Intensity Calibration Method for Mingantu Radio Spectral Heliograph Images (Postprint)

Authors:

Date: 2024-06-03T00:00:00+00:00

Abstract

The Mingantu Spectral Radioheliograph (MUSER) can achieve high temporal, spatial, and frequency resolution imaging of solar radio emissions within an ultra-wide frequency band of 0.4–15;GHz. Radio brightness temperature is a crucial parameter for describing solar physical processes and plays a vital role in studying various radio radiation mechanisms, solar magnetic fields, and non-thermal particle acceleration during solar eruptions. Therefore, brightness temperature calibration of MUSER-observed images is essential. This paper introduces a method suitable for image intensity calibration of radioheliographs. Solar radio images contain structural information about the solar disk. By fitting the visibility function of short baselines from the radioheliograph to a Bessel function of the first kind, one can obtain the radio radius and intensity of the quiet solar disk in the images. Subsequently, using the Rayleigh-Jeans law and daily solar radio flux, the daily calibration factor G_c for the images can be calculated, thereby enabling intensity calibration of MUSER images. Applying this method to actual MUSER observational data, including various scenarios such as quiet Sun conditions and solar radio bursts, the error in G_c generally does not exceed 10%. The resulting quiet Sun brightness temperatures show high correlation with other quiet Sun results, demonstrating the feasibility and effectiveness of this method.

Full Text

Intensity Calibration Method for Mingantu Spectral Radioheliograph Images

ZHOU Zhi-chao[1,2], CHEN Lin-jie[1], YAN Yi-hua[1,2], WANG Wei[1]

[1]State Key Laboratory of Space Weather, National Space Science Center, Chinese Academy of Sciences, Beijing 100190
[2]University of Chinese Academy of Sciences, Beijing 100049

Abstract

The Mingantu Spectral Radioheliograph (MUSER) enables high-time, high-spatial, and high-frequency resolution solar radio imaging within an ultra-wide frequency band of 0.4–15 GHz. Radio brightness temperature is a crucial parameter for describing solar physical processes and plays a vital role in studying different radio radiation mechanisms, solar magnetic fields, and non-thermal particle acceleration during solar eruptions. Consequently, brightness temperature calibration of MUSER observational images is essential. This paper introduces a calibration method suitable for radioheliograph image intensity calibration. Solar radio images contain structural information about the solar disk. By fitting the visibility functions of short baselines from the radioheliograph to the first-order Bessel function, we can obtain the radio radius and intensity of the quiet solar disk in the image. Then, using the Rayleigh-Jeans law and daily solar radio flux, we can calculate the daily calibration factor G_c for the images, thereby achieving intensity calibration of MUSER images. Applying this method to actual MUSER observational data, including various conditions such as quiet Sun and solar radio bursts, the error in G_c remains essentially within 10%. The resulting quiet Sun brightness temperature shows high correlation with other quiet Sun results, demonstrating the feasibility and effectiveness of this method.

Keywords: Sun: radio radiation, instrumentation: radioheliograph, instrumentation: calibration

---

Solar radio observations provide information about plasma and high-energy particle dynamics from the solar chromosphere to the interplanetary space—information unattainable through other observational means—making radio observations an important tool for solar physics research. Solar radio observations cover the quiet Sun, flares, coronal mass ejections (CMEs), and interplanetary particles. Solar radio radiation originates from thermal particles (free-free emission), moderately relativistic particles (gyrosynchrotron radiation), and unstable anisotropic particles (such as electron beams producing plasma radiation and loss-cone distributions generating electron cyclotron maser emission). Solar radio bursts contain information related to eruption types, such as solar flares, CMEs, and various thermal and non-thermal processes. Solar eruptions are considered transient energy release processes resulting from magnetic topology reorganization or magnetic reconnection. X-ray observations indicate that non-thermal particles are highly correlated with energy release processes, with substantial flare energy accumulation occurring during the initial stages of solar flares. Therefore, observations of different types of solar radio bursts are crucial for understanding particle acceleration mechanisms and the origin and evolution of solar eruptions.

With more than seventy years of solar radio observations, observational instruments have evolved from early radio flux meters and spectrometers to modern radio spectroheliographs. The Mingantu Spectral Radioheliograph (MUSER) is a solar-dedicated radio telescope employing synthetic aperture imaging technology, simultaneously achieving high temporal, spatial, and frequency resolution solar imaging within the ultra-wide frequency band of 0.4–15 GHz. Broadband spectral radio imaging provides rich information about coronal magnetic fields, energy release mechanisms, generation and propagation of high-energy particles, and corresponding radiation mechanisms, enabling further study and revealing of radiation mechanisms in the solar chromosphere and corona. Radio brightness temperature is a very important physical parameter for studying solar physical processes, making brightness temperature calibration of radioheliograph images essential.

MUSER employs synthetic aperture imaging to observe the Sun at radio wavelengths. When the field of view is small, the radio image $I(l, m)$ of the observed sky region can be obtained through the following two-dimensional Fourier transform:

$$I_D(l, m) = \iint_{\text{baselines}} V(u, v) e^{j2\pi(ul+vm)} du dv,$$

where $V(u, v)$ is the visibility function, u and v are coordinate components in the plane perpendicular to the phase reference position, u is defined toward the north through the origin plane, v is toward the east, l and m are the corresponding coordinate components in the image plane representing direction cosines of the u and v axes, and j is the imaginary unit. The visibility function $V(u, v)$ is obtained by correlating signals from any two antennas in the array and corresponds to Fourier components of the radio image $I(l, m)$. Fourier inversion of visibility functions obtained from all antenna pairs in the radio array yields the radio image of the observed sky region. Since the number of antennas in a radio array is limited in practice, not all Fourier components of the radio image can be obtained. In this case, the resulting radio image $I_D(l, m)$, missing some Fourier components, is called a dirty image. Therefore, further deconvolution processing is required to obtain the true radio image $I(l, m)$.

In actual observations, however, the visibility function for a baseline (antennas p and q) in equation (1) can be expressed as:

$$r_{pq} = |V_{pq}| g_{pq} \exp[-j(\phi^V_{pq} + \phi^{\text{err}}_{pq})],$$

where r_{pq} represents the observed interference response of baseline $(p-q)$, $|V_{pq}|$ is the amplitude of the visibility function, ϕ^V_{pq} is the phase of the visibility function, g_{pq} is the amplitude gain of the interferometer element, and ϕ^{err}_{pq} is the phase error introduced by instrumental effects. Therefore, calibration of the visibility function is required before imaging. Currently, MUSER uses Fengyun series geostationary satellites and radio burst sources on the solar disk for phase calibration. Additionally, MUSER can utilize two 20 m low-frequency antennas and one 16 m high-frequency antenna with a cryogenic receiver under construction for array calibration. Since MUSER' s correlator performs 2-bit quantization and correlation, system gain has minimal impact on correlation results, and thus system gain calibration is not considered in this study.

MUSER has already observed many types of solar radio burst events, including quasi-periodic pulsating radio bursts before and during solar flares, Fiber burst structures, Spike burst structures, and Lace burst structures. However, MUSER images have not yet undergone intensity calibration. To fully utilize the value of MUSER images in solar physics research, this paper proposes an intensity calibration method specifically for MUSER images.

In brightness temperature calibration studies of solar radio images, the Siberian Radioheliograph (SRH) obtains calibration by analyzing intensity histograms of dirty solar images to identify two peaks corresponding to sky background intensity and quiet solar disk intensity (in arbitrary units). Using quiet Sun brightness temperature values obtained by Zirin et al. during the solar minimum period of 1986–1987 through single-dish antenna observations, image intensity calibration is achieved through the following formula:

$$C(\nu) = [Q(\nu) - Q_{\text{lev1}}(\nu)]\,\frac{T_{\text{quiet}}(\nu)}{Q_{\text{lev2}}(\nu) - Q_{\text{lev1}}(\nu)},$$

where $C(\nu)$ is the calibrated image value, ν represents frequency, $T_{\text{quiet}}(\nu)$ is the quiet Sun brightness temperature obtained from Zirin et al.' s observations with only one fixed value per frequency, and $Q_{\text{lev1}}(\nu)$ and $Q_{\text{lev2}}(\nu)$ are the two peaks in the intensity histogram. For intensity calibration of radio sources, the Expanded Owens Valley Solar Array (EOVSA) can obtain the brightness temperature of a corresponding radio source through its flux density and area.

However, SRH' s calibration method is only suitable for quiet Sun and weak burst event images, and quiet Sun brightness temperatures differ between solar maximum and minimum. Therefore, based on daily solar radio flux, this paper proposes a brightness temperature calibration method for radioheliograph images. Section 2 details the calibration method and principles, Section 3 applies the method to actual MUSER observational data, presents and analyzes the calibrated results, and concludes the paper.

2.1 Quiet Solar Disk Radio Radius and Intensity

Following EOVSA' s approach for estimating the radio radius and intensity of the quiet solar disk in radio images, radioheliograph solar image data contains solar disk structural information, and short-baseline visibility functions reflect large-scale structures in the image. Therefore, short-baseline visibility functions should conform to the Fourier transform pattern of a disk, satisfying the first-order Bessel function, with amplitude expressed as:

$$A = Q_0 \frac{2J_1(z)}{z},$$

where $J_1(z)$ is the first-order Bessel function, Q_0 is the disk intensity value, and z is a quantity related to the solar disk diameter, expressed as:

$$z = \pi D \rho,$$

where D is the solar diameter in radians, ρ is the uv distance in units of wavelength λ (i.e., $\rho = \sqrt{u^2 + v^2}$), and D is not the photospheric diameter but the radio diameter at different frequencies. By adjusting the disk intensity Q_0 and diameter D in equations (4) and (5), the corresponding curve A can be modified. Using actual short-baseline visibility data to fit the closest curve A yields the corresponding disk intensity and diameter.

SRH analyzes radioheliograph dirty image histograms by statistically examining intensity values in regions outside 1.2 solar radii and within 0.8 solar radii, with the peaks of these two parts corresponding to sky background intensity and quiet solar disk intensity values, respectively, where G_c is the calibration factor for radioheliograph images:

$$T_{\text{quiet}} = G_c \cdot Q_{\text{lev2}}.$$

However, since quiet solar disk intensity is tens of thousands of times greater than sky background intensity, the sky background intensity cannot be sensitively reflected in radioheliograph images. Therefore, when using SRH's method, we only statistically analyzed regions within 0.8 solar radii in MUSER images, as shown in [Figure 1: see original paper]. Figure 1(a) shows the uncalibrated dirty image $I_D(l, m)$ of MUSER at 1.7125 GHz on July 5, 2016, where the area inside the yellow line represents the optical solar disk region, the red dashed line indicates 0.8 solar radii, and the color bar represents the magnitude (in arbitrary units) in the dirty image. Figure 1(b) shows the statistical results of intensity values within 0.8 solar radii from Figure 1(a), with the black curve representing the statistical results, the red dashed line representing the fitted Gaussian curve, and the expected value of the Gaussian fit corresponding to the second peak Q_{lev2}, i.e., the quiet solar disk intensity value $T_{\text{quiet}}/G_c = 774806 \pm 152638$ obtained through histogram statistics.

Additionally, using the method of fitting first-order Bessel functions, we analyzed the visibility function amplitudes observed by MUSER over several hours on July 5, 2016. By varying the disk intensity Q_0 and diameter D in equations (4) and (5), we fitted a curve A closest to the observed data, i.e., finding a pair (Q_0, D) that minimizes the root-mean-square difference. This (Q_0, D) corresponds to the quiet solar disk intensity value T_{quiet}/G_c and solar disk diameter

D_{sun} in MUSER images. [Figure 2: see original paper] shows the visibility function amplitudes observed by MUSER over several hours on July 5, 2016, and the fitting results, where black asterisks represent MUSER observational data at 1.7125 GHz, and the red curve is the best-fit curve A corresponding to a disk diameter D of 35.2 arcminutes and $T_{\text{quiet}}/G_c = 199540 \pm 8961.2$.

Comparing the two methods for obtaining quiet solar disk intensity values T_{quiet}/G_c, we find that the value obtained through image intensity histogram statistics is larger. The main reason is that although the Sun was relatively quiet on July 5, 2016, with no radio burst events, several active regions existed on the solar disk, and some relatively strong structural information can be observed in the radio images. This leads to a statistically obtained solar disk intensity larger than the true value. Conversely, the method using short-baseline visibility function amplitude fitting to first-order Bessel function curves is unaffected by these factors, as the fitting result depends only on the disk structural information contained in the image. Therefore, this method yields more accurate quiet solar disk intensity than histogram statistics, confirming that SRH' s histogram-based calibration method is only suitable for quiet Sun and relatively weak radio burst event images.

2.2 Image Calibration Using Solar Radio Flux

According to the Rayleigh-Jeans law, solar brightness temperature relates to solar radio flux as:

$$T_b = \frac{c^2}{2k_B\nu^2}\frac{S}{\Omega},$$

where T_b is solar brightness temperature, c is the speed of light, k_B is the Boltzmann constant, Ω is the solid angle corresponding to the solar radio radius, and S is the solar radio flux. Solar radio flux S can be obtained from daily data of the Radio Solar Telescope Network (RSTN).

However, solar radio images are not always flat disk sources. Active regions on the disk introduce errors, as solar radio flux consists of contributions from both the flat disk and active regions. Therefore, if we subtract the flux contributed by active regions, the Rayleigh-Jeans formula can approximately yield the radio brightness temperature of the solar disk. Here, we calculate the flux contributed by active regions through their intensity and area in the radio image, as well as the intensity of the entire disk. Since sky background radiation has a brightness temperature of approximately 3 K, far smaller than solar brightness temperature, sky background radiation is neglected for simplified calculation.

The calibration factor G_c for MUSER images can be expressed as:

$$G_c = \frac{T_b}{Q_m},$$

where Q_m is the average intensity value of the flat region on the disk in the uncalibrated image. Image calibration can then be achieved by dividing by the calibration factor G_c.

3.1 Analysis of Calibration Factor G_c Results

The calibration factor G_c in this method is the ratio of intensity in uncalibrated images to radio brightness temperature. Under ideal conditions, G_c should be a fixed value. However, according to synthetic aperture principles, radio arrays only sample partial Fourier components of radio sources, and for the same antenna array, the sampling function varies with solar position. During periods when the Sun is at higher elevation angles, short-baseline uv distances change minimally, resulting in smaller temporal variations in total intensity of radio images and thus relatively stable calibration factors during this period. However, in actual observations, antenna servo failures and unsatisfactory correlation results from some baselines cause daily sampling functions to differ, necessitating daily intensity calibration of MUSER images.

We calculated G_c for MUSER observational data on July 5, 2016. Using the method in Section 2.1, we fitted a solar radio diameter of 35.2 arcminutes at 1.7125 GHz. According to RSTN data, the corresponding solar radio flux at 1.7125 GHz was 57.77 solar flux units (sfu). Using the calibration method in Section 2.2, we obtained the corresponding calibration factor G_c as shown in [Figure 3: see original paper]. The average value yields a daily calibration factor of $G_c = 6.526 \pm 0.658$. [Figure 4: see original paper] shows the G_c values obtained at different frequencies on November 22, 2015, with calibration factors at 1.26 GHz, 1.36 GHz, 1.46 GHz, 1.66 GHz, 1.71 GHz, and 1.86 GHz being 7.066 ± 0.407, 9.122 ± 0.607, 8.247 ± 0.718, 9.387 ± 0.737, 8.919 ± 0.703, and 6.577 ± 0.568, respectively. These calculated G_c values remain relatively stable throughout each day, with errors within 10%, indirectly reflecting the stability and reliability of this calibration method.

3.2 Analysis of Calibrated MUSER Images

We applied this method to calibrate MUSER observational data from July 5, 2016 and November 22, 2015, corresponding to quiet Sun and solar radio burst conditions, respectively. For July 5, 2016, [Figure 5: see original paper] compares the calibrated average quiet Sun brightness temperature with the power values received by antenna A2. Figure 5(a) shows the power values (in arbitrary units) received by antenna A2 on July 5, 2016, while Figure 5(b) shows the average brightness temperature of the solar disk after image calibration. The Sun was essentially quiet that day, and both the power values received by antenna A2 (in arbitrary units) and the calibrated average brightness temperature of the solar disk remained essentially unchanged.

For the MUSER data on November 22, 2015, a solar radio burst event occurred that day. Active region AR12454 produced GOES soft X-ray class C5.1

flares from 01:37-02:27 UT, C1.2 flares from 03:17-03:25 UT, and C5.6 flares from 05:31-05:38 UT. MUSER observed solar radio bursts during 04:51-04:53 UT and 05:35-05:38 UT, while RSTN also observed radio bursts at frequencies of 1415 MHz, 2695 MHz, 4995 MHz, 8800 MHz, and 15400 MHz during corresponding time periods. [Figure 6: see original paper] shows the brightness temperature changes of the radio source corresponding to active region AR12454 during the 04:51-04:53 UT burst period after calibration, along with single-antenna power values. Figure 6(a) shows the power values (in arbitrary units) received by antenna A2 on November 22, 2015, while Figure 6(b) shows the maximum brightness temperature values in the calibrated images during the radio burst period, i.e., the brightness temperature variations of the radio source corresponding to active region AR12454. We also calculated the correlation coefficient R between the power data in Figure 6(a) and the brightness temperature data in Figure 6(b), with results shown in [Figure 7: see original paper]. The figure clearly demonstrates that the brightness temperature of the radio source during the burst period and the power values received by the single antenna (in arbitrary units) exhibit the same variation trend, with a correlation coefficient greater than 0.95.

[Figure 8: see original paper] compares the quiet Sun brightness temperature observed by MUSER with other results. Red diamond symbols represent MUSER observations, the red line is the fitted curve from these observations, the black line shows Zirin et al.' s results, and the green line represents Tan et al.' s results combining quiet solar atmospheric electron density and temperature models with more than ten years of observations from the Huairou Spectrometer. The MUSER fitted curve falls between the other two results and shows very high correlation with Tan et al.' s brightness temperature curve, reaching 0.96. These results reflect the accuracy of the calibration results.

In radio astronomical observations, brightness temperature of radio images is an important physical parameter for astrophysical research, and its calibration constitutes an important part of radio telescope data processing. Solar radio observations differ from weak cosmic radio source observations. Since solar radio signals are strong, radioheliographs do not require extremely high sensitivity. Solar radio radiation has a large dynamic range and complex physical structure, including both large-scale extended sources and small-scale structures such as active regions, flares, and prominences. Therefore, traditional radio telescope calibration methods cannot be used for radioheliograph image intensity calibration.

Based on the fact that solar radio image data contains solar disk structural information primarily reflected in short-baseline visibility data, this paper proposes a brightness temperature calibration method for radioheliograph images. By fitting first-order Bessel functions to short-baseline amplitude information, we can obtain the radio radius and intensity of the quiet solar disk in the image. Then, using the Rayleigh-Jeans law and daily solar radio flux, we can determine the daily image calibration factor G_c, thereby achieving radioheliograph image calibration.

Applying the proposed method to MUSER solar image brightness temperature calibration, including both quiet Sun and solar radio burst conditions, the results show that daily calibration factors have small errors. The calibrated brightness temperature shows the same variation trend as single-antenna received power values, with strong correlation. Meanwhile, the quiet Sun brightness temperatures obtained at different frequencies are consistent with results from other literature, demonstrating the effectiveness and reliability of this calibration method.

References

[1] Yan Y H. Chapter 3: Solar Radio Spectral Imaging Observations // Shi J K, Yeh T, Liu Z X. Advances in Space Physics (Vol. 5). Beijing: Science Press, 2015: 71-85
[2] Aschwanden M. Physics of the Solar Corona: An Introduction with Problems and Solutions. Second Edition. Berlin: Springer, 2005: 639-640
[3] Chen P F. LRSP, 2011, 8: 1
[4] Lin R P. Particle Acceleration and Transport in the Heliosphere and Beyond. AIP Conference Proceedings, Kyoto, Japan, June 20-25, 2008
[5] Chen X Y, Yan Y H, Tan B L, et al. ApJ, 2019, 878: 78
[6] Yan Y H, Zhang J, Wang W, et al. EM&P, 2009, 104: 97
[7] Yan Y H, Chen Z J, Wang W, et al. FrASS, 2021, 8:
[8] Thompson A R, Moran J M, Swenson G W. Interferometry and Synthesis in Radio Astronomy. Third Edition. New York: Springer Nature, 2017: 91-94
[9] Wang W, Yan Y H, Liu D H, et al. Chinese Journal of Electronics, 2019, 47: 4
[10] Zhou Z C, Yan Y H, Chen L J, et al. RAA, 2022, 22:
[11] Geng L H, Yan Y H, Chen Z J, et al. 2016 URSI Asia-Pacific Radio Science Conference, Seoul: IEEE, 2016:
[12] Zhang M H, Zhang Y, Yan Y H, et al. RAA, 2021, 21:
[13] Zirin H, Baumert B M, Hurford G J. ApJ, 1991, 370: 779
[14] Fedotova A, Altyntsev A, Kochanov A, et al. STP, 2019, 5: 27
[15] Fleishman G D, Loukitcheva M A, Kopnina V Y, et al. ApJ, 2018, 867: 81
[16] Ranganath G S. Resonance, 2008, 13: 115
[17] Penzias A A, Wilson R W. ApJ, 1965, 142: 419
[18] Tan C M, Yan Y H, Tan B L, et al. ApJ, 2015, 808: 61

Note: Figure translations are in progress. See original paper for figures.