Real-Time Digital FFT Spectrometer for the Delingha 13.7-meter Telescope (Postprint)

Authors: Li Zhenqiang, Zhang Xuguo, Li Jibin, Sun Jixian, Lu Dengrong, Dong Shouhao, Li Yapeng, Li Shengxue

Date: 2021-09-29T00:00:00+00:00

Abstract

In radio astronomy, spectrometers serve as spectrum analysis devices at the back end of receivers and differ significantly from commercial general-purpose spectrometers due to stringent requirements for real-time performance and low noise. Radio astronomy spectrometers have evolved through several generations into real-time digital spectrometers based on chips such as Analog-to-Digital Converters (ADC) and Field Programmable Gate Arrays (FPGA). Real-time digital spectrometers offer advantages in wide bandwidth, high frequency resolution, high dynamic range, and long-term stability; more importantly, they feature compact size and relaxed environmental requirements. The back end of the Delingha 13.7-meter telescope receiver is equipped with 18 channels of real-time digital Fast Fourier Transform (FFT) spectrometers. This paper introduces the performance and maintenance of the real-time digital FFT spectrometers for the 13.7-meter telescope.

Full Text

Real-time Digital FFT Spectrometer for the Delingha 13.7 m Telescope

LI Zhen-qiang, ZHANG Xu-guo, LI Ji-bin, SUN Ji-xian, LU Deng-rong, DONG Shou-hao, LI Ya-peng, LI Sheng-xue

1. Qinghai Station, Purple Mountain Observatory, Chinese Academy of Sciences, Delingha 817000, China

2. Key Laboratory of Radio Astronomy, Chinese Academy of Sciences, Nanjing 210008, China

Abstract: In radio astronomy, spectrometers serve as critical spectrum analysis equipment at the receiver backend, with stringent requirements for real-

time performance and low noise that distinguish them substantially from commercial general-purpose spectrum analyzers. Following several generations of development, radio astronomy spectrometers have evolved into real-time digital spectrometers built upon Analog-to-Digital Converters (ADCs) and Field Programmable Gate Arrays (FPGAs). These real-time digital spectrometers offer numerous advantages including wide bandwidth, high frequency resolution, large dynamic range, and long-term stability, while also featuring compact size and modest environmental requirements. The Delingha 13.7 m telescope employs eighteen real-time digital Fast Fourier Transform (FFT) spectrometers at its receiver backend. This paper describes the performance characteristics and maintenance practices of these real-time digital FFT spectrometers for the 13.7 m telescope.

Keywords: Field Programmable Gate Array (FPGA); Fast Fourier Transform (FFT); Real-time digital spectrometer; Superconducting Spectroscopic Array Receiver (SSAR)

The Delingha 13.7 m telescope is one of China' s important radio telescopes, conducting observational research in modern astronomy and astrophysics across several frontier areas including molecular clouds and star formation in the Milky Way, planetary nebulae, late stellar evolution, interstellar medium physics, and interstellar molecular line surveys. Spectral line profiles and widths represent crucial features in molecular spectroscopy. The line profile most directly reflects the physical structure, velocity field, and line optical depth of the emitting region. Physical structures can be either homogeneous or inhomogeneous (such as clumps, filaments, and cavities), while velocity fields include both thermal and non-thermal components (such as systematic motions and turbulence). Thermal velocity fields produce Gaussian line profiles, and microturbulence in turbulent motions yields approximately Gaussian profiles as well. Systematic motions—including expansion, collapse, and rotation—can all be analyzed through corresponding line profiles. When foreground clouds absorb photons, relative motion between clouds introduces asymmetry into the spectral lines. During molecular cloud collapse, absorption shifts toward the red wing, creating characteristic line profiles with stronger blue wings than red wings. When fitting spectral lines with Gaussian functions, wings extending beyond the Gaussian profile on one or both sides indicate high-velocity mass outflows in molecular clouds, with most molecular outflows exhibiting bipolar structures. Line broadening arises from various causes, most commonly representing Doppler shifts from molecular motions, but also resulting from blending or overlapping of different velocity components, or from non-thermal velocity fields (turbulent and systematic motions).

The digital Fast Fourier Transform (FFT) spectrometer forms an integral component of the Delingha 13.7 m telescope receiver system, performing spectral analysis of radio signals collected by the antenna and receiver. Radio astronomy spectrometers have specific requirements, generally demanding high real-time performance and low noise. Depending on observational targets, they typically also require wide bandwidth, high frequency resolution, and long-term stability.

The Delingha 13.7 m telescope completed site selection from 1978–1981, began construction in 1982, and commenced astronomical observations in the 13 mm band in 1990. In 1990, the telescope' s spectrometer was the CFR-256-1 multi-channel filter-bank type, featuring a center frequency of 529 MHz with 256 channels and 1 MHz resolution. This spectrometer consisted of bandpass filters and detectors, suffering from poor channel-to-channel consistency and adjacent-channel crosstalk. Subsequently, the team experimented with Surface Acoustic Wave (SAW) spectrometers and developed Acousto-Optical Spectrometers (AOS). In 1996, the telescope began 3 mm band observations using a Schottky receiver, upgrading to a superconducting receiver in 1998 that dramatically improved sensitivity and introduced superconducting technology into Chinese astronomical observations. Following the successful development of the 3 mm band multi-line system in 2002, the telescope adopted three AOS units as its backend spectral processing system. The AOS units provided bandwidths of 42.8/43.1/145.3 MHz with 1024 channels each, achieving frequency resolutions of 80/86/208 kHz. These three AOS units corresponded to three interstellar molecular lines of CO isotopologues (12CO, 13CO, and C18O), enabling the 13.7 m telescope to simultaneously observe three CO molecular lines.

An acousto-optical spectrometer primarily comprises a laser source, beam expander, acousto-optic deflector, Fourier lens, photodiode array, and preprocessor. The laser source requires a stable monochromatic light source, while the beam expander expands the laser to form a parallel beam. The acousto-optic deflector serves as the core component, receiving the intermediate frequency (IF) signal from the receiver and converting the electrical signal into ultrasonic waves that create a phase grating within the acousto-optic crystal to diffract the incident laser. After passing through the Fourier lens, the diffracted light forms an optical image that is received by the photodiode and ultimately converted into digital signals for processing. Compared with multi-channel filter-bank spectrometers, acousto-optical spectrometers have fewer components and offer better reliability and stability. Such spectrometers have been deployed at numerous radio observatories. The acousto-optical spectrometer developed by the University of Cologne operated on the Submillimeter Wave Astronomy Satellite (SWAS), providing 1.4 GHz bandwidth with 1365 channels and power nonlinearity of less than 1%. Its Allan variance stability reached 100 seconds under ambient temperature variations of 1°C per hour. The instrument weighed 7.8 kg and consumed only 5.4 W, with low power consumption representing a major advantage that contributed significantly to its selection for the SWAS mission.

With the development of multi-bit ADCs capable of gigahertz sampling rates, massive digital processing chips, and high-speed bus technologies, real-time Fast Fourier Transform (FFT) digital spectrometers have advanced rapidly. These instruments are particularly convenient for integration with multi-beam receivers in radio astronomy. Real-time digital FFT spectrometers were first applied to the Delingha 13.7 m telescope in 2007. By the end of 2010, the multi-beam receiver—Superconducting Spectroscopic Array Receiver (SSAR)—was installed, initiating the telescope' s era of single-dish multi-beam observations. The SSAR backend employs eighteen real-time digital FFT spectrometers for spectral processing, which continue in operation today.

SSAR represents China' s first multi-beam receiver in radio astronomy and the world' s first sideband-separating multi-beam receiver at millimeter wavelengths. After more than a decade of astronomical observations, SSAR has undergone numerous component and technology upgrades, including improved radio frequency interference (RFI) resistance, elimination of local oscillator (LO) system harmonic interference, reduction of LO system baseline phase noise, and automated LO power adjustment, all of which ensure reliable and stable astronomical observations. As the backend spectral processing system, the real-time digital FFT spectrometer constitutes a crucial foundational component for SSAR' s superior performance. This paper introduces the performance parameters and maintenance work conducted on these spectrometers over the past decade.

1. Introduction to the Delingha 13.7 m Telescope and Real-time Digital FFT Spectrometer

The Delingha 13.7 m telescope features an alt-azimuth mounted Cassegrain antenna operating within a radome transparent to millimeter waves. The antenna has a 13.7 m aperture with pointing accuracy better than 5 arcseconds and surface accuracy better than 80 micrometers. The SSAR front end is located on the antenna platform and rotates with the antenna during observations. The receiver' s corrugated horn feed resides at the Cassegrain focus, with astronomical signals entering the horn directly after reflection from the primary and secondary mirrors without passing through additional optical components, thereby minimizing signal loss. The horn is followed by a sideband-separating (2SB) superconductor-insulator-superconductor (SIS) mixer that converts the 3 mm band signals to an intermediate frequency (IF) range of 2.14–3.14 GHz, which precisely covers the three CO molecular lines, while separating the upper and lower sidebands for output. The mixer is followed sequentially by a low-noise High Electron Mobility Transistor (HEMT) amplifier and a Heterojunction Bipolar Transistor (HBT) amplifier operating at 50 K. These components constitute the receiver front end, which operates inside a high-vacuum, cryogenic dewar. Figure 1 [Figure 1: see original paper] shows the Delingha 13.7 m telescope antenna and receiver front end. SSAR is a nine-beam focal plane array receiver with eighteen outputs. The eighteen signals from the front end are transmitted via cables to the indoor IF module and ultimately to the real-time digital FFT spectrometers for spectral processing. SSAR' s nine beams employ a single digital local oscillator (LO) source, which is split into nine LO signals with relatively consistent power levels via the LO distribution system for use by the 2SB SIS mixers.

The application of the nine-beam receiver and On-The-Fly (OTF) observation mode has qualitatively enhanced the telescope' s observational capabilities. The

Delingha 13.7 m telescope now produces approximately 12.2 million astronomical spectra annually—about sixty times the previous output. The development of multi-beam receivers has enabled the telescope to undertake ambitious survey projects such as the "Milky Way Imaging Scroll Painting" (MWISP) survey. Leveraging the telescope' s multi-beam receiver, multi-line observation capability, high spatial resolution, complete spatial sampling, and large sky coverage, MWISP conducts CO multi-line surveys of the northern Galactic plane within $±$5° latitude, nearby star-forming regions, and high-galactic-latitude molecular clouds, covering an observational area of 2,700 square degrees. This survey investigates molecular cloud structures and their distribution in the Milky Way, as well as interactions between molecular clouds and other interstellar material, providing crucial insights for understanding the origins of stars, planets, and even the universe itself. After nearly a decade of observations, MWISP is now essentially complete and has yielded a series of important scientific results.

SSAR employs eighteen real-time digital FFT spectrometers, as shown in Figure 2 [Figure 2: see original paper], with the left panel displaying the nine upper sideband channels and the right panel the nine lower sideband channels. The spectrometers connect to the IF module, which converts the 2.14–3.14 GHz signals from the receiver front end to 0–1 GHz and sets the total power to approximately -5 dBm via an internal Electrically Adjustable Attenuator (EAA) for spectral processing by the real-time digital FFT spectrometers.

The spectrometer hardware consists of the Acqiris AC240 spectrum analyzer. The AC240 contains two 8-bit ATMEL TS8388B ADC chips and a Xilinx Virtex-II Pro 70 FPGA for massive digital processing, equipped with a high-speed PCI data bus. The ADC sampling rate is 1 GS/s, and with two ADCs operating in interleaved mode (180° phase difference), the effective sampling rate reaches 2 GS/s. The FFT data processing core was jointly developed by the Purple Mountain Observatory and Shanghai Weijiete Electromechanical Technology Co., Ltd.

The spectrometer' s single-point sampling interval of 5 ns determines a maximum analysis bandwidth of 1 GHz. Each spectrum samples 32,768 points, yielding 16,384 channels after FFT transformation. The sampling time for one spectrum is 16.384 s, with FPGA-based FFT processing completed within this same timeframe, ensuring continuous spectral acquisition without idle time and guaranteeing uninterrupted astronomical observations. The number of sampling points per spectrum is determined by the FFT algorithm.

Digital spectral analysis typically employs three algorithms: Fourier transform, autocorrelation, and digital filter bank methods. Autocorrelation and digital filter bank methods require enormous computational resources and are time-consuming. While conventional Fourier transform methods share this characteristic, the computational load decreases dramatically when the data length is an exact power of two—this optimized version being the Fast Fourier Transform, which enables FPGA completion within 16.384 s. FFT processing requires windowing to truncate the finite-length data. Common window functions include rectangular, Hanning, Hamming, and Blackman windows. The Delingha telescope' s real-time digital FFT spectrometer utilizes the rectangular window function, which features a narrow main lobe and large side lobes, providing high frequency identification accuracy but lower amplitude identification precision. For molecular line observations, frequency resolution is paramount, while signal intensity values are calibrated using the chopper wheel method. Therefore, as long as the real-time digital FFT spectrometer maintains sufficient linearity, the rectangular window function represents an excellent choice.

The spectrometer can be configured via firmware for three bandwidth analysis modes: 1 GHz, 200 MHz, and 500 MHz. The most frequently used mode for astronomical observations over the years has been the 1 GHz bandwidth mode, where each channel corresponds to a frequency bandwidth of 61.035 kHz. For observations of narrow astronomical lines requiring high frequency resolution, the IF module output bandwidth can be filtered to 0–200 MHz and the spectrometer loaded with the 200 MHz mode. In this configuration, the spectrometer maintains its 16,384 channels, but each channel corresponds to a frequency bandwidth of 12.207 kHz—providing a fourfold improvement in frequency resolution.

The host computer controls the real-time digital FFT spectrometer via local area network to set the integration time. With a single spectrum acquisition time of 16.384 s, the spectrometer achieves integration by accumulating multiple spectra. Processed data are transferred through the LAN to a disk array for storage.

2. Performance and Maintenance of the Real-time Digital FFT Spectrometer

As the final stage of the SSAR receiver system, the FFT spectrometer converts telescope observations from analog to digital signals, and its linearity directly impacts signal intensity calibration accuracy. The FFT spectrometer' s linearity encompasses both total power linearity and point-frequency signal linearity. The linearity is primarily determined by the ADC, while the window function used during FFT affects signal intensity but has minimal impact on linearity. Theoretically, the FFT spectrometer should exhibit good linearity, which we have verified through testing.

The FFT spectrometer demonstrates lower noise than commercial general-purpose spectrum analyzers, as shown by our comparative analysis.

2.1. Linearity of the Real-time Digital FFT Spectrometer

We tested the total power linearity using the configuration shown in Figure 3 [Figure 3: see original paper]. The noise source consisted of the SSAR front end with the superconducting mixer biased in its linear region, providing a stable noise source. This was followed by the IF module, whose internal electrically adjustable attenuator was used to vary the receiver output power. The FFT spectrometer’ s total power linearity was calculated by comparing the total power measured by a power meter with the integrated value across all channels from the FFT spectrometer.

When the electrically adjustable attenuator was set at 1 dB intervals, the resulting FFT spectrometer spectra are shown in Figure 4 [Figure 4: see original paper]. The figure reveals that interference signals appear when the input broadband signal power is weak, introduced by internal digital circuits—an area where electromagnetic shielding improvements are needed in the next-generation FFT spectrometer. Because the 1 dB steps of the electrically adjustable attenuator are not precisely calibrated, the spectral spacing in the figure varies considerably. Fitting the power meter measurements against the FFT spectrometer’ s integrated spectral power yields the total power linearity results shown in Figure 5 [Figure 5: see original paper]. The FFT spectrometer achieves a total power linearity of 96.3% across a linear range from -25 dBm to 3 dBm, demonstrating excellent linearity and high dynamic range.

Astronomical observations with the 13.7 m telescope primarily focus on spectral lines, making the point-frequency signal power linearity of the FFT spectrometer critically important. In the test configuration shown in Figure 3 [Figure 3: see original paper], the broadband noise total power at the FFT spectrometer input was set to -8 dBm (a typical state for astronomical observations). A point-frequency signal was coupled into the broadband noise via the IF module before entering the FFT spectrometer. By measuring the input power of the point-frequency signal against the signal power obtained by the FFT spectrometer, we calculated the point-frequency signal linearity, as shown in Figure 6 [Figure 6: see original paper]. The point-frequency signal power linearity of the FFT spectrometer is 100%. Figure 7 [Figure 7: see original paper] displays the FFT spectrometer spectra at 4 dB power intervals for the point-frequency signal. Due to the presence of broadband noise, the spectral intensities in the figure are not exactly 4 dB apart. When signal strength is high, the signal spreads from its original single channel into multiple channels, caused by spectral leakage from the rectangular window function used in the FFT.

2.2. Noise Comparison Between Real-time Digital and Commercial FFT Spectrometers

Radio astronomy spectrometers exhibit lower noise than commercial spectrum analyzers. We compared the spectral characteristics of the FFT spectrometer and an Agilent E4407B commercial spectrum analyzer when acquiring the same spectrum, as shown in Figure 8 [Figure 8: see original paper]. The FFT spectrometer integration time was 5 seconds, while the E4407B integration time was 270 seconds. Comparing the 0.2–0.4 GHz spectrum reveals that the FFT spectrometer produces lower noise in significantly less time.

2.3. Maintenance of the Real-time Digital FFT Spectrometer

The eighteen real-time digital FFT spectrometers operate within two chassis. The observatory is located at an altitude of 3,200 meters where the air is relatively thin, and the spectrometers work continuously throughout the year, making heat dissipation critically important. Excessive internal temperature causes spectral anomalies. The spectrometers include temperature alarms that provide timely warnings when temperatures become too high. During operation, we employ fans to increase air circulation and enhance heat dissipation from internal components. When spectral anomalies occur due to high temperature, restarting the spectrometer after cooling restores normal operation. Over more than ten years of continuous operation, the FFT spectrometers have remained stable with few failures, apart from temperature-related anomalies. A power supply failure occurred in 2011, as shown in Figure 9 [Figure 9: see original paper], which was quickly repaired to restore normal operation.

During the annual instrument maintenance period each July, we perform maintenance on the FFT spectrometers. After a full year of operation, dust accumulates inside the spectrometer chassis, so we clean both the chassis interior and the spectrometer board components.

The FPGA and ADC chips generate the most heat in the spectrometer. To enhance heat dissipation, the chip surfaces connect to metal plates via metal posts, with thermal grease applied at the contact points between chips and posts to improve thermal conductivity. Over extended operation, the thermal grease dries out and its thermal conductivity degrades. Therefore, we replace the thermal grease at high-power chips and metal contact points, as shown in Figure 10 [Figure 10: see original paper], to improve heat dissipation and ensure stable long-term spectrometer operation.

3. Summary

Real-time digital FFT spectrometers based on high-speed sampling ADCs and massive digital processing FPGA chips offer numerous advantages, including fast spectral processing speed, low noise, wide bandwidth, high frequency resolution, large dynamic range, and long-term stability, making them the most advantageous radio astronomy spectrometers currently available. Additionally, they feature compact size, modest environmental requirements, and low cost. As technology advances, FFT spectrometers are developing toward even higher bandwidths. In 2010, the XFFT (eXtended bandwidth FFT spectrometer) at the APEX (Atacama Pathfinder Experiment) telescope achieved a processing bandwidth of 2.5 GHz with 32K channels. In China, the ultra-wideband universal digital backend (CRANE) for the Five-hundred-meter Aperture Spherical Telescope (FAST) processes 3 GHz bandwidth with millions of channels (4,194,304). The latest generation of real-time digital FFT spectrometers from Shanghai Xunxi Electronic Technology Co., Ltd. can achieve processing bandwidths up to 5 GHz. These developments ensure that the Delingha 13.7 m telescope is well-positioned for expansion to wider IF bandwidths. In future real-time digital FFT spectrometer development, digital circuits will require enhanced electromagnetic shielding to avoid spurious single-channel artifacts. As processing bandwidths increase, the power consumption of high-speed sampling ADCs and massive digital processing FPGA chips will also increase, making thermal management for both individual chips and multi-channel spectrometer integrated chassis a critical consideration for ensuring stable long-term operation.

References

[1] LI Z Q, ZHANG X G, XU Y, et al. Operation of Multibeam Receiver of Delingha 13.7m Telescope[J]. Acta Astronomica Sinica,2021,62(3):24.

[2] SUN J, LI S Z. Fundamentals of molecular Astrophysics[M].BEIJING: Beijing Normal University Press. 2003:169

[3] LI B. Studying Methods and Prospects of Melecular Astronomy[J]. Journal of Linyi Teachers’ College, 2010, 32(6):39-43.

[4] HAN P. Site Choosing of Qing-Hai Millimeter-Wave Radioastronomy Station of Purple Mountain Observatory[J]. Acta Astronomica Sinica, 1985, 26(2):89-98

[5] LIANG Z Y, RONG Y H, WAN X M, et al. The Filter-Bank Spectrometer of Model CFR-256-1[J].Publications of Purple Mountain Observatory, 1991, 10(1):56-63.

[6] CHEN D P,GONG J J, ZHOU X W, et al. A New Type of Radio Astronimical Spectrometer–SAW Spectrometer[J]. Chinese Journal of Astronomy and Astrophysics, 13(1):7.

[7] DING Z G, HUANG G L, XU ZQ, et al. Prospects of the Application of Integrated Acousto-Optical Spectrum Analuzer (IAOSA) to Radio Astronomy[J]. Publications of Purple Mountain Observatory, 1995(1).

[8] ZHENG X W, LEI C M. Measurement for the Performance of an Acousto-Optic spectrograph[J]. Acta Astronomica Sinica, 1997(4).

[9] MAO R Q. The Stability of the Spectrum System on the 13.7m Telescope and Optimizing the Use of Telescope Time[J]. Publications of Purple Mountain Observatory, 1998(3):13-17.

[10] YANG J, SHI S C,PEI L B, et al. 3mm band multi-line system[Z]. Second Prize of National Science and Technology Progress Award,2006

[11] LIN Z H. Development and Applied Research of Real-time FFT Spectrometer with Wide Bandwidth and High Frequency Resolution[D].Nanjing: Purple Mountain Observatory, Chinese Academy of Sciences,2007

[12] KLUMB M , FREICK J , TOLLS V , et al. Submillimeter Wave Astronomy Satellite (SWAS) acousto-optical spectrometer[C]. SPIE’ s 1994 International

Symposium on Optics, Imaging, and Instrumentation, 1994, 2268:305-315.

[13] FREICK J , KLUMB M , SCHIEDER R T, et al. SWAS-AOS: the first acousto-optical spectrometer in space[C]. SPIE' s International Symposium on Optical Science, Engineering, and Instrumentation, 1999,3759.

[14] LIN Z H,YAO Q J,YANG J.New Progress on Digital Spectrometer for Radio Astronomy[J]. Progress in Astronomy, 2008, 26(2):175-183.

[15] SHAN W L, YANG J , SHI S C, et al. Development of Superconducting Spectroscopic Array Receiver: A Multibeam 2SB SIS Receiver for Millimeter-Wave Radio Astronomy[J]. IEEE Transactions on Terahertz Science & Technology, 2012, 2(6):593-604.

[16] YANG J, CAO N. Superconducting Spectroscopic Array Receiver[J].Bulletin of Chinese Academy of Sciences, 2011, 26(4): 478-481.

[17] LI Z Q, LI J B , ZHANG X G, et al. Research on Receiver Anti-RFI of Delingha 13.7 m Telescope[J]. Acta Astronomica Sinica, 2019, 60(3):24.

[18] LI Z Q , LI J B , ZHANG X G , et al. Research on Receiver Anti-RFI of Delingha 13.7 m Telescope[J]. Chinese Astronomy and Astrophysics, 2019, 43(4):590-608.

[19] LI Z Q , ZHANG X G, LI J B, et al. The harmonic interference problem of LO in Delingha mm wave telescope[J]. Astronomical Research & Technology, 2020,17(1):60-67.

[20] LI Z Q , ZHANG X G, LI J B, et al. Investigation of LO-Coupled Noise for a Sideband Separation Superconducting SIS Receiver[J]. Acta Astronomica Sinica, ,2020, 61(2):73-84.

[21] LI Z Q , ZHANG X G, LI J B, et al. Investigation of LO-Coupled Noise for a Sideband Separation Superconducting SIS Receiver[J]. Chinese Astronomy and Astrophysics, 2020, 44(3):383-398.

[22] ZUO Y X, SHAN W L, YANG J. Optical Design Considerations for a Millimeter-Wave Focal Plane Array[C]. 2008 Global Symposium on Millimeter Waves,2008:197-200.

[23] BENZ A O , GRIGIS P C , HUNGERBUHLER V , et al. A broadband FFT spectrometer for radio and millimeter astronomy[J]. Astronomy & Astrophysics, 2005, 442(2): 767-773.

[24] LIN Z H, YANG J, LI S, et al.Broadband High Resolution Real-Time Fast Fourier Transform Digital Spectrometer : 2.009100278232E11[P]. 2011-08-17.

[25] YANG J.Atmospheric Attenuation and Intensity Calibration for Millimeter and Submillimeter-Wave Observations[J]. Acta Astronomica Sinica, 1999, 19(1):55-62.

[26] KLEIN B, HOCHGÜRTEL S, KRÄMER I, et al. High-resolution wideband Fast Fourier Transform spectrometers[J]. Astronomy & Astrophysics, 2012,

542(2): 1075-1082.

[27] ZHANG X, YU X Y, DUAN R, et al. FAST Digital Backend and Algorithm Simulation for Broadband Million Channel Spectrometer[J]. Progress in Astronomy, 2016, 34(2):249-257.

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