A Broadband Digital Spectrometer for the Deep Space Network

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Abstract

The Deep Space Network (DSN) enables NASA to communicate with its spacecraft in deep space. By virtue of its large antennas, the DSN can also be used as a powerful instrument for radio astronomy. Specifically, the 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 17–27 GHz. This spectral range covers a number of atomic and molecular lines, produced in a rich variety of interstellar gas conditions. Lines include hydrogen radio recombination lines (RRLs), cyclopropenylidene (C_3H_2), water masers (H_2O), and ammonia (NH_3). A new high-resolution spectrometer was deployed at CDSCC in 2019 November and connected to the K-band down converter. The spectrometer has a total bandwidth of 16 GHz. Such a large total bandwidth enables, for example, the simultaneous observations of a large number of RRLs, which can be combined together to significantly improve the sensitivity of these observations. The system has two firmware modes: (1) a 65k-pt fast Fourier transform to provide 32,768 spectral channels at 30.5 kHz and (2) a 16k-pt polyphase filter bank to provide 8192 spectral channels with a 122 kHz resolution. The observation process is designed to maximize autonomy, from the principle investigator's inputs to the output data in FITS file format. We present preliminary mapping observations of hydrogen RRLs in Orion KL mapping taken using the new spectrometer.

Unified Astronomy Thesaurus concepts: Spectrometers (1554); Astronomical instrumentation (799)

1. Introduction

Spectroscopic observations in the radio part of the electromagnetic spectrum provide key information in the physical and chemical state of a variety of astrophysical environments. These environments include the ionized medium created by massive stars, traced via observations of hydrogen radio recombination lines (RRLs), the densest parts of molecular clouds where star formation takes place, and protoplanetary disks where planets form, both of which are traced by observations of molecular line emission. All these science applications can be more efficient with the capability to observe spectral lines over a large instantaneous bandwidth. Spectral lines from RRLs and complex molecules are dispersed over a large range of frequencies, and therefore stacking techniques can be used for obtaining sensitive observations. Additionally, broadband capabilities are required for efficient spectral line surveys of star-forming regions in the Milky Way and nearby galaxies.

The spectral range of approximately 17–27 GHz (K band) covers a number of atomic and molecular lines, produced in a rich variety of interstellar gas conditions. Lines include hydrogen RRLs, cyclopropenylidene (C_3H_2), water (H_2O), and ammonia (NH_3). Also, redshifted spectral lines can be observed in the K band from distant galaxies, e.g., silicon monoxide (SiO). In Table 1, we present a selection of key molecular and ionic species that can be observed in the K band.

In this paper, we present a new broadband spectrometer that covers 16 1 GHz intermediate frequencies (IFs) in the 17–27 GHz range simultaneously, allowing efficient line surveys in galactic and extragalactic sources. This spectrometer operates in the K band and has been installed at the Deep Space Network (DSN) Complex in Canberra, Australia.

In Section 2 we describe the architecture of the spectrometer; in Section 3 we describe the data products; in Section 4 we describe the implementation and verification; and in Section 5 we present our conclusions and possible paths toward the future.

2. Architecture

The 70 m antenna Deep Space Station 43 (DSS-43, also known as "Tidbinbilla 70 m") at the Canberra Deep Space Communications Complex (CDSCC) within NASA's Deep Space Network is equipped with a K-band radio astronomy system. Operating over the 17 GHz to 27 GHz frequency range, the analog portion of the K-band system produces 40 IFs, each of 1 GHz bandwidth (Kuiper et al. 2019). These IFs from the Wide Band Down Converter (WBDC) at DSS-43 are distributed to the new spectrometer. The full spectrometer can process up to 16 1 GHz IFs.

As an initial implementation, two modes were designed (Table 2). The focus was on providing a sufficient spectral resolution for many forms of spectroscopy. Data from the Radio Astronomy spectrometer is provided in single-dish FITS (SDFITS[5]) format (Garwood 2000).

2.1. Hardware Overview

The spectrometer consists of four CASPER Reconfigurable Open Architecture Computing Hardware 2 (ROACH-2)[6] boards as shown in Figure 1. Each board has 2 analog-to-digital converters (ADC) cards, a field programmable gate array and PowerPC microprocessor. The ADC cards are CASPER 8 bit 5 gigasamples s^{-1} ADC cards. Each ADC card has two inputs resulting in each board having a total of four inputs.

A Valon 5009 dual frequency synthesizer controls the 2 GHz clock for each of the ROACH-2 boards. The Valon synthesizer

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[5] The Registry of FITS Conventions, https://fits.gsfc.nasa.gov/fits_registry.html
[6] CASPER ROACH-2 boards, https://casper.ssl.berkeley.edu/wiki/ROACH2.

Table 1
Selected Lines in the 17–27 GHz Range[a]

Line Name	Frequency (GHz)	Maser or Thermal?[b]
H72α	17.258	Thermal
H71α	17.992	Thermal
NH_3 (7, 3)	18.017	Thermal
NH_3 (10, 7)	18.285	Thermal
NH_3 (6, 1)	18.391	Thermal
H70α	18.769	Thermal
H69α	19.591	Thermal
CH_3OH $(2_1 - 3_0)$	19.967	Both (II)
H68α	20.462	Thermal
NH_3 (8, 6)	20.719	Both
NH_3 (9, 7)	20.735	Thermal
C6H $(15/2 - 13/2)$	20.792	Thermal
NH_3 (7, 5)	20.804	Thermal
NH_3 (11, 9)	21.071	Both
NH_3 (4, 1)	21.134	Thermal
H67α	21.385	Thermal
H_2O $(6_1 - 5_2)$	22.235	Maser
CCS $(2_1 - 1_0)$	22.344	Thermal
H66α	22.364	Thermal
HC_7N (20→19)	22.559	Thermal
NH_3 (2, 1)	23.099	Thermal
CH_3OH $(9_2 - 10_1)$	23.121	Maser (II)
H65α	23.404	Thermal
CH_3OH $(10_1 - 9_2)$	23.444	Thermal
NH_3 (1, 1)	23.694	Thermal
NH_3 (2, 2)	23.722	Thermal
NH_3 (3, 3)	23.870	Both
NH_3 (4, 4)	24.139	Thermal
NH_3 (5, 5)	24.533	Both
NH_3 (6, 6)	25.056	Both
H64α	24.509	Thermal
CH_3OH $(3_{2\,3\,1})$	24.928	Both (I)
CH_3OH $(4_{2\,4\,1})$	24.933	Both (I)
CH_3OH $(2_{2\,2\,1})$	24.934	Both (I)
CH_3OH $(5_{2\,5\,1})$	24.959	Both (I)
CH_3OH $(6_{2\,6\,1})$	25.018	Both (I)
CH_3OH $(7_{2\,7\,1})$	25.124	Both (I)
H63α	25.686	Thermal
HC_5N (109)	26.626	Thermal
H62α	26.939	Thermal

Notes.
[a] Adapted from Table 1 in Walsh et al. (2011).
[b] For CH_3OH masers, they are identified either as Class I or II.

Table 2
DSN Radio Astronomy Spectrometer Modes

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 filter bank-based (122 kHz $\approx$1.7 km s^{-1} at 22 GHz)

receives a 10 MHz reference signal provided by the Frequency and Timing Standard system available at CDSCC.

The ROACH-2 boards are controlled by a Dell PowerEdge R510 server. The server controls the boards by running Bash scripts, which call the Python software discussed in Section 2.2. The server is connected to the DSN complex's Local Area Network (LAN), and the ROACH-2 boards are connected via a

network switch to the server. The ROACH-2 boards form an internal network behind the switch.

2.2. Software Design

The software design is shown in Figure 2. The configuration file contains information such as the DSN antenna pointing file name, experiment stop time, gap time between scans, observation mode, IF configuration, and system temperature. Further detail on the information included in the configuration file and how the principle investigator (PI) supplies the input parameters can be found in Section 3.1.

The Query box represents the query script, which creates an observation file based on the schedule listed in the DSN antenna pointing file. The times in the observation file and pointing file slightly differ since the observation file takes into account antenna slew time between sources.

The Grab Data box represents the grab data script which controls the four ROACH-2 boards. The grab data script starts and stops data acquisition on the ROACH-2 boards based on the observation file. Data acquisition begins at the specified start time in the observation file. Data acquisition ends when either the stop time in the observation file is reached or when the target number of samples is reached for a given scan. Further details on how the target number of samples is calculated can be found in Section 3.1. For each scan, 16 spectra data files are created.

The Append FITS box represents the append fits script. This script converts the binary spectra data results to FITS bin tables. The resulting FITS file includes one primary header and 16 bin tables for each scan.

2.3. Firmware Design

There are two firmware modes: a 65k-pt fast Fourier transform (FFT) with 32,768 spectral channels with a 30.5 kHz resolution and a 16k-pt polyphase filter bank (PFB) with 8192 spectral channels with a 122 kHz resolution. The 8k mode scripts refer to the 16k-pt PFB and the 32k mode scripts refer to the 65k-pt FFT. The PI selects the mode for their track. For RRL mapping, the 65k-pt FFT mode is operationally used.

A general firmware block diagram is shown in Figure 3 for both 8k and 32k modes. The 32k mode is described as follows for a single input on a single ADC. The ADC data from a single input is 65536 real samples. The ADC data is then put through an FFT. The FFT results in 32,768 complex channels. The complex magnitude is taken. The accumulator (ACC) block is the accumulator that averages the data a certain number of times as specified by acc_len.

The accumulator integrates the data as 32 bit samples. Then the averaged FFT data is split into four 8192 channel buffers, which have 32 bits/channel. Each 8192 channel buffer is put in a store register. For example, the data for one of the ADC inputs is stored in the first four store registers. The other ADC input stores its data in the next four store registers and so on. This firmware process is duplicated four times, once for each of the four inputs on each ROACH-2 board. The 8k firmware mode process is similar. The ADC data from a single input is 16384 real samples. After the PFB, there are 8192 complex channels. After integration, the data is split into four 2048 channel buffers.
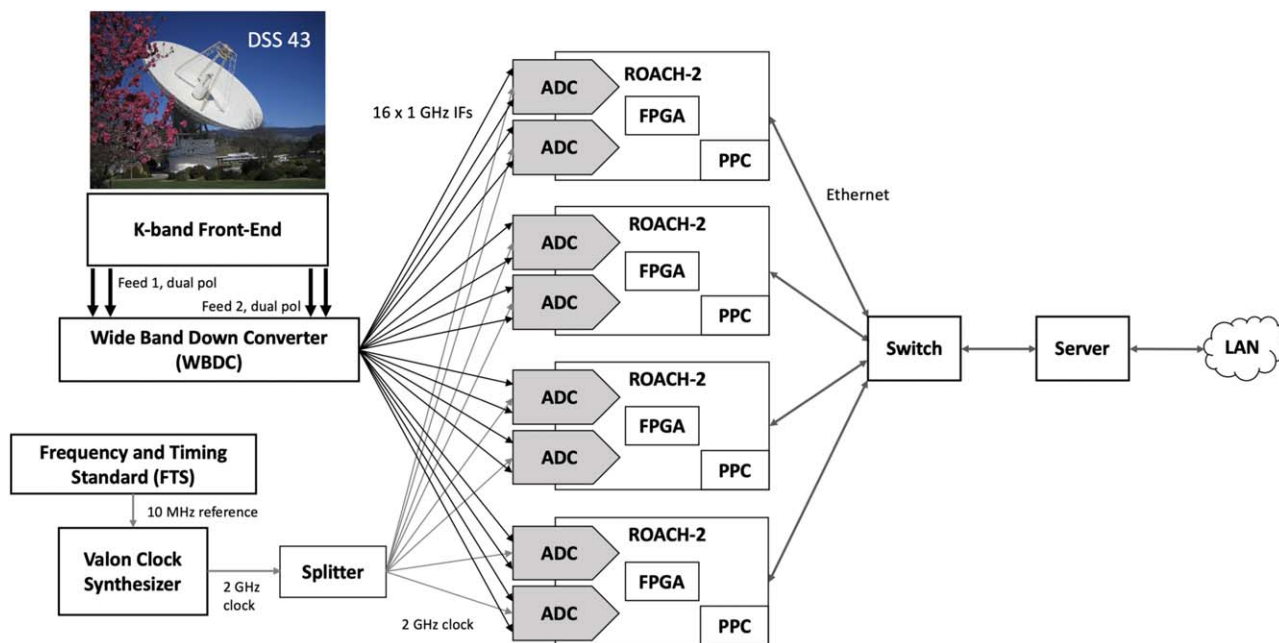
Figure 1. Spectrometer architecture diagram showing the signal path from DSS-43 to the spectrometer.
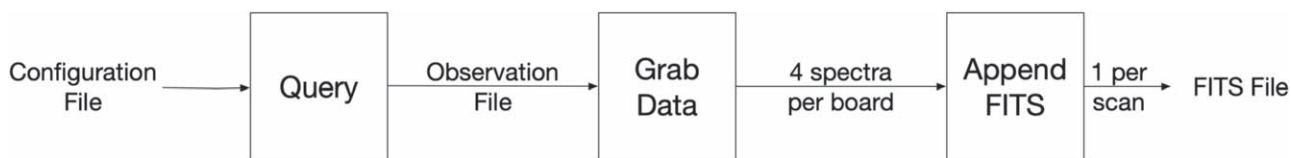

Figure 2. Software process diagram shows three scripts: query, grab data, and Append FITS that run during an observation.
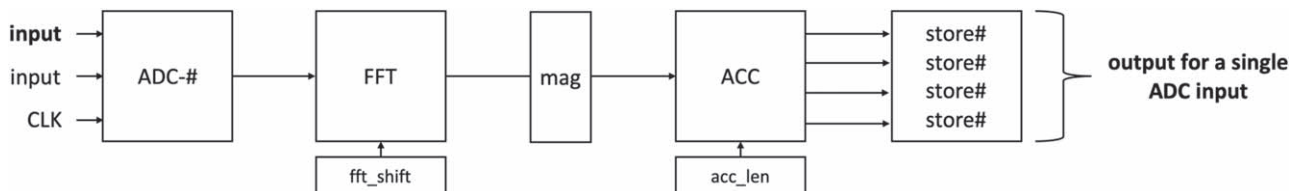

Figure 3. Firmware block diagram showing the process for a single input to a single ADC for both firmware modes.

3. Data Products

The spectrometer and associated software are designed to produce a set of data products, consistent with the model used in many NASA missions and radio observatories. There is a set of Level 0 data products that are intended to form a self-contained set of data from which all subsequent processing can proceed. Higher-level data products are generated but in a manner that allows either for alternate processing or modified processing.

3.1. Input Parameters

The PI provides the input parameters listed in Table 3. The available coordinate system is equatorial. The R.A. and decl. must be in the J2000 epoch. The *K* band in the range of 17–27 GHz is currently the only available band. However, the IF inputs to the spectrometer can be manually connected to the *X*-band or *Ku*-band downconverters if desired.

The information from the PI is used to create the configuration file is the input to the spectrometer's software.

Table 3
PI Input Information for an Observation

Item Name	Description
Group name	PI-specified group name
Source name	PI-specified source name for each source
R.A.	Epoch J2000 (hh:mm:ss)
Decl.	Epoch J2000 (sdd:mm:ss)
Spectral resolution	30.5 kHz or 122 kHz
Start time	For all scans (yy:doy:hh:mm:ss)
Final stop time	Stop time for the final scan (yy:doy:hh:mm:ss)
Observation mode	OTF or PSW
Sample cadence	Two options available for each spectral resolution
IF selection	16 IFs within 17 GHz–27 GHz dual-polarized IFs

These input parameters are also used to generate the set of pointing files that are used within the DSN to point the antenna.

The sample cadence or sample integration time is the time that the spectrometer accumulates for. This sample cadence can be calculated using the clock rate, the number of samples, and

the acc_len register value. The sample cadence calculations are shown in Equations (1) and (2):

$$\text{number\_of\_samples}/\text{clock\_rate} = \text{time\_per\_sample} \quad (1)$$

$$\text{acc\_len} * \text{time\_per\_sample} = \text{sample\_cadence}. \quad (2)$$

The sample cadence options for the 30.5 kHz spectral resolution are 4.29 s and 2.15 s. The sample cadence options for the 122 kHz spectral resolution are 1.07 s and 2.15 s.

For a given scan, the target number of samples is calculated using the sample cadence, the duration of the scan, and a value called allowance. Allowance accounts for the time it takes for the script to read the data from the store registers. Introducing it ensures that the scan will not last longer than anticipated. For 32k mode, allowance is 1.75 s, and for 8k mode, it is 0.85 s. The calculation for the target number of samples is shown in Equation (3):

$$\text{target\_number\_of\_samples} = \frac{(\text{duration} - \text{allowance})}{\text{sample\_cadence}}. \quad (3)$$

3.2. Level 0 Data

The Level 0 data are provided as SDFITS format files (Garwood 2000). The primary header contains relevant data about the antenna and details of the observations, with Table 4 in the Appendix providing an illustration of such a header. The observation modes are either on the fly mapping (OTF) or position switching (PSW). PSW is a single integration in a given position following with an integration in the emission–free region (the "off" position). In the OTF mode (Mangum et al. 2007; Wong et al. 2016), the telescope moves at a certain rate while the spectrometer collects data followed by an observation on the "off" position, enabling efficient spectral line mapping. Additional data tables (structured as FITS `BINTABLE`s) are provided, which contain the spectra data and information about the observation that is used for subsequent processing to higher-level data products, such as the system temperature for each sample, and the angular offset from the source coordinates for OTF mode. There are 16 bin tables per scan, one for each input of the spectrometer. The bin tables are composed of seven columns by n rows. The number of rows is determined by the number of samples in the spectrum. The sample cadence calculation is shown in Section 3.1. If a sample is not complete before the observation time ends, it is not included in the spectra. Each bin table has a header; Table 5 of the Appendix provides an illustration of such a header. The seven columns are as follows: spectrum data, the antenna's elevation in meters as a function of time during each scan, an estimate of the system temperature T_{sys} in Kelvins as a function of time during each scan, the bandwidth in in Hz, duration in seconds, the R.A. offset in degrees, and the decl. offset in degrees. The last two columns (the R.A. offset and decl. offset) are relevant for OTF observations.

3.3. Level 1 Data

These data products are intended to be a notional processing of the Level 0 data, in a manner that is consistent with producing data products sufficient for analysis and publication but also for alternate or additional processing. The intent is to provide a basic estimate of the antenna temperature using the standard PSW technique,

$$T_{ant}^* = \frac{T_{on} - T_{off}}{T_{off}} T_{sys}, \quad (4)$$
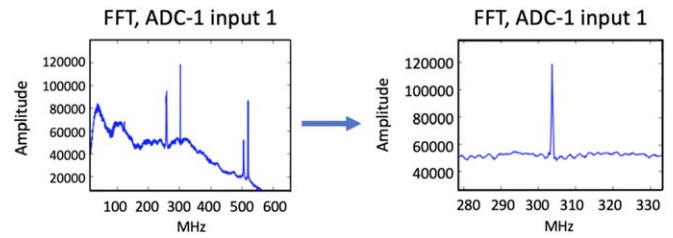
Figure 4. On the left is the plot of the down converted Juno X-band carrier and on the right is a zoomed-in plot of Juno X-band carrier at 303.75 MHz.

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 calibrated data is then written in the FITS format and, optionally, in the GILDAS/CLASS format (Grenoble Image and Line Data Analysis Software/Continuum and Line Analysis Single-dish Software; Pety 2005), for further processing.

The Level 1a data product performs the first portion of the calibration, forming the factor $(T_{on} - T_{off})/T_{off}$ using the *nearest-neighbor* "off" scan. This division in the calibration is structured in this manner for a number of motivations. With this initial "on −off" calculation, an investigator can assess the calibration at this stage, there may be some cases in which only relative calibration (without the system temperature) may be valuable, and there are alternate approaches to identifying the "off" scan (e.g., linear interpolation between the two "off" scans nearest in time).

The Level 1b data product uses the Level 1a data product and an estimate of the system temperature T_{sys} to form the antenna temperature T_{ant}^* of Equation (4).

4. Implementation and Commissioning

The spectrometer was installed and commissioned in the signal processing center at the CDSCC in 2019 November. In the following we describe the steps taken to test the system during commissioning.

4.1. Testing

The spectrometer has a test software that provides real-time ADC and FFT plots. This software was used for commissioning and operations. ADC samples can be captured and an FFT can be computed in software. When the spectrometer arrived at CDSCC, both firmware modes were tested with K-band inputs to check out the system after transport and ensure that no damage had occurred. The firmware accumulates a single sample and calculates an FFT, and this was also plotted and compared to the software-computed FFT.

On 2019 November 21 at 22:53 UTC, the spectrometer was also tested with dual-polarization X-band IFs as inputs. These operational bands are about 600 MHz wide and are typically used for spacecraft communications and tracking. The Juno spacecraft was being tracked at the time of the test and was emitting a carrier signal with a well-known frequency. Although the X-band IFs do not exercise the full 1 GHz capability of each spectrometer input, this was a valuable test in validating the end-to-end system from a spacecraft all the way to the spectrometer processing.

Figure 4 shows a single polarization of the X-band carrier from the Juno spacecraft during the test. The 0–600 MHz in the plot corresponds to 8100–8700 MHz. The signal is using the standard DSN X-band signal path for spacecraft communications, which
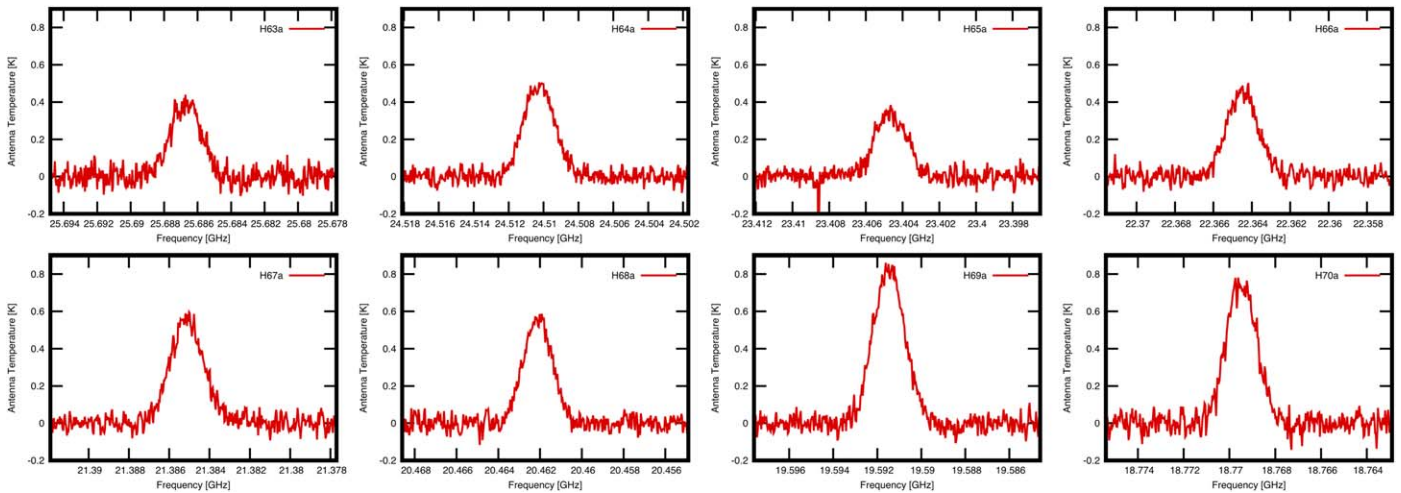
Figure 5. Hydrogen RRLs of 18–26 GHz for Orion KL. The intensities obtained for the hydrogen recombination lines in Orion KL are consistent with those observed by Gong et al. (2015) with a Effelsberg 100 m telescope.

are typically between 8200 and 8600 MHz and correspond to 100–500 MHz in Figure 4. The *X*-band signal was down converted by 8.1 GHz to an intermediate frequency of 303.75 MHz and then processed and recorded by the spectrometer. The right plot shows a zoomed-in version of the spectrum near the Juno carrier. This plot shows the spectrometer measurement matched the expected 303.75 MHz frequency.

4.2. Verification

In Figure 5, we show a sample observation of hydrogen recombination lines in Orion KL. On 2019 November 24 we observed eight RRLs simultaneously, from H70α to H63α, each in two polarizations. The intensities obtained for the hydrogen recombination lines in Orion KL are consistent with those observed by Gong et al. (2015) with Effelsberg 100 m telescope, for a main–beam efficiency of 0.5 and $S_\nu/T_A^* = 1.9$ Jy K^{-1} (Kuiper et al. 2019). Note the difference in frequency response for each IF is caused by the front end *K*-band system (see Figure 6 in Kuiper et al. 2019). A powerful application for the spectrometer presented here is the possibility of stacking different RRLs to significantly improve the signal-to-noise ratio of these observations, enabling the detection of faint lines, or for efficient OTF mapping over large spatial scales.

5. Conclusion

A new high-resolution spectrometer was designed, implemented, and deployed to CDSCC in 2019 November. The spectrometer can process and record 16 1 GHz inputs simultaneously, providing a factor of 4 improvement in efficiency compared to the previous

capability. This large total bandwidth, for example, enables the simultaneous observations of a large number of RRLs, which can be combined together to significantly improve the sensitivity of these observations. The spectrometer software interfaces with the DSN and the PI to control observations and generate SDFITS files.

On 2019 November 21 at 22:53 UTC, the spectrometer was tested using the Juno spacecraft signal and the *X*-band system. It was then connected to the *K*-band down converter and commissioned by observing the 18–26 GHz hydrogen RRLs in Orion KL. After commissioning was completed, an extensive mapping campaign of the Carina Nebula began. Over 30 observations took place from 2019 November to 2020 March. In 2020 March, DSS-43 scheduled downtime began, which resulted in the *K*-band system also going offline. Observations are planned to begin again in early 2021. The new high-resolution spectrometer will enable future *K*-band observations by the DSN.

6. Future Work

Additional modes could be implemented in the future. For instance, a third mode providing an FFT-based 512M spectral point spectrum (a 1.9 Hz spectral resolution) has been investigated.

Facility: Deep Space Network.

Appendix
DSN SDFITS Header Example

Tables 4 and 5 illustrate an example of an SDFITS file header provided by the DSN Radio Astronomy spectrometer. Table 4 shows an example of a primary header and Table 5 shows an example of a bintable header.

Table 4
Illustrative SDFITS Primary Header

SDFITS KEY-VALUE Pairs	Comment
SIMPLE = T	/conforms to FITS standard
BITPIX = 8	/array data type
NAXIS = 0	/number of array dimensions
EXTEND = T	
ORIGIN = "Python script"	/File origin
TELESCOP = "DSS 43"	/Observer
START = "2020-069T11:14:10"	/Start time
STOP = "2020-069T11:15:00"	/Stop time
DATE = "2020 069"	/Date this file was written
SITELEV = "688.867"	/Site elevation in meters
SITELAT = "−35"	/Site latitude in degrees
SITELONG = "148"	/Site longitude in degrees
DURATION = "00:00:10"	/Duration of scan hh:mm:ss
SOURCE = "G305.1+0.0_OFF"	/Object
RA = "196.8749"	/Right ascension in degrees
DEC = "−62.0600"	/decl. in degrees
INSTRUME = "DSN RA SPECTROMETER"	/Instrument
GUIDEVER = "1.0"	/ROACH-2 User Guide version
FITSVER = "1.7"	/FITS definition version
OBSMODE = "PSW"	/Observation mode
COMMENT ROACH-2 DSN RA spectrometer	
END	

Table 5
Illustrative SDFITS Bin Table Header

SDFITS KEY-VALUE Pairs	Comment
XTENSION = "BINTABLE"	/binary table extension
BITPIX = 8	/array data type
NAXIS = 2	/number of array dimensions
NAXIS1 = 131088	/length of dimension 1
NAXIS2 = 2	/length of dimension 2
PCOUNT = 0	/number of group parameters
GCOUNT = 1	/number of groups
TFIELDS = 7	/number of table fields
ORIGIN = "roach5-spec4"	/ROACH-2 board specification
CTYPE1 = "FREQ"	/CTYPE1
CRVAL1 = 21000000000.0	/Hz
CRPIX1 = 0	/CRPIX1
CDELT1 = 30517.578125	/Hz
BUNIT = "K"	/Kelvin
POL = "H"	/Polarization
EXTNAME = "SINGLE DISH"	/extension name
TTYPE1 = "SPECTRUM"	
TFORM1 = "32768E"	
TTYPE2 = "TSYS"	
TFORM2 = "E"	
TTYPE3 = "ELEVATION"	
TFORM3 = "E'	
TTYPE4 = "BANDWID"	
TFORM4 = "E"	
TTYPE5 = "DURATION"	
TFORM5 = "E'	
TTYPE6 = "RAOFFSET"	
TFORM6 = "E"	
TTYPE7 = "DECOFFSET"	
TFORM7 = "E"	
COMMENT individual 1 GHz output from roach5-spec4	
END	

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References

Garwood, R. W. 2000, in ASP Conf. Ser. 216, Astronomical Data Analysis Software and Systems IX, ed. N. Manset, C. Veillet, & D. Crabtree (San Francisco, CA: ASP), 243
Gong, Y., Henkel, C., Thorwirth, S., et al. 2015, A&A, 581, A48
Kuiper, T. B. H., Franco, M., Smith, S., et al. 2019, JAI, 8, 1950014
Mangum, J. G., Emerson, D. T., & Greisen, E. W. 2007, A&A, 474, 679
Pety, J. 2005, in Semaine de l'Astrophysique Francaise, ed. F. Casoli et al. (Les Ulis: EDP Sciences), 721
Walsh, A. J., Breen, S. L., Britton, T., et al. 2011, MNRAS, 416, 1764
Wong, G. F., Horiuchi, S., Green, J. A., et al. 2016, MNRAS, 458, 151