)). Consequently, it is necessary to apply equation 7 \[ T_b = \left( \frac{FPBW}{\theta} \right)^2 \cdot T_a \] (7)

From the result obtained for \( T_a \), and considering an FPBW of 2.20 ° and a value for \( \theta \) of 0.55 ° for the day of observation, we calculated a \( T_b \) of 143.97 K for the lunar transit of Figure 5, when the Moon was in 321 ° in phase. The value of \( \theta \) and the phase angle of the Moon for the day of observation were taken from the prediction of the Institute of Theoretical Physics and Astrophysics of the Federal Polytechnic School of Zurich (https://portia.astrophysik.uni-kiel.de/~koeppen/10GHz/predict.html).

2.5. Software
As shown in [20], the Compact Radio Telescope software utilities are divided into the windows “Data Acquisition”, “Scanning” and “Calibration”, which allow the observation of celestial bodies and the calibration of the reception and aiming system. In the case of lunar observation, the “Calibration” window allows carrying out the tuning of the radio telescope positioning system, as shown in Figure 1. To carry out the observation of the Moon, we developed the window “Lunar Cycle”, presented in Figure 6. This application enables the calibration of the receiver system as described in Section 2.2. In addition, this new window allows carrying out the observation and make progress in the calculation of the brightness temperature as illustrated in sections 2.3 and 2.4 respectively. The software installer is available for download under the General Public License at: https://observatorioastronomico.upt.edu.co/radioastronomia/compact-radio-telescope-crt-software.html. The detailed flow diagrams and the source code of the algorithm of each window are in the User Guide, available at this same Website.
3. Results

We performed the observation of the Moon from May 1 to July 31, 2021, using the Ku band radio telescope of the OAUTP, with which the variation of the brightness temperature of the Moon at a wavelength of 2.77 cm was recorded during 3 consecutive lunar cycles. The results obtained are presented in Figures 7, 8 and 9. The construction of the closest sinusoidal approximation of the data collected was carried out for each cycle. From the obtained approximation the average temperature, the maximum temperature ($T_{MP}$) and the minimum temperature ($T_{MB}$) were interpolated. In addition, the advance ($\alpha$) between the full Moon and the maximum brightness temperature was calculated, which occurs as a consequence of the penetration capacity of electromagnetic waves at low frequencies [18]. When observed at wavelengths near the visible, such as infrared, the brightness temperature calculated represents the lunar surface temperature, so the value of $\alpha$ is minimal. As the observation wavelength increases, the calculated brightness temperature will correspond to the temperature of the rock under lunar dust, which takes longer to heat up, resulting in an increase in the magnitude of $\alpha$ [4].

3.1. May

Figure 7 shows the graphic representation of the variation of the brightness temperature of the Moon obtained as a function of the observation phase from the data presented in Table 1. The sinusoidal approximation obtained is presented in red, defined by the equation: $T_b = 227.02K + 59.14cos(\text{Phase}[°] + 80.5°)$. From the calculated curve we obtained a value for the average temperature, $T_{MP}$ and $T_{MB}$ of 227.02, 286.16 and 167.87 K respectively. The corresponding value of $\alpha$ has a magnitude of 80.5 °, corresponding to 6.26 days.
Figure 7. Sinusoidal approximation of the brightness temperature of the Moon depending on the observation phase for the month of May 2021.

3.2. June
The graphical representation of the values obtained for the month of June (Table 5) is presented in Figure 8 together with the sinusoidal approximation calculated for this cycle ($T_b = 203.54K + 64.22\cos(Phase^\circ) + 80.5^\circ$). From the sinusoidal approximation obtained we estimated a magnitude for the average temperature, $TMP$ and $TMB$ of 203.54, 267.76 and 139.32 K respectively. As seen in the lower part of Figure 8 a delay $\alpha$ of 80.5 $^\circ$ is evidenced, equivalent to 6.26 days.

Table 4. Brightness temperatures calculated for the Moon during the lunar cycle in May 2021 from observations made with the Ku-band radio telescope of the OAUTP.

| Phase[^\circ] | $T_b$[K] |
|--------------|---------|
| 102          | 269     |
| 148          | 264     |
| 263          | 154     |
| 290          | 181     |
| 332          | 209     |
| 340          | 235     |
| 343          | 204     |

Figure 8. Sinusoidal approximation of the brightness temperature of the Moon, depending on the observation phase for the month of June 2021.

Table 5. Brightness temperatures calculated for the Moon during the lunar cycle in June 2021 from observations made with the Ku-band radio telescope of the OAUTP.

| Phase[^\circ] | $T_b$[K] |
|--------------|---------|
| 19           | 239     |
| 77           | 265     |
| 97           | 276     |
| 106          | 268     |
| 150          | 205     |
| 208          | 169     |
| 254          | 145     |
| 293          | 168     |
| 321          | 145     |

3.3. July
When carrying out the observation during the month of July, the brightness temperatures presented in Table 6 were obtained. The graphic representation of the experimental data and the sinusoidal curve calculated for this case ($T_b = 214.18K + 64.78\cos(Phase^\circ) + 71^\circ$) is presented
in Figure 9. From the results obtained, we estimated the values for the average temperature, $TMP$ and $TMB$ of 214.18, 278.96 and 149.4 K respectively. As shown in the lower area of Figure 9, $\alpha$ has a value of de 71 °, equivalent to 5.52 days.

![Figure 9. Sinusoidal approximation of the brightness temperature of the Moon, depending on the observation phase for the month of July 2021.](image)

3.4. Compilation and comparison of results
By unifying the values presented in 3.1, 3.2 and 3.3, we obtained the graphical representation shown in Figure 10, in which the periodic variation of the brightness temperature of the Moon at the wavelength of 2.77 cm can be observed. After constructing the nearest sinusoidal approximation ($T_b = 213.15K + 62.40\cos(Phase[°] + 74°)$), we estimated an average temperature, $TMP$ and $TMB$ of 213.15, 275.55 and 150.75 K and a magnitude for $\alpha$ of 74 °, equivalent to 5.75 days.

![Figure 10. Periodic variation of the brightness temperature of the Moon for the cycles of May (0 - 360 °), June (360 - 720 °) and July (720 - 1080 °).](image)

The results obtained for the average temperature, $TMP$, $TMB$ and $\alpha$ after unifying the results of sections 3.1, 3.2 and 3.3 are presented in Table 7 (column 4). We compared these

### Table 6. Brightness temperatures calculated for the Moon during the lunar cycle in July 2021 from observations made with the Ku-band radio telescope of the OAUTP.

| Phase[°] | $T_b[K]$ |
|---------|----------|
| 81      | 276      |
| 156     | 221      |
| 168     | 206      |
| 179     | 197      |
| 215     | 171      |
| 227     | 137      |
| 300     | 168      |
| 305     | 200      |
| 334     | 192      |
values with those reported in the literature by works in which the Moon was also observed in the Ku band using radio telescopes with antennas of about 1 m in diameter ([19] and [18]). Columns 5 and 6 of Table 7 show a greater correspondence of our results with the values reported by [18]. This similarity is explained because the methodology implemented in [18] for the calculation of the brightness temperature of the Moon makes use of a procedure similar to that presented in [22], on which this work is based.

**Table 7.** Comparison of the results obtained from the Moon observations made using the Ku-band radio telescope of the OAUTP (This Work) against lunar cycle observations using antennas of about 1 m diameter reported in the literature

|                | Monstein (2001) [19] | Chen (2020) [18] | This Work (2021) | Difference (%) |
|----------------|----------------------|------------------|------------------|----------------|
| Average (K)    | 213                  | 196.88           | 213.15           | 0.07 % 8.26 %  |
| TMP (K)        | 236                  | 229.10           | 275.55           | 16 % 20 %     |
| TMB (K)        | 192                  | 164.44           | 150.75           | 21 % 8.3 %    |
| Delay (days)   | 5                    | 5.48             | 5.75             | 15 % 4 %      |

We compared the values obtained in this work with the results presented in the literature that focus on lunar radio observation at different wavelengths. As seen in the third column of Table 8, the average brightness temperature of the Moon decreases as the wavelength of observation increases. This variation is the result of the increase in the penetration capacity of electromagnetic waves as the wavelength increases, so the temperature reading is given in the rock under the lunar surface, which reaches a lower average temperature. On the other hand, as can be seen in the fourth column of Table 8, delay \( \alpha \) has an opposite behavior, increasing as the observation wavelength increases. Again, this phenomenon is due to the fact that the temperature reading comes from the rock under the lunar surface, which takes longer to heat up as it goes deeper.

**Table 8.** Comparison of the results obtained from the observations made using the Ku-band radio telescope of the OAUTP (This Work) against observations of the lunar cycle at different frequencies reported in the literature.

| Wavelength [cm] | Average temperature [K] | \( \alpha \) [days] |
|-----------------|--------------------------|---------------------|
| Piddington (1949) [17] | 1.25 | 292 | 3.70 |
| Monstein (2001) [19] | 2.77 | 213 | 5.00 |
| This Work (2021) | 2.77 | 213 | 5.75 |
| Chen (2020) [18] | 3.00 | 196 | 5.48 |
| Strezhenva (1961) [24] | 3.20 | 245 | 4 |

4. Conclusions

The results presented in Figure 10 show the periodic variation of the brightness temperature of the Moon during its translation cycle at the wavelength of 2.77 cm. As can be seen in the third column of Table 8, the average brightness temperature shows a considerable decrease as the wavelength increases, going from 292 K at 1.25 cm to 196 K at 3 cm. On the other hand, as observed in the fourth column of Table 8, delay \( \alpha \) increases as the observing wavelength increases, presenting a value of 3.7 days, in 1.25 cm, and 5.48 days in 3 cm. The results obtained
in this paper show the strong dependence of the average brightness temperature of the Moon and of delay $\alpha$ with the frequency of observation, which complements the values presented in the literature for these variables in the different microwave spectrum bands.

The results obtained confirm the usefulness of the methodology presented in this paper for the calibration of compact Ku-band radio telescopes when considering the thermal noise generated by the system, the atmosphere, and the cosmic microwave background. This expands the potential of this type of instrument for the scientific study of radio sources other than the Sun, in this case, the Moon. In addition, the implementation of the CRT application, and in particular the new window “Lunar Cycle”, facilitated the compilation of the brightness temperatures calculated during the evolution of the lunar cycle, allowing to visualize in real time the behavior of this variable depending on the observation phase.

The implementation radio telescopes focused on Ku-band built with satellite television technology, opens the door to the development of radio astronomy in educational institutions and in countries with volatile climatic conditions. Consequently, it is pertinent to promote collaboration between institutions that use these equipments, encouraging the observation of objects other than the Sun and the Moon through baseline interferometry techniques. Examples of similar programs are found in NASA’s RadioJove project [25] and Standford Solar Center’s Super-SID [26], which encourage the participation of low-scale observatories and amateur astronomers in radio-observation programs around the world through low-cost set ups.

Acknowledgments

The authors express their gratitude to the Vicerrectoría de Investigaciones, Innovación y Extensión de la Universidad Tecnológica de Pereira, Colombia, for its financial support in the execution of the research project “Evaluación de las Capacidades Científicas y Didácticas del Radiotelescopio en Banda KU del Observatorio Astronómico UTP”, code 3-21-1.

References

[1] Kuznetsov I A, Zakharov A V, Dolnikov G G, Lyash A N, Afonin V V, Popel S I, Shashkova I A and Borisov N D 2017 Solar System Research 51 611–622
[2] Kost P M, Linke S, Gundlach B, Lethuillier A, Baasch J, Stoll E and Blum J 2021 Acta Astronautica 187 429–437
[3] de Parter I and S Kurth W 1999 Chapter 32 - the solar system at radio wavelengths Encyclopedia of the Solar System ed Weissman P R, McFadden L A and Johnson T V (Boston: Elsevier) pp 735 – 772 1st ed
[4] Morabito D, Imbriale W and Keihm S 2008 Antennas and Propagation, IEEE Transactions on 56 650 – 660
[5] Su Y, Feng J, Zhang X, Zhou J, Li J, Kong D, Zheng L and Li C 2011 Brightness temperature distribution of the moon EPSC-DPS Joint Meeting 2011 vol 2011 p 783
[6] Williams J P, Paige D, Greenhagen B and Seton-Nash E 2016 Icarus 283 300–325
[7] Ulrich I, Cogwell J R, Davis J H and Calvert T A 1974 Moon 10 163–174
[8] hu G p, Zheng Y C, Xu A A and Tang Z S 2015 IEEE Geoscience and Remote Sensing Letters 13 182–186
[9] Kallunki J 2019 Physics & Astronomy International Journal 3 110–112
[10] Yang H and Burgdorf M 2020 Remote Sensing 12 1129
[11] Higuita J, Salazar E and Ramírez I 2019 Journal of Physics: Conference Series 1247 012034
[12] Golovachev Y, Etinger A, Pinhasi G A and Pinhasi Y 2019 International Journal of Circuits 13 690–695
[13] Saje T and Vidmar M 2017 Journal of Microelectronics, Electronif Components and Materials 47 113–128
[14] Celary D 1999 Journal of the Royal Astronomical Society of Canada 93 40 – 43
[15] Bhatia R S, Martí-Canales J, De Matos C, Fritzsche B, Haiduk F, Knochel U and Furse C 2006 IEEE Antennas and Propagation Magazine 8 144 – 152
[16] Tinti M 2013 Progress In Electromagnetics Research 37 159–170
[17] Piddington J and Minnett H 1949 Australian Journal of Scientific Research A2 63–67
[18] Chen T, Stupar D I, Welch C, Yao H and Hu Z 2020 Advances in Space Research 65 2912 – 2925
[19] Monstein C 2001 The Moon’s temperature at 2.77 cm accessed: 2021-08-1 URL https://www.
[20] Galeano D and Quintero E 2021 Astronomische Nachrichten submitted
[21] Jewell P R 2002 Millimeter wave calibration techniques Single-Dish Radio Astronomy: Techniques and Applications (Astronomical Society of the Pacific Conference Series vol 278) ed Stanimirovic S, Altschuler D, Goldsmith P and Salter C pp 313–328 ISBN 1-58381-120-6

[22] Köppen J 2020 Flux calibration of esa-dresden accessed: 2021-08-6 URL https://portia.astrophysik.uni-kiel.de/~koeppen/10GHz/flux.html

[23] Gulkis S and de Pater I 2003 Radio astronomy, planetary Encyclopedia of Physical Science and Technology (Third Edition ed Meyers R A (New York: Academic Press) pp 687 – 712 3rd ed

[24] Strezhneva K M and Troitsky V S 1962 The phase dependence of radio emission of the moon on 3.2cm The Moon vol 14 ed Kopal Z and Mikhailov Z K pp 501–510

[25] Galvis D, Galeano D and Quintero E 2019 Sun and Geosphere 14 185–191

[26] Galvis Rodriguez H, Quintero Salaza E and Cardona L 2016 TECCIENCIA 11 41–46