

## Solar Radio Observations and Simulations of Occlusion Effects: Postprint

**Authors:** Geng Lihong, Sucang, Du Jing, Liu Donghao, Yan Yihua, Linjie Chen, Wang Wei

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### Abstract

Occlusion effects represent a critical consideration in the design of complex multi-antenna systems. Upon completion of the second phase of the national major science and technology infrastructure project, the Meridian Project, the total number of antennas at Mingantu Station will reach 373 units. Constrained by test site availability, model complexity, and computational requirements, the occlusion effects of electrically large obstacles are particularly difficult to measure experimentally and predict theoretically. Observation data from the Mingantu Station Solar Radio Telescope (MST) in the S/C/X bands during 2017-2020 reveal occlusion effects with the 20 m antenna and distant hills serving as obstacles, which can be categorized into three distinct characteristic regions: antenna, atmospheric, and hilly zones. Based on the single-knife-edge diffraction loss prediction method outlined in ITU-R P.526-15 recommendations, simulation modeling and approximate calculations were conducted for the 20 m antenna reflector. The observational and simulation results demonstrate essentially consistent trends in diffraction loss variation with frequency, indicating that occlusion effects are related to wavelength, obstacle characteristics, their distances and angles relative to the source and receiving antennas, as well as the antenna beam and dynamic range of the receiving equipment.

### Full Text

### Preamble

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### Solar Radio Observations and Simulations of Shadowing Effects

**Authors:** Geng Lihong<sup>1</sup>, Su Cang<sup>1</sup>, Du Jing<sup>1</sup>, Liu Donghao<sup>2</sup>, Yan Yihua<sup>1</sup>, Chen Linjie<sup>1</sup>, Wang Wei<sup>1</sup>

**Affiliations:**

1. State Key Laboratory of Space Weather, National Space Science Center, Chinese Academy of Sciences, Beijing 100190, China

2. Key Laboratory for Exploration in the Moon and Deep Space, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China

**Email:** genglihong@nssc.ac.cn

**Abstract**

Shadowing effects are a critical consideration in the design of complex multi-antenna systems. After completion of the Meridian II program—a major national science and technology infrastructure project—the Mingantu Station will house 373 antenna sets. Limited by test sites, model complexity, and computational requirements, shadowing effects—particularly for electrically large obstacles—are typically difficult to measure and predict. Solar radio observation data from the Mingantu Solar Radio Telescope (MST) in S/C/X bands between 2017 and 2020 reveal shadowing effects with the 20 m antenna and distant hills as obstacles, which can be divided into three regions with distinct characteristics: antenna, atmosphere, and hills. Based on the single knife-edge diffraction loss prediction method recommended by ITU-R P.526-15, a simulation model of the 20 m antenna reflector was built and approximate calculations were performed. The observed and simulated results show consistent trends in diffraction loss variation with frequency, demonstrating that shadowing effects are related to wavelength, obstacle characteristics, distance and angle relative to the source and receiving antenna, receiving antenna beamwidth, and system dynamic range.

**Keywords:** shadowing effect; solar radio observation; Meridian II program; Mingantu Solar Radio Telescope; ITU-R P.526-15; diffraction loss; S/C/X bands

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**Introduction**

The Mingantu Field Scientific Observation and Research Station (hereinafter Mingantu Station), located in Zhengxiangbai Banner, Inner Mongolia (115°15 E, 42°12 N), serves as an important platform for broadband, high-resolution solar radio imaging and spectral observations, solar physics and space weather research, science education, and international exchange. After completion of the Meridian II program—the Ground-Based Comprehensive Monitoring Network for Space Environment (a major national science and technology infrastructure project)—the station will deploy 373 antennas of various types. Current facilities include the Mingantu Spectral Radiograph (MUSER) with 40 parabolic antennas of 4.5 m diameter [1], a solar radio spectrometer and calibration system with 1 m, 2 m, and 4.5 m parabolic antennas, a very low frequency observation device with 224 dipole antennas [2], and the Mingantu Solar Radio Telescope

(MST) with a 3 m parabolic antenna [3]. Additional facilities under construction include the Interplanetary Scintillation Monitor with a  $140\text{ m} \times 40\text{ m}$  cylindrical parabolic antenna [5] and the Decameter-Wave Radioheliograph. These constitute a complex electromagnetic environment and antenna layout, where shadowing effects represent a key design consideration. Limited by test sites, model complexity, and computational requirements [6-7], shadowing effects—particularly for electrically large obstacles—are typically difficult to measure and predict. At Mingantu Station, the 20 m antenna, 3 m antenna, and distant hills create a unique system for measuring shadowing effects on the MST.

## Solar Radio Observations and Data Processing

The MST operates in the S/C/X bands [3], which are critical for F10.7 index observations in space weather forecasting. The half-power beamwidths of the 3 m parabolic antenna are approximately  $1.5^\circ$ ,  $0.8^\circ$ , and  $0.5^\circ$  for the S, C, and X bands, respectively. After calibrating the temperature response, the root-mean-square errors of absolute flux compared with the Nobeyama Radio Polarimeter (NoRP) [9] are 2.7 sfu, 5.7 sfu, and 14.9 sfu for the S, C, and X bands, respectively, with relative errors of 4%, 6%, and 8%. This paper focuses on the data processing procedure for the shadowed portions of observations. Between 2017 and 2020, there were 149, 251, and 283 effective observation days for the three bands.

[Figure 1: see original paper] shows the 20 m antenna and 3 m antenna of MST at Mingantu Station. The 20 m antenna is used for calibration of the low-frequency array system of MUSER and is typically stowed in a zenith-pointing position. Shadowing of the MST occurs during winter afternoons at low solar elevation angles, with a relative angle of approximately  $11^\circ$  between the two antennas.

[Figure 2: see original paper] illustrates the geometric positional relationship between the 20 m antenna and 3 m antenna of MST. [Figure 3: see original paper] displays observed solar flux curves for a single day with shadowing, showing regular patterns in the continuous radio flux variation between 4:00 pm and 5:30 pm at 1 s time resolution. [Figure 4: see original paper] presents radio flux and contour plots for multiple days with shadowing (S-band left-polarization observations between 4:00 pm and 5:30 pm, days 300-365 of 2019).

Since solar trajectories do not coincide exactly year-to-year, we synthesized data from 2017-2020. The processing steps include: (1) subtracting observation values from reference values to eliminate solar and background radio flux and temperature variation effects; (2) defining the additional loss due to shadowing as “shadowing loss”; (3) interpolating effective observation data at corresponding solar hour angle and declination coordinates, rejecting outlier values; and (4) calculating total shadowing loss for both polarizations.

[Figure 5: see original paper] shows the observed diffraction loss in equatorial coordinates for S-band left-polarization, with an angle range of  $37^\circ$ - $73^\circ$  in hour

angle and  $-23.44^\circ$  to  $-12.2^\circ$  in declination. The MST uses an equatorial mount, so shadowing has minimal impact on observation efficiency. Through coordinate transformation from equatorial to horizontal [10], the shadowing effects are converted to the horizontal coordinate system shown in [Figure 6: see original paper], which overlays the observed shadowing positions on all solar trajectories tracked by the MST from 2017-2020. The contours of the 20 m antenna and distant hills are visible, with a site photo from the 3 m antenna shown in the top-right corner.

[Figure 7: see original paper] shows solar orbits in horizontal coordinates from 2017-2020 with observed shadowing effects overlaid at the bottom. Using contour plots to further analyze shadowing effects in horizontal coordinates, [Figure 8: see original paper] presents the shadowing effect contours for MST in S/C/X bands and dual circular polarizations. The upper and lower rows correspond to left- and right-polarizations, showing no significant difference. The left, middle, and right columns correspond to S, C, and X bands, respectively, divided by shadowing characteristics into antenna, atmosphere, and hill regions.

The shadowing azimuth ranges are approximately  $15^\circ/14^\circ/12^\circ$  for S/C/X bands. Antenna region shadowing is primarily diffraction, with maximum shadowing losses about 4.0/2.8/5.3 dB above background and minima about 0.6/0.4/0.1 dB below background (the minima are limited by the receiver noise floor, as discussed below). Atmospheric region losses follow ITU-R P.676-13 [11], with attenuation increasing with frequency and decreasing elevation angle (approximately 0.2/0.25/1.1 dB for S/C/X bands at  $10^\circ$  elevation, consistent with line-of-sight atmospheric attenuation of 0.02 dB/km at 10 GHz). Hill region diffraction attenuates rapidly due to the large distance ( $\sim 50$  km) between the hills and the MST, with losses of about 1.0 dB.

## ITU-R P.526-15 Principle and Simulation Model

The ITU-R P.526-15 recommendation, first established in [year] and updated to version 15 in [year], provides propagation prediction curves that integrate analytical solutions for diffraction problems with empirical data. It offers algorithms for single knife-edge, double knife-edge, and single rounded-edge diffraction. This section calculates only the additional propagation loss caused by the 20 m antenna reflector. The reflector is constructed from stainless steel mesh with  $10 \text{ mm} \times 10 \text{ mm}$  openings. In the approximation, mesh transmission effects are neglected, and the reflector edge thickness relative to wavelength is considered negligible, allowing it to be treated as a sharp knife-edge obstacle. The geometric relationship between the MST receiving antenna and the 20 m antenna is readily determined.

For diffraction loss prediction, the engineering parameters of obstacles and terrain must be understood. In the antenna reflector model, the xy-plane passes through the antenna aperture projection, with the xz-plane showing the reflector profile. The origin O is the antenna center, with y- and z-axes representing

width and height directions, respectively. The MST feed (point R) has coordinates (0, -104, 0). The calculation range for point A (intersection of the incoming wave direction with the xz-plane) is (0:15, 0, -10:10). Point B represents diffraction points along the aperture edge and parabolic edge, with the reflector dimensions being 40 m × 15 m. The focal ratio  $f/D = 0.35$ , with the upper edge 10 m above point R.

[Figure 9: see original paper] illustrates a point on the 20 m antenna reflector edge as a single knife-edge obstacle. [Figure 10: see original paper] shows the simulation model of the 20 m antenna reflector. For each incoming direction A, the true diffraction loss  $J_1$  at edge point B is calculated. The minimum diffraction loss  $J_{\min}$  is then convolved with the MST receiving antenna beamwidth M (10/5/3 for S/C/X bands) to obtain  $J_c$ :

$$J_c = 20 \log \left( \sum_{j=1}^m \sum_{k=1}^n 10^{-J_{jk}/20} \right)$$

where m and n are determined by calculation step size. The total diffraction loss at receiver R for incoming waves from direction A is the minimum of all  $J_c$  values within the beamwidth. Calculation complexity depends on grid size (0.2 m for S/C/X bands). If point A lies within the parabolic projection area, the incoming wave is considered to arrive directly without diffraction.

## Results and Discussion

Figure 11 presents simulation results of diffraction loss from the 20 m antenna reflector based on the single knife-edge obstacle model for different frequency bands. The convolution results with grid sizes J(1) to J(5) and 0.2 m resolution show that the shadowing region expands with the receiving antenna aperture. The simulation trends are basically consistent with observations. Using the same approximate beamwidth M for S/C/X bands, the results demonstrate that diffraction effects diminish with increasing frequency. In addition to the comprehensive geometric parameters, the effects also depend on operating wavelength.

The simulation and observed results show that shadowing effects are related to wavelength, obstacle characteristics, distance and angle among obstacle, source, and receiving antenna, receiving antenna beamwidth, and system dynamic range. Data recovery requires precise determination of comprehensive geometric parameters and receiver dynamic range.

The Daocheng Solar Radio Telescope of Meridian II in Sichuan consists of parabolic antennas forming a 300 m diameter array. Simulations of shadowing effects between adjacent and triple-antenna units at 300 MHz show that corresponding amplitude and phase deviations can be compensated through post-processing. Based on these results, shadowing spacing less than [value] may be acceptable.

The first-generation Arecibo radio telescope white paper [13] proposed a concept design where antennas are mounted on a co-planar rotating structure to form an aperture equivalent to a single large antenna. Multi-antenna systems may benefit from such co-planar configurations to avoid inter-antenna shadowing while meeting spatial resolution requirements when economically feasible.

## Conclusion

The S/C/X-band solar radio observations from the Mingantu Solar Radio Telescope provide a new perspective for studying large-scale obstacle shadowing effects. The ITU-R P.526-15 recommended single knife-edge obstacle diffraction loss prediction method, applied through simulation modeling of the 20 m antenna reflector, yields results consistent with observations. Shadowing effects depend on wavelength, obstacle characteristics, relative geometry, antenna beamwidth, and system dynamic range. The ultra-wideband radio spectrometer and other Meridian II equipment to be deployed at Mingantu Station will enable more comprehensive studies of shadowing effects and radio wave propagation characteristics.

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