

## Postprint of Spectral Line Observations and Data Calibration for the Shanghai Astronomical Observatory 65-meter Radio Telescope

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### Abstract

Spectral line observation constitutes one of the primary observing modes of the 65 m radio telescope at the Shanghai Astronomical Observatory. Building upon the joint development of pulsar and spectral line observation backends with the National Radio Astronomy Observatory of the United States, we have developed observation control software, designed hardware and software for flux calibration, and established frequency calibration procedures. Extensive observational testing has validated the effectiveness of the observation and data calibration system, which was opened to domestic users in the second half of 2015 and has since yielded numerous observational results. This work details the composition and functionality of the backend, the workflow of the observation control software, presents the processing methods and results of flux calibration and frequency calibration in conjunction with observational data, and outlines prospective work plans.

### Full Text

## Spectral Line Observation and Data Calibration of the 65m Radio Telescope at Shanghai Astronomical Observatory

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## Abstract

Spectral line observation is one of the primary observing modes of the Shanghai Astronomical Observatory radio telescope. In collaboration with the National Radio Astronomy Observatory (NRAO), we have developed a pulsar and spectral line observation terminal, along with observation control software, hardware and software systems for flux calibration, and a frequency calibration program. Extensive testing has demonstrated the effectiveness of the observation and data calibration system, which was opened to domestic users in the second half of 2015 and has since produced numerous observational results. This paper details the components and functions of the terminal, the workflow of the observation control software, presents the methods and results of flux calibration and frequency calibration using actual observation data, and outlines future development plans.

**Keywords:** spectral line observation; observation control software; flux calibration; frequency calibration

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## 1. Introduction

Spectral line observation represents a key research direction for the Tianma 65m Radio Telescope (TM 65m), currently Asia's largest fully steerable radio telescope. With broad frequency coverage spanning L, S/X, C, Ku, K, X/Ka, and Q bands, the telescope can observe atomic hydrogen lines, formaldehyde absorption lines, hydrogen recombination lines, silicon monoxide masers, and methanol masers. In 2014, we installed the Digital Backend System (DIBAS), a pulsar and spectral line observation terminal jointly developed with NRAO, to meet the spectral line observation requirements. We have since developed observation control software, configured a spectral line amplitude calibration system, and created spectral line data calibration programs. This terminal and data preprocessing system now operates successfully and is available to domestic users. This paper introduces the terminal's composition and functions, the observation control software, and the methods and test results for flux and frequency calibration.

## 2. Terminal Structure and Functions

The primary function of the DIBAS pulsar and spectral line observation terminal is to detect the spectrum of signals at specific frequencies and bandwidths received by the telescope. The terminal comprises data acquisition hardware, high-performance servers, and data storage systems.

The data acquisition hardware converts electrical signals from the telescope into digital signals for subsequent processing and storage. As shown in Figure 1: see original paper, the hardware includes analog filters, a frequency synthesis module, high-speed analog-to-digital converters (ADCs), and Roach II boards.

Analog filters limit the intermediate frequency (IF) signal bandwidth to facilitate ADC sampling. The frequency synthesis module uses a hydrogen maser frequency standard to generate highly stable and reliable signals for the ADC sampling clock and as the timing reference for the entire terminal. The ADCs convert electrical signals into digital signals, and the Roach II boards, which contain Field Programmable Gate Arrays (FPGAs), perform down-conversion, filtering, and data framing before transmitting the data via 10 Gbps network to the high-performance server group. A single data acquisition hardware set can process 1.5 GHz bandwidth data.

The high-performance server group consists of multiple computers equipped with Graphics Processing Units (GPUs) running terminal data processing software. Based on the selected observation mode, the software computes spectra at different resolutions and performs integration for specified durations. The processed data is then stored in Single Dish Flexible Image Transport System (SDFITS) format in the data storage system. For data storage, an 80 TB Lustre file system composed of two servers is configured, mapping the entire file system to the high-performance server group to enable concurrent read/write access. This storage can be easily expanded to accommodate various data formats from pulsar and spectral line observations.

The terminal offers 29 observation modes with different bandwidths and spectral resolutions, broadly categorized as follows: modes 1-3 are wideband low-resolution modes; modes 4-9 are medium bandwidth modes; modes 10-19 are single-window tunable narrowband high-resolution modes; and modes 20-29 are tunable narrowband high-resolution modes. Observers can select appropriate modes based on their scientific objectives .

### 3. Observation Control

Based on the DIBAS terminal, we have developed observation control and data preprocessing software supporting position-switching (Position On/Off) mode. The observation control software operates via Python scripts that control the antenna, IF distribution unit, and up/down converters. For flux calibration in spectral line observations, the terminal outputs control signals to periodically inject noise from a solid-state noise source of known temperature into the receiver. [Figure 2: see original paper] shows the block diagram of the observation control system.

During observations, the appropriate receiver is selected based on the target frequency band, and the sub-reflector and feed are adjusted to optimal positions. To optimize signal transmission, Tianma Telescope replaced coaxial cables with optical fibers in 2014, transmitting signals from the receiver to the terminal room over approximately 400 meters. The signal is split into multiple copies, with the up/down converters setting appropriate local oscillator (LO) frequencies based on observation requirements. The IF distribution unit then provides the IF signal to DIBAS and other terminals.

The current control software can automatically observe multiple sources in sequence. To adjust the signal power in the transmission chain, we have developed automatic gain adjustment software that monitors IF signal power and adjusts the gain of up/down converters and the IF distribution unit to maintain optimal operating levels.

#### 4. Data Calibration

Tianma Telescope's spectral line data calibration includes flux calibration and frequency calibration. After these calibrations, the data is converted into MB-FITS format, which can be read and analyzed using the GILDAS software suite.

**4.1 Flux Calibration** The energy received by the radio telescope is equivalent to a system noise temperature  $T_{\text{sys}}$ . To accurately determine  $T_{\text{sys}}$ , the noise temperature of the solid-state noise source must be calibrated. Typically, a solid-state noise source is coupled at the receiver front end, and calibration is performed by switching the noise source on and off. Two primary methods exist: noise diode measurement and reference radio source calibration.

In the centimeter wave band, we employ position-switching observations. The system noise temperature comprises multiple components: sky background noise temperature, atmospheric microwave radiation, ground radiation leakage, galactic continuum radiation, and receiver noise temperature. The position-switching method involves pointing at the source and then offsetting from it within minutes, recording data for each position. By subtracting the off-source data from the on-source data, other components can be removed under the assumption that they remain constant during this period.

The terminal records power spectrum information while the control software records antenna position and other parameters. We have developed near-real-time processing software to complete these tasks. The data calibration flowchart is shown in [Figure 3: see original paper].

For flux calibration, the DIBAS terminal generates a periodic signal to control the receiver's periodic coupling of the noise source into the received signal. During system installation, the transmission time of this periodic signal is measured to select appropriate noise power values[1]. Each data file contains multiple time-ordered data groups. For position-switching observations, the terminal discards data during noise source transitions. Both on-source and off-source observations correspond to noise source on/off states.

Using the 6.668 GHz methanol maser in W3OH as an example, [Figure 4: see original paper] shows the observed data. Panels (a) and (b) display the spectral data with noise source on and off for on-source and off-source positions, respectively. The W3OH source has very weak continuum radiation except for a strong spectral line near 6.668 GHz, showing no significant difference between noise on/off states in the off-source data. Let  $P_{\text{calon}}$  and  $P_{\text{caloff}}$  represent the

spectral data with noise on and off when pointing at the source, while  $\overline{P}_{\text{calon}}$  and  $\overline{P}_{\text{caloff}}$  represent the corresponding off-source data.

First, the off-source data is used to calculate the system noise temperature. Considering that the noise source is active only half the time, only half of  $T_{\text{cal}}$  is calculated. The system temperature is computed by averaging across frequency channels:

$$T_{\text{sys}} = \frac{\langle \overline{P}_{\text{calon}} - \overline{P}_{\text{caloff}} \rangle}{\langle \overline{P}_{\text{calon}} + \overline{P}_{\text{caloff}} \rangle} \times \frac{T_{\text{cal}}}{2}$$

Then, using  $T_{\text{sys}}$ , the source temperature  $T_{\text{src}}$  is calculated for different frequency channels:

$$T_{\text{src}} = \frac{P_{\text{calon}} - P_{\text{caloff}}}{P_{\text{calon}} + P_{\text{caloff}} - \overline{P}_{\text{calon}} - \overline{P}_{\text{caloff}}} \times T_{\text{sys}}$$

The intensity of the W3OH methanol maser is 2143.5 K. For this observation,  $T_{\text{sys}} = 23.7$  K at an elevation of  $51.7^\circ$ , yielding an equivalent flux density of 3572.5 Jy (Jansky) [FIGURE:4(c)].

**4.2 Frequency Calibration** Frequency calibration corrects the observatory's motion to the Local Standard of Rest (LSR) frame. The processing includes four main components: the radial component of the Sun's velocity relative to the LSR, the radial component of the Earth-Moon barycenter's velocity relative to the Sun, the radial component of the observatory's velocity relative to the Earth-Moon barycenter, and the radial component of the observatory's velocity relative to the Earth's center[6]. Referencing programs from the Delingha station of Purple Mountain Observatory and using the SLALIB library, we developed calibration software and validated our results against published international data.

[Figure 5: see original paper] compares Tianma Telescope's W3OH observations with reference data, showing consistent velocities. To verify frequency calibration stability, we conducted a 6-hour observation using mode 14 with 0.13 km/s velocity resolution, processing only frequency calibration. Figure 5: see original paper shows the spectral line profiles for each hourly scan in different colors, demonstrating excellent consistency and confirming stable frequency calibration over the 6-hour period.

[Figure 6: see original paper] presents additional observations of methanol masers in W75N and NGC7538, with spectral line velocities and widths matching published results.

**4.3 MBFITS Data Format** After flux and frequency calibration, the observed data is converted to MBFITS format, which includes antenna position,

atmospheric opacity, system noise temperature, and other parameters. These files can be read and analyzed using the GILDAS software suite. [Figure 7: see original paper] shows the results of reading an MBFITS file, with header information including source name (W3OH, CH3OH), system noise temperature (23 K), elevation (51.7°), velocity resolution, and rest frequency. The graphical display includes both velocity and frequency axes, where frequency represents the received frequency.

## 5. Summary and Future Plans

Based on the DIBAS terminal, we have developed observation control and data calibration software, conducted extensive observations, and compared results with published data, confirming the system's correctness. Since the second half of 2015, this system has been open to domestic users and has successfully performed numerous observations. Future work will focus on developing frequency switching observation modes, improving flux calibration methods, eliminating bandpass effects, and implementing atmospheric opacity calibration for high-frequency observations to obtain more accurate and reliable data.

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### Footnotes:

[http://www.gb.nrao.edu/~rmaddale/GBT/Commissioning/Rcvr\\_Tcal/memo22\\_NoiseDiode.pdf](http://www.gb.nrao.edu/~rmaddale/GBT/Commissioning/Rcvr_Tcal/memo22_NoiseDiode.pdf)

[http://www.gb.nrao.edu/GBT/DA/gbtidl/gbtidl\\_calibration.pdf](http://www.gb.nrao.edu/GBT/DA/gbtidl/gbtidl_calibration.pdf)

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