

Postprint: Development of the Analog Receiver for the High-Frequency Array of the Mingantu Radio Spectral Heliograph

Authors: Geng Lihong, YAN Yihua, Song Qinghui, Wei Lihui, Chen Zhijun, Wang Wei, Liu Fei, TAN Chengming

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Abstract

This paper presents the overall design scheme and development status of the analog receiver for the high-frequency array of the Mingantu Radio Spectral Heliograph (MUSER), elaborating on the adopted technologies including optical transmission, temperature control, filtering, and LTCC (Low Temperature Co-fired Ceramics), as well as the reliability assurance measures specifically implemented for the radio heliograph array. Following comprehensive system specification tests and temperature environmental tests for amplitude and phase stability, the results demonstrate that the performance, functionality, and stability specifications of the analog receiver system meet the design requirements of the overall system.

Full Text

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Authors: Geng Lihong^{1,2}, Yan Yihua^{1,2}, Song Qinghui³, Wei Lihui³, Chen Zhijun^{1,2}, Tan Chengming¹

¹ National Astronomical Observatories, Chinese Academy of Sciences, Beijing

² Key Laboratory of Solar Physics, Chinese Academy of Sciences, Beijing

³ The 54th Research Institute of CETC, Shijiazhuang, Hebei

Abstract

This paper presents the overall design scheme and development of the high-frequency array analog receiver for the Mingantu Radio Spectral Heliograph (MUSER). The adopted technologies—including optical transmission, thermal control, filtering, and Low-Temperature Co-fired Ceramic (LTCC)—are described in detail, along with reliability assurance measures specifically implemented for the radio heliograph array. Comprehensive system index testing and amplitude-phase stability tests under temperature-controlled environments demonstrate that the analog receiver system meets all design requirements for performance, functionality, and stability.

Keywords: radio heliograph; analog receiver; array; optical transmission; stability

1. Introduction

The Mingantu Radio Spectral Heliograph (MUSER), formerly known as the Chinese Spectral Radioheliograph (CSRH), is a dedicated high-resolution centimeter-decimeter wave radio heliograph for solar imaging observations recently completed at the Mingantu observation station of the National Astronomical Observatories. MUSER consists of two synthetic aperture arrays: MUSER-I (0.4–2.0 GHz, 40 antennas with 4.5 m diameter) and MUSER-II (2–15 GHz, 60 antennas with 2.0 m diameter). With long baselines extending up to 3 km, the instrument achieves high spatial resolution, while its high-speed data acquisition and processing capabilities provide exceptional temporal and spectral resolution. The development and construction of MUSER have attracted considerable attention in the international solar physics community [1].

For MUSER-II, maintaining high amplitude and phase consistency across the array during reception is critical for obtaining high-quality solar radio spectral images. This requirement poses a significant challenge in the development of the MUSER-II analog receiver system.

2. MUSER-II Analog Receiver Technical Specifications

The MUSER-II analog receiver employs full-band RF reception and optical transmission to process solar radio emissions in the 2–15 GHz range. The system performs low-noise amplification, polarization selection (left/right circular), and transmission via an equal-length fiber network spanning 3.4 km to the central observation room. The signals are then down-converted to an intermediate frequency (IF) with 400 MHz bandwidth (or 80 MHz in narrowband mode) and output to the backend digital receiver for analog-to-digital conversion and digital correlation processing.

The analog receiver enables real-time control of polarization/frequency switching and channel attenuation, with real-time status feedback. Flexible frequency channel coding combinations and rapid switching establish stable operation times, enabling versatile observation modes—including single or dual circular polarization observations with higher temporal resolution at certain frequencies, as well as avoiding heavily interfered bands. The main technical specifications are listed in , and the conventional 400 MHz bandwidth observation mode is shown in [Figure 1: see original paper].

3. MUSER-II Analog Receiver Composition

The receiver system comprises outdoor reception units (with backup channels), indoor reception units, RF reception channels, and cable/fiber optic assemblies. [Figure 2: see original paper] illustrates the block diagram of a single channel.

4. Design Challenges and Technical Solutions

4.1 Solar Signal Characteristics and Dynamic Range Statistical analysis of solar radiation flux density data from 1996-2010 reveals that the quiet Sun' s flux density increases by approximately 10 dB at 15 GHz and 30 dB at 2 GHz during maximum solar activity. For MUSER-II antennas with 40% efficiency, the output power ranges from -71 dBm (2 GHz) to -61 dBm (15 GHz) for the quiet Sun, and from -41 dBm (2 GHz) to -41 dBm (15 GHz) during bursts. With a system noise figure of approximately 5 dB, the minimum detectable signal power is about -68 dBm to -66 dBm.

4.2 Optical Transmission Link Design Unlike the Giant Metrewave Radio Telescope (GMRT), which uses optical fiber for IF signal transmission, MUSER-II employs single-mode low-loss fiber for direct RF transmission over 2-15 GHz. The control and status signals between indoor and outdoor units also use fiber optics. To mitigate temperature effects, cables are buried 2.5 m underground to avoid frozen soil and maintain thermal stability. However, RF transmission via fiber requires careful consideration of length variations with temperature. MUSER-II uses optical time-domain reflectometry to measure fiber lengths, achieving a maximum length difference of approximately 15 cm to 2 cm across 60 channels. Compensation via patch cords reduces this to \$ \$1.23 dB variation at 1310 nm. With an expected ambient temperature variation of less than 0.1°C and a thermal coefficient of 2 ppm/m/°C, the resulting phase variation is about 1.8° at 15 GHz, comparable to the system' s phase compensation precision of 1° achieved through daily satellite observations.

The optical link uses Miteq transceivers with built-in two-stage amplifiers and monitoring boards, providing an instantaneous linear dynamic range of \$ \$32 dB and maximum input power handling of -15 dBm to +10 dBm. Both optical transmitters (outdoor) and receivers (indoor) are thermally stabilized. [Figure 4: see original paper] shows the block diagram of the broadband RF optical transmission link.

4.3 Dynamic Range Management Digital attenuators compensate for dynamic range limitations and meet input requirements for optical transceivers and ADCs. The outdoor front-end output amplifier is followed by an attenuator to protect the expensive optical transmitter. During burst events, indoor/outdoor digital attenuators must be set to match the optical transceiver and ADC input range (500 mVpp corresponding to -2 dBm). details the power levels at main nodes in the analog receiver chain.

4.4 Thermal Control for Stability System stability is primarily affected by amplifier performance variations with ambient temperature. MUSER-II requires phase error $\leq \pm 4^\circ$ (RMS) and amplitude variation $\leq \pm 5\%$ (RMS) across the full band. Temperature-sensitive components—including outdoor low-noise amplifiers, optical transmitters, and optical receivers—are housed in thermally controlled enclosures. The outdoor unit maintains $\pm 0.5^\circ\text{C}$ precision (10-40°C range), while indoor optical receivers are placed in constant-temperature boxes. Thermal design ensures minimal temperature variation between channels, with maximum inter-channel temperature differences of 3.48°C and 3.33°C across operating ranges, guaranteeing excellent relative phase stability. [Figure 5: see original paper] illustrates the thermal control units.

4.5 High-Stability Local Oscillator The local oscillator uses a Symmetri-com SA.33 rubidium clock locked to a 10 MHz oven-controlled crystal oscillator (OCXO) as the reference. Frequency accuracy is $< 9.85\text{E-}11$, with phase noise ≤ -93 dBc/Hz @ 10 Hz, ≤ -120 dBc/Hz @ 100 Hz, and ≤ -137 dBc/Hz @ 1 kHz. Dual LO units provide redundancy, with switching time < 50 s. [Figure 6: see original paper] shows the LO and distribution block diagram.

4.6 LTCC Technology Low-Temperature Co-fired Ceramic (LTCC) technology enables high-integration, miniaturized multi-chip modules with three-dimensional multilayer wiring. Key components—including front-end switch amplifiers, channel filters, and mixers—are fabricated using LTCC production lines. Design measures include: (1) efficient grounding via star/cross vias and alternating ground layers; (2) coaxial-like interlayer transitions to address substrate flatness and conductor losses; (3) Kovar metal frames for sealed assembly; and (4) broadband amplitude equalization.

4.7 Amplitude Equalization With optical transceiver gain flatness of ± 1.5 dB and front-end component variations of ± 1 dB, microwave broadband amplitude equalization is essential to achieve $\leq \pm 2$ dB overall flatness. The equalizer design uses multiple cascaded notch units on ceramic substrates with resistive sputtering, with matching circuits at input/output ports to approximate desired responses.

5. System Features

5.1 Dual IF Bandwidth Output The receiver provides dual IF bandwidths of 400 MHz and 80 MHz, corresponding to different frequency channel configurations, both centered at 250 MHz. This design balances engineering, astronomical, and anti-interference requirements.

5.2 Broadband Anti-Interference Design Front-end amplifiers use low-noise GaAs MMICs with 50 dB burnout immunity. For out-of-band interference (e.g., FM broadcast, GSM), limiters and fixed attenuators prevent saturation and protect optical transmitters. Channel preselection filter banks provide additional protection.

5.3 Three-Stage Frequency Conversion and Filter Banks The receiver implements three-stage downconversion from 2–15 GHz to 250 MHz IF, using five sub-octave preselection filters to suppress image and IF frequencies. Filters combine bandpass and low-pass designs on gold-plated ceramic substrates, achieving >50 dB image rejection, >40 dB IF suppression, and rectangular coefficient <1.5:1. [Figure 7: see original paper] shows the channel link diagram.

5.4 Timing and Interface Design Polarization switching and microwave switch control use RS422 differential-level real-time synchronization from the outdoor monitoring unit. Frequency channel selection, attenuator settings, and status monitoring are controlled via network interface from the indoor unit. Control signals use RS422 to reduce data rates, while status monitoring uses network interface.

6. Reliability Design and Quality Assurance

6.1 Modular Architecture The modular design facilitates batch production, maintenance, and fault isolation. The system comprises: (a) 8 channel chassis (with 2 spares) and 60 outdoor front-ends in standard rack-mount enclosures; (b) channelized modular design with isolation, shielding, and filtering; (c) comprehensive signal, power, and control cable management. [Figure 8: see original paper] and [Figure 9: see original paper] illustrate the signal flow and modular design.

6.2 Built-in Calibration A 100 MHz reference from the LO unit drives a calibration source covering 2–15 GHz with ± 2.5 dB flatness. Network-controlled switching enables flexible channel testing and calibration. Powering off the calibration source prevents interference leakage.

6.3 Quality Control Measures All processes—from design to maintenance—implement quality control: circuit simulation analysis, surge-protected power inputs, screened components, temperature-sensitive material avoidance, and

high/low temperature environmental testing. Outdoor enclosures use water-proof magnesium-aluminum alloy with sealed connectors. The entire batch follows identical processes, with precision thermal control preventing parameter drift. Key components feature self-test and status reporting capabilities.

7. Performance Testing

Comprehensive tests confirm all specifications are met [9]. Thermal chamber tests from 10°C to 35°C (120 min dwell) measured amplitude-phase stability across channels. Results show phase stability $\pm 4^\circ$ (RMS) and amplitude stability $\leq \pm 5\%$ (RMS) when temperature variation is controlled within 5°C. Field measurements at Mingantu station using spectrum analyzers connected to the IF output demonstrate stable performance when antennas scan the Sun and track satellites. [Figure 10: see original paper] shows phase difference versus temperature at 2 GHz and 15 GHz, while [Figure 11: see original paper] displays satellite and solar signals in C/Ku bands. [Figure 12: see original paper] shows the physical implementation.

8. Conclusion

The MUSER-II analog receiver development represents a systematic engineering achievement, benefiting from comprehensive design, testing, and management efforts. After more than one year of continuous operation at Mingantu station, the receiver performance and functionality remain stable. Issues such as electromagnetic compatibility between subsystems and embedded module timing have been resolved. To adapt to dusty environments, further sealing of optical interfaces is planned. Full system performance testing and trial observations are ongoing.

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