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DSN Radio Astronomy Spectrometer

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Abstract

The Deep Space Network (DSN) enables NASA to communicate with its deep space spacecraft. By virtue of its large antennas, the DSN can be used as a powerful instrument for radio astronomy. In particular, Deep Space Station (DSS) 43, the 70 m antenna at the Canberra Deep Space Communications Complex (CDSCC) has a K-band radio astronomy system covering a 10 GHz bandwidth at 17 to 27 GHz. This spectral range covers a number of atomic and molecular lines, produced in a rich variety of interstellar gas conditions. A new high-resolution spectrometer was deployed at CDSCC in November 2019 and connected to the K-band downconverter. The system has two different firmware modes: 1) Using a 65k-pt FFT to provide 32,768 spectral channels at 30.5 kHz (0.45 km/s velocity resolution) and 2) Using a 16k-pt polyphase filterbank (PFB) to provide 8,192 spectral channels with ~122 kHz resolution (1.8 km/s velocity resolution). Previous work extensively described the spectrometer system. In this paper we present added functionality and updates to the commissioned spectrometer. The changes include developments in system timing, metadata, firmware and data products.

1 Introduction

The spectrometer was installed and commissioned at Canberra Deep Space Communications Complex (CDSCC) in November 2019 [7]. Over 30 observations took place from December 2019 to March 2020. In March 2020, the 70 m antenna Deep Space Station (DSS) 43 downtime began. The downtime allowed for spectrometer software and firmware development. The spectrometer improvements were based on feedback from the Principle Investigator (PI) and observer at CDSCC. In §2 we describe the spectrometer system, in §3 we describe the improvements to system timing, in §4 we describe the improvement to system firmware, in §5 we present the metadata addition and in §6 we present the updated data products.

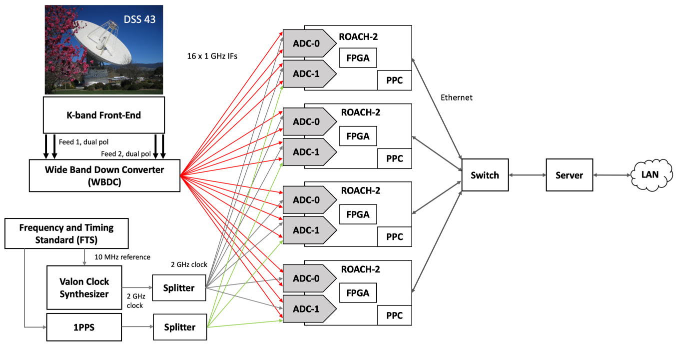

Figure 1. Spectrometer architecture diagram showing the signal path from DSS-43 to the spectrometer.

Mode	Description
1	32k spectral channels FFT-based (30.5 kHz $\approx$ 0.4 km s^{-1} at 22 GHz)
2	8k spectral channels, polyphase filterbank-based (122 kHz $\approx$ 1.7 km s^{-1} at 22 GHz)

Table 1. DSN Radio Astronomy Spectrometer Modes

2 System Overview

The spectrometer system is diagrammed in Figure 1. The spectrometer is comprised of four Reconfigurable Open Architecture Computing Hardware (ROACH)-2 boards created by CASPER (Collaboration for Astronomy Signal Processing and Electronics Research)[3][4]. Each ROACH-2 can process up to four, 1 GHz inputs, resulting in a total bandwidth of 16 GHz. The spectrometer receives 2 GHz clock and 1 Pulse Per Second (PPS) signals from the Complex's Frequency and Timing Standard subsystem. A server and switch create a local network for the spectrometer. The server is connected to the Complex's Local Area Network (LAN).

The spectrometer has two firmware modes shown in Table 1. One mode is a 32768 spectral channel Fast Fourier Transform (FFT)-based mode. The other is an 8192 spectral channel Polyphase Filterbank(PFB)-based mode. Further detail about the firmware can be found in §4.

The spectrometer also has two operating modes: on the fly mapping (OTF) and position switching (PSW). In PSW mode, the telescope slews to a designated source position, stops, then the spectrometer collects data for a certain amount of time (the integration time) at this "on" position. This is followed by data collection at an emission free position (or "off"position). An observation switches between "on" and "off" positions. In OTF mode [2] [8] , the telescope moves at a certain rate and the spectrometer collects data during this motion (rather than stopping at several points), followed by single observation on the "off" position, enabling efficient spectral line mapping.

3 Timing

The spectrometer is designed to maximize automation, with the goal that its operation be completely automated. As such, it is crucial that the spectrometer collects data only when it is scheduled to and that this timing is carefully coordinated. To ensure this, the spectrometer is connected to a 1 PPS signal from the FTS subsystem. Right before a scan is scheduled to start, the software resets the ROACH-2 board "arm" registers which prepares the firmware for data collection. On the next second boundary (in this case the start time of the scan), the 1 PPS resets the counter logic in the ROACH-2 boards. Resetting the counter logic aligns the data samples from the boards to UTC and restarts data accumulation, effectively restarting data collection at that particular point in time. Additionally, resetting all of the boards at the same time ensures that the software receives data from each ROACH-2 board at the same time, i.e. four samples, one from each board, will be received at once.

While the 1 PPS signal ensures that data collection is synchronized and begins at the correct time, further measures were taken to ensure that data collection ends when it should. A common problem occurred when a sample would finish accumulation shortly before the stop time of a scan, resulting in the process of reading the data and writing to binaries going past the stop time. To solve for this, the time needed to read/write was experimentally determined and accounted for in the software when determining when to stop collecting data. Now the software will stop earlier if the time needed for another sample to finish and for its data to be processed would go past the stop time of the scan.

4 Firmware

To support the spectrometer's addition of a 1 PPS signal, both spectrometer firmware modes were modified to monitor the PPS state by synchronously blinking a LED. This feature is useful upon spectrometer installation and debugging efforts to ensure the ROACH-2 boards are actively receiving a legitimate 1 PPS signal from the FTS subsystem.

As shown in Table 1, two spectrometer firmware modes are available: a 65k-pt FFT-based mode and a 16k-pt Polyphase Filterbank (PFB)-based mode. In the presence of Radio Frequency Interference (RFI), strong narrowband signals can saturate adjacent channels, known as *spectral leakage* [6]. Since the PFB-based mode has lower spectral leakage, it is the desired mode of operation when RFI is present during observations. However, given a limited amount of FPGA resources and that a PFB-based mode requires more resources than an FFT, it has a lower spectral resolution.

5 Metadata

The following subsection details how the spectrometer receives metadata such as system temperature.

5.1 System Temperature

The spectrometer receives system temperature data from the K-band Front-End subsystem of DSS 43. Before an observation, a calibration must be performed. The results of the calibration are power data and a power conversion factor. The power conversion factor is used to convert the power data in kW to temperature in Kelvins.

In Figure 2, the network connections between the spectrometer server and Front-End server are shown. On each server there is a software process running (in the figure these processes are shown as yellow blocks). The spectrometer server uses the roach process to communicate with the Front-End server. The Front-End server uses its FE process to run the calibration using the Front-End hardware. The system temperature data is then sent back to the spectrometer server where it is available to be added to the data products. System temperature metadata are used in the Level 1 processing. System temperature is stored as a column along with the spectrum data as described in §6.

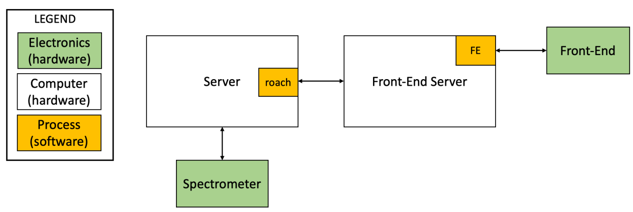

Figure 2. This diagram shows the Front-End and spectrometer server connection. This connection is necessary for the spectrometer server to receive system temperature data.

6 Data Products

The data products are FITS files written in single dish FITS (SDFITS)[1] format.

[1]The Registry of FITS Conventions, `https://fits.gsfc.nasa.gov/fits\_registry.html`

6.1 Level 0

The Level 0 data product provides all necessary information for a PI to process data using their own processing methods. For each scan, the SDFITS file is organized in the following format: 1 primary header and 16 data bintables. The primary header contains information such as observation duration, source name, right ascension, declination, and observation mode. The 16 data bintables correspond to each spectrometer input. The header of each bintable has the frequency (Hz) along with other information. Each data bintable has 7 columns: spectrum data, antenna's elevation (m) as a function of time during each scan, system temperature estimate (K) as a function of time during each scan, bandwidth (Hz), duration (s), right ascension offset (degrees), and declination offset (degrees) [7]. The right ascension offset and declination offset are relevant only for OTF observations. The system temperature is computed by interpolating the data taken with the calibration described in §5.1 at the time the observations were taken.

6.2 Level 1

The purpose of the Level 1 data processing pipeline is to calibrate the Level 0 raw spectra taken by the ROACH-2 spectrometers, so they can be used for scientific analysis and interpretation. The pipeline takes a pair of raw ON-source and OFF-source spectra, in the case of observations in position-switching mode, or a pair of raw on-the-fly scan and an OFF-source position to compute the antenna temperature, defined as,

$$T_A^* = \frac{T_{on} T_{off}}{T_{off}} T_{sys}, \tag{1}$$

where T_{on} is the measured temperature (power) toward a source, T_{off} is the measured temperature (power) toward an "off" position, and T_{sys} is the system temperature. The data are corrected for antenna gain variations as a function of source elevation using the fit described in Equation (2) in [1]. The calibrated data are then written in the FITS format and, optionally, in the GILDAS/CLASS format [5], for further processing.

7 Conclusion

The spectrometer installed and commissioned at CDSCC in November 2019 was recently updated. The updates were to the system's timing, metadata, firmware and data products. The addition of a 1 PPS signal to the spectrometer ensured greater timing precision. The firmware was also updated so the observer can monitor the PPS state via LED lights. Another update was to the metadata and in turn also an update to the data products. Instead of the inclusion of system temperature in the data products being a manual process, the metadata now automatically flows to the spectrometer server. Spectrometer observations are set to begin after the DSS 43 downtime ends in early 2021. Future work includes the capability for the spectrometer to receive antenna on source updates and weather data.

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