Complex Electromagnetic Environment and Interference Mitigation Measures at Mingantu Observation Base (Postprint)

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Abstract

Radio Frequency Interference (RFI) is an unavoidable issue for radio astronomy observational instruments. The Mingantu Observation Base of the National Astronomical Observatories (Inner Mongolia) features a complex electromagnetic environment composed of multiple radio observational instruments with distinct characteristics, various electromagnetic radiation sources, and their propagation paths. The existing ultra-wideband high-resolution solar radio imaging instrument—the Mingantu Ultrawide Spectral Radioheliograph (MUSER)—and the forthcoming Solar Interplanetary Monitoring System of the Meridian Project Phase II, which includes a meter-decameter radio heliograph, an interplanetary scintillation telescope, and an ultra-wideband radio spectrometer, collectively cover a frequency range of 1 MHz–15 GHz. The observational data are utilized for research on key problems in solar physics and space weather monitoring and forecasting, thereby imposing more stringent requirements on the electromagnetic environment. This paper introduces the observational instruments and geographical setting of the Mingantu Observation Base, presents preliminary RFI monitoring results as demonstrated by azimuth-frequency power spectra, three-dimensional radiation patterns, and time-frequency power spectra, and discusses RFI prevention, mitigation, and self-monitoring strategies.

Full Text

Preamble

Complex Electromagnetic Environment and RFI Mitigation Measures at Mingantu Observing Station

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Abstract

Radio Frequency Interference (RFI) is an unavoidable challenge for radio astronomical observatories. The Mingantu Observing Station of the National Astronomical Observatories in Inner Mongolia hosts multiple radio telescopes with distinct characteristics, creating a complex electromagnetic environment shaped by various radiation sources and propagation paths. The existing ultra-wideband, high-resolution solar radio imaging instrument—the Mingantu Spectral Radioheliograph (MUSER)—and the upcoming solar interplanetary monitoring system for the Meridian Project Phase II, which includes the Meter-Decameter Radioheliograph, Interplanetary Scintillation Telescope, and Ultra-Wideband Radio Spectrometer, collectively cover frequencies from 1 MHz to 15 GHz. These observations are critical for addressing key research questions in solar physics and space weather monitoring and forecasting, imposing stringent demands on the electromagnetic environment. This paper introduces the observational facilities and geographic setting of the Mingantu Observing Station, presents preliminary RFI monitoring results through azimuth-frequency power spectra, three-dimensional radiation patterns, and time-frequency power spectra, and discusses RFI prevention, mitigation, and self-monitoring strategies.

Keywords: Solar physics; Space weather; Radioheliograph; Meridian project; RFI mitigation
Classification: P16

In radio astronomy, ambitious plans exist to deploy future radio observatories or arrays on the far side of the Moon to escape increasingly severe RFI from Earth, atmospheric window constraints, and limitations on spectrum allocation for radio astronomy. On January 4, 2019, the three 5-meter antennas of the first low-frequency radio spectrometer aboard the Chang' e-4 lander were deployed on the lunar far side, with eagerly anticipated results. Ground-based radio telescopes, however, lack such advantages. On January 9, 2019, two astronomy papers on fast radio bursts published in *Nature* sparked intense controversy: were they an unexplained natural phenomenon, evidence of extraterrestrial intelligence, or merely radiation from human "microwave ovens"? Even though solar radio emissions are stronger than those from most celestial objects, solar radio instruments still suffer from complex electromagnetic interference. RFI remains a problem that all sensitive ground-based radio telescopes must address.

Main Equipment and Geographic Environment at Mingantu Observing Station

The Mingantu Observing Station of the National Astronomical Observatories, Chinese Academy of Sciences (115°15 E, 42°12 N, 1365 m altitude) currently operates the ultra-wideband, high-resolution solar radio imaging instrument—the

Mingantu Spectral Radioheliograph (MUSER-I and MUSER-II)—the Mingantu three-band Solar Telescope (MST), two 20-meter diameter decimeter-wave alt-azimuth parabolic antennas, and a new digital very-low-frequency radio imaging telescope array (Ultra-P) under testing. Between 2019 and 2022, the Meridian Project Phase II solar interplanetary monitoring system will be constructed, including the Meter-Decameter Radioheliograph (MUSER-III), Interplanetary Scintillation Telescope (IPS), and Ultra-Wideband Radio Spectrometer. summarizes the main specifications of existing and planned instruments, with frequency coverage from 1 MHz to 15 GHz for research on critical problems in solar physics and space weather monitoring and forecasting. Typically, ground-based radio telescopes are blocked by Earth' s ionosphere above 10 MHz, with space-based instruments like WIND/Waves observing below this threshold. However, ionospheric and thermospheric parameters vary with solar activity, and during solar minima, the ionospheric cutoff frequency may drop below 5 MHz, potentially enabling Ultra-P to image cosmic signals below 10 MHz from the ground for the first time. The Mingantu Observing Station is gradually developing into a large-scale radio astronomy facility, particularly for solar radio observations, featuring diverse equipment types, over 300 receiving antennas distributed across three spiral arms and a central area spanning approximately 10 km^2, ultra-wide frequency bands, and an open grassland geographic setting surrounded by relatively dense villages, creating a complex electromagnetic environment.

presents the main specifications of current and future instruments at Mingantu Observing Station, including device names, observational targets, intermediate frequency bandwidth, number of elements, polarization, and distribution range.

As shown in [FIGURE:1(a)], the MUSER antenna array can be seen from a hillside south of the station, arranged along three spiral arms (A, B, and C axes). [FIGURE:1(b)] displays the observatory layout overlaid on Google Maps, with red dots indicating antenna array elements for MUSER I-III and Ultra-P along the spiral arms. The central yellow rectangles denote the office/living and observation areas, with yellow arrows highlighting facilities and buildings in these zones. The station is surrounded by herders' pastures, with red circles marking five herder groups totaling 105 households located 2–5 km from the station center; Group 3 is only about 300 meters from the outermost antenna on Arm B. The observation area contains the dense central regions of MUSER-I and MUSER-II outdoor antenna units, while the observation building houses MUSER indoor analog receivers, digital receivers, and monitoring systems.

Construction of the Meridian Project Phase II instruments will begin in 2019, with the office/living area expanding eastward and southward. [Figure 2: see original paper] schematically shows the relative positions of each facility, with the central dipole array for MUSER-III at the bottom and three 140 m × 40 m north-south oriented parabolic cylindrical antennas arranged east-west. The research building in the office/living area will house massive data storage and processing facilities, laboratories, and other research infrastructure, while the comprehensive building primarily contains residential power facilities.

Preliminary RFI Monitoring at Mingantu Observing Station

In complex electromagnetic environments, RFI monitoring is essential for developing appropriate anti-interference measures to prevent, control, and mitigate interference, ensuring normal operation and data reliability of radio telescopes. [Figure 3: see original paper] shows partial RFI monitoring results at Mingantu Observing Station, with frequency on the horizontal axis and intensity on the vertical axis, illustrating RFI variation with frequency and direction. [FIGURE:3(a)] displays RFI in the 470–960 MHz band received by the 20 m antenna at 35° elevation and -45° azimuth. [FIGURE:3(b)] shows a 0.4–2.0 GHz RFI measurement using a MUSER-I 4.5 m antenna, with mobile phone signals near 960 MHz being the primary interference source. [FIGURES:3(c) and 3(d)] present 250–290 MHz RFI monitoring at 60° elevation for two azimuths (0° = north).

[Figure 4: see original paper] shows long-term RFI monitoring in the 1–100 MHz band using a linear antenna, with time/date on the horizontal axis, frequency on the vertical axis, and intensity represented by color.

Three-dimensional RFI representation provides a more comprehensive and effective reflection of RFI distribution, as shown in [FIGURES:5] through [9]. For solar observation equipment, [Figure 5: see original paper] presents MUSER-I receiving unit IA9 measurements of left-hand circularly polarized RFI in the 0.4–2.0 GHz band along the solar orbit (Right Ascension: -90° to +90°, Declination: 19.15°, May 17, 2015), with X-axis representing frequency, Y-axis RA coordinate, and Z-axis relative power, showing RFI spectral distribution along the solar track. Similarly, [Figure 6: see original paper] shows left-hand circularly polarized RFI distribution in the 2.0–2.8 GHz band along the solar orbit from MUSER-II receiving unit HA9. [Figure 7: see original paper] displays differences between left- and right-hand circularly polarized RFI spectra from MUSER-I. [Figure 8: see original paper] compares left-hand circularly polarized RFI distribution with azimuth at 40° elevation in the 0.4–0.8 GHz and 1.6–2.0 GHz bands, measured by the 20 m antenna and MUSER-I receiving system.

[Figure 9: see original paper] shows three-dimensional radiation pattern scanning centered on the Sun using the 20 m antenna and MUSER-I receiving system, comparing left- and right-hand polarization RFI effects for frequency channels 30# and 47#, demonstrating differences in received circularly polarized signals at the same frequency. While RFI spectra typically show intensity variations over time, as in W.A. Baan et al.' s study of RFI mitigation at the Westerbork Synthesis Radio Telescope, [FIGURES:5–9] combine observational targets and modes to reflect RFI spectral spatial distribution. If long-term monitoring reveals stable RFI distribution, this will provide valuable reference for developing RFI mitigation strategies.

In summary, RFI varies with frequency, polarization, pointing direction, and time, as well as with antenna height and pattern, system performance, observational targets and modes, and the distance and direction of RFI sources relative to monitoring equipment. System differences must be considered when evaluating RFI impact on observational systems using monitoring results.

RFI Mitigation Measures at Mingantu Observing Station

3.1 Establishment of Electromagnetic Quiet Zone and Environmental Protection

RFI originates from both external and internal sources. For external RFI, site selection and establishment of an electromagnetic quiet zone are primary measures for radio observatories. The FAST project, for example, implemented the 2019 revised "Guizhou Province 500-meter Aperture Spherical Radio Telescope Electromagnetic Wave Quiet Zone Protection Measures," establishing a 5 km radius core zone, 5–10 km intermediate zone, and 10–30 km remote zone centered on the site. Following consultation with local authorities, Inner Mongolia issued regulations in 2007 establishing a 10 km radius radio quiet zone centered on Mingantu Observing Station. In 2012, a mobile communication tower approximately 2 km south of the station was shut down. In 2014, fiber optic multimedia communication networks were installed for 105 households in five surrounding herder groups, enabling internet access, landline telephone, television, and WeChat while maintaining friendly relations between herders and the station. Coordination has prevented construction of new mobile base stations and 500 kV high-voltage power lines within the quiet zone. With the advent of 5G communications, quiet zone protection measures require updating. [FIGURE:10(a) and (b)] show significant RFI improvement after tower closure, while [FIGURE:10(c)] illustrates the fiber optic multimedia communication network routes.

3.3 MUSER Broadband Anti-Interference Design

MUSER incorporates multiple anti-interference designs. These include using optical cables buried beneath the frozen soil layer for long-distance signal transmission to reduce loss, temperature variation, and interference effects; routing the 10 kV power line underground near the station; installing lightning protection spark gaps and bird deterrents along high-voltage lines; and equipping all outdoor foundation distribution boxes with surge protectors during the July–August rainy and lightning season. System stability and reliability are fundamental to RFI mitigation, with high-precision temperature control for temperature-sensitive components. Since most RFI enters through antenna sidelobes, the antenna pattern sidelobes are required to be at least 14 dB below the main lobe.

MUSER-I: Strong mobile phone interference in the 0.8–1.2 GHz band affected normal system operation. Adjusting the spare local oscillator frequency to operate in the 1.0–1.4 GHz band avoided strong interference. Front-end low-noise amplifiers include limiters, and automatic gain control activates when RFI exceeds safety thresholds. Modular channel design reduces inter-channel interference.

MUSER-II: Front-end low-noise amplifiers include limiters, and channel preselection filter banks provide over 50 dB suppression. Fixed attenuators at front-end component outputs prevent optical transmitter burnout from strong interference. Dual intermediate frequency bandwidth outputs of 400 MHz/80 MHz accommodate engineering, astronomical, and anti-interference requirements, allowing receivers to avoid interference bands and enabling higher time resolution observations in certain bands. Bandpass filters at IF outputs further remove out-of-band noise. LTCC (Low-Temperature Co-fired Ceramics) technology miniaturizes the system and enhances reliability and stability.

3.4 Research on Interference Mitigation Methods

A signal is judged to be RFI if it is unwanted but detectable in the required observation and affects observation progress. Some interference may affect observations despite being difficult to detect, making mitigation much more challenging.

In RFI identification, dispersion measure is an important criterion for distinguishing human-generated signals from radio source signals due to different propagation paths and distances. Many RFI detection, identification, and mitigation studies employ statistical analysis and machine learning using big data. Radio astronomical source information and receiver system noise follow ideal Gaussian distributions, making power detection typically Gaussian-based. Gaussian models require mean and standard deviation parameters, where mean estimation errors affect standard deviation estimation. Uncontaminated data samples follow a chi-square distribution with two degrees of freedom, requiring only one mean parameter to define signal statistics. Thresholds are set as recursively estimated means multiplied by a user-defined coefficient, with the strongest signals symmetrically discarded to prevent anomalous mean values from RFI. Threshold setting simultaneously determines false alarm and missed detection rates. For detecting strong radar pulse interference, requiring multiple consecutive power values to exceed the threshold before triggering data blanking significantly reduces false alarm rates when hardware costs are acceptable. However, this approach performs poorly for weak radar pulses; triggering blanking based on the total number of threshold-exceeding samples within a time period is more effective.

The 21CMA, dedicated to detecting cosmic dawn and reionization, uses statistical methods to identify and remove non-Gaussian RFI signals, introducing visibility function coefficients to further compress rapidly time-varying RFI. Incorporating prior knowledge into RFI detection further reduces RFI impact on radio observations. Since high redshift shifts HI spectral lines into radar-allocated bands, Allal et al. implemented FPGA-based real-time statistical analysis for radar pulse blanking at the Nancay decimeter-wave radio telescope, using cyclostationary characteristics to distinguish RFI pulses from pulsar pulses, as most communication signals contain hidden periodicity. Simulations show cyclostationary detection outperforms power detectors in pulsar observations. Inserting cyclostationary detectors at different equipment locations enables detection of different RFI types.

For large single-dish radio telescopes, adaptive sidelobe cancellation is a common anti-interference method. It exploits correlation between auxiliary arrays and interference signals in the main antenna, along with interference spatial characteristics, to obtain optimal weight vectors for the auxiliary array, creating nulls in the interference direction in the synthesized antenna pattern. Briggs et al. used independent RFI reference signals and closure relations to remove RFI from radio spectra, obtaining reference signals from cross-correlation between signals received by reference antennas or feeds pointing at noise sources and observed radio source radiation.

For interferometers, correlation techniques offer the possibility to identify and mitigate RFI from interferometric data with higher time and frequency resolution than analyzing final visibility functions. During RFI method development and testing, software correlation for RFI identification provides greater flexibility and shorter development cycles than hardware approaches. RFI affects radio telescope arrays differently due to array element positions, with more severe problems for short baselines. However, single-dish observations (continuum or spectral) are more susceptible to interference because increased integration time improves sensitivity to both radio signals and RFI. On the FASR (frequency agile solar radio-telescope) test system, a variance-analysis-based method for statistical excision of RFI from power spectra was proposed and tested, identifying and removing non-Gaussian RFI from Gaussian solar radio bursts.

RFI can be identified through morphological analysis of received signal time-frequency power spectra, azimuth-frequency power spectra, and three-dimensional radiation patterns. As shown in [FIGURES:5-9], most RFI is confined to specific frequency ranges but exists throughout the observation path with intensity fluctuations. For a few stable interferences confined to specific pointing directions and frequency bands identified through long-term monitoring, spatial filtering can be applied for mitigation.

Radio detection is crucial for solar physics and solar-terrestrial space science, particularly for studying solar non-thermal particle acceleration, emission, and propagation during solar eruptions. New solar radio telescopes are always developed from scientific requirements rather than being limited to protected radio astronomy frequency bands. While most RFI is considered strong, intense solar flares can increase radio flux density by 20–30 dB or more, containing sub-second pulsating quasi-periodic structures and ultra-fine structures. Weak RFI may also be confused with solar radio radiation. Long-term observations show solar radio bursts often consist of series of processes with different timescales, with spike radiation being the smallest temporal and spatial scale, representing an elementary burst process corresponding to single magnetic reconnection and energy release. According to solar radio astronomy research, identifying spike bursts is a basic requirement for new-generation solar radio telescopes. Observing small-scale magnetic activities is significant for understanding the elementary processes of solar storms and their overall nature. Distinguishing RFI from solar radio signals, regardless of RFI strength, is both important and challenging.

The electromagnetic environment at Mingantu Observing Station is complex, and no single RFI mitigation method satisfies all equipment requirements; multiple methods may be needed even for the same instrument. Much work remains in this area.

RFI Monitoring

Mobile communications are the primary RFI source at Mingantu Observing Station, and the approaching 5G era will further alter the electromagnetic environment. Long-term RFI monitoring is a prerequisite for mitigation. RFI monitoring typically uses isotropic antennas; for example, GMRT employs four identical LPDAs mounted on a 20 m tower to monitor electromagnetic interference and determine interference direction. The 65 m Tianma radio telescope began RFI monitoring in 2008 for site electromagnetic environment assessment. WSRT' s RFI omnidirectional antenna spectrum monitoring system operates unattended 24/7. LOFAR experiences minimal RFI impact due to precise detection methods, strong filtering, high receiver system linearity, and antennas installed close to the ground, though digital broadcast and wind turbine interference must still be considered. Reducing time and frequency resolution during monitoring causes RFI occupancy to increase approximately linearly, imposing requirements on RFI monitoring system resolution in frequency, time, and space. RFI monitoring systems should aim to achieve RFI mitigation for observational equipment, considering both real-time pre-detection and offline RFI detection from large telescope array interferometric data. Instruments like MUSER are sensor arrays distributed over large areas, where precise calibration is key to producing meaningful scientific images, requiring solutions for antenna gain and phase variations along with atmospheric and ionospheric disturbances. As shown in Section 2, system complexity, differences between array elements, frequency channels, and polarizations undoubtedly increase challenges for system calibration and RFI mitigation. In addition to conventional RFI monitoring methods, we propose an RFI self-monitoring scheme that utilizes the radio telescope itself, supplemented by omnidirectional and reference antennas.

RFI impact on observational equipment involves multiple factors related to both RFI sources and telescopes. RFI mitigation is systematic work. Targeted RFI mitigation method research is an important topic in radio astronomy. Implemented RFI mitigation measures have ensured MUSER' s normal operation, while upcoming instruments for Meridian Project Phase II will extend frequency coverage to 1 MHz–15 GHz, imposing higher electromagnetic environment requirements. The complex variations and distributions of multiple instruments and RFI in polarization, time, frequency, and space at Mingantu Observing Station, along with numerous random and ambiguous factors, demonstrate environmental complexity. Electromagnetic quiet zone protection, EMC, RFI monitoring identification and assessment, and mitigation still face enormous challenges. A combined RFI monitoring scheme employing reference antennas or arrays, omnidirectional antennas, and radio telescopes themselves will provide more effective information for RFI mitigation.

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