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PAPER

A Prototype Radio Transient Survey Instrument for Piggyback Deep Space Network Tracking

This paper describes NASA's Deep Space Network (DSN) as a tool for making radio transient observations; DSN's low-noise large aperture antennas are suitable for surveying transients.

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ABSTRACT | Traditional astronomy has focused on properties of the steady-state universe. Recent discoveries of strong, isolated radio pulses have, however, invigorated interest in transient phenomena. These radio transient events are rare, necessitating long observing times to give reasonable statistics. The National Aeronautics and Space Administration/Jet Propulsion Laboratory (NASA/JPL) Deep Space Network (DSN) tracks spacecraft continuously with several large antennas having low system noise temperature. The DSN also returns substantial predetection bandwidth from the antennas (400 MHz at X-band), currently processing only a fraction of that band for spacecraft tracking. This unused wideband capability is ideal for study of the radio transient sky. Here we describe and show initial performance results of a prototype receiver to search for such transients. This prototype is implemented as a firmware change in an operational DSN tracking receiver and can thus run in parallel with operational spacecraft tracks using existing spare receiver hardware. An operational version of this system could be deployed throughout the DSN to acquire data over extended periods and substantially improve the statistics of rare radio transient events.

KEYWORDS | Pulsar; reconfigurable radio; rotating radio transient; software-defined radio

I. INTRODUCTION

Recent discoveries [1], [2] of strong, isolated radio pulses have invigorated interest in transient phenomena as probes of fundamental physics and astrophysics. The National Aeronautics and Space Administration/Jet Propulsion Laboratory (NASA/JPL) Deep Space Network (DSN) has a unique unused capability: the DSN tracks continuously with several large antennas having low system temperature and highly precise frequency and timing references. Substantial analog bandwidth (400 MHz at X-band) is returned from the antennas to the signal processing center at each DSN complex. Only a small fraction of that band is processed for spacecraft tracking, however. This wideband capability is ideal for studying the background transient radio sky, especially for rare events requiring long observation times to give reasonable statistics. Examples of known signals are the recently discovered Rotating RAdio Transients (RRATs) [1] and the discovery of a strong, isolated possibly extragalactic pulse [2] (although subsequent pulse searches yielded similar detections that may have terrestrial origins [3]). RRATs (galactic sources) challenge our understanding of pulsar astrophysics [4]–[6]. If extragalactic, a mechanism for the enormously strong pulse reported in [2] is unknown.

Here we describe development and initial testing of a prototype survey instrument to search for radio transient events, taking advantage of the existing but unused DSN capabilities: "RRAT TRAP" = Rotating RAdio TransienT Receiver And Processor.

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II. DESIGN AND IMPLEMENTATION

Pulses propagating through the interstellar medium (ISM) are dispersed due to the frequency-dependent refractive index of the ISM plasma [7]. The energy arrives first at higher radio frequency and later at lower radio frequency. RRAT TRAP uses this signature to search for pulses of astronomical origin: the power in channels of a filterbank are detected, separately delayed one with respect to the other to correct for dispersion, and then the power is summed incoherently to obtain a de-dispersed time series [8]. The hardware platform for the RRAT TRAP prototype was the DSN's standard telecom software-defined radio receiver, which is used operationally to track spacecraft. The receiver hardware consists of a VMEbus chassis containing JPL-designed and commercial off-the-shelf boards (Fig. 1). The core of the receiver is the JPL Digital Signal Processor Printed Wiring Assembly (DSP-PWA) with a Xilinx Virtex-4 field-programmable gate array (FPGA). The DSN receiver is converted to a RRAT detector by modifying the startup script to load a different configuration into the FPGA and run different software on the control computer.

The signal is first received from the antenna, down-converted from S-band (2.2–2.3 GHz), X-band (8.2–8.6 GHz), or Ka-band (31.8–32.3 GHz) to an intermediate frequency (IF of 100–600 MHz) (Fig. 2). A synthesizer local oscillator (LO) in the IF-to-digital converter (IDC) converts the IF signal to 200-MHz center frequency at the input of the analog-to-digital converter (ADC). By selecting different LO frequencies, the signal used for transient surveys can be kept separate from that used for spacecraft tracking. Using undersampling techniques and antialiasing filter of 80-MHz noise bandwidth, the 200-MHz IF is down-converted to 40-MHz center frequency (0–80-MHz bandwidth) by sampling at 160 megasamples/s. Although the receiver operates on an 80-MHz bandwidth, the FPGA implementation can be scaled to the full front-end analog bandwidth by using a different hardware platform. The DSP-PWA processes the digitized 8-b IF signal of 80-MHz bandwidth into a filterbank [7], [8], and the detected signal from each channel is processed in real time to search for pulses. In the prototype, we focused on performance parameters (Table 1) appropriate for DSN center frequencies and moderate-to-large dispersion measure (DM $=$ electron column density between the source and earth; conventional units: cm^{-3} pc) pulses. Two time resolutions were implemented, 100 μs and 1 ms. The step between DMs is calculated based on the frequency resolution of the filterbank, number of filterbank channels, and maximum DM, such that the error in the DM would give a smearing time less than the time resolution. For the time resolution of 1 ms, real-time de-dispersion for 98 positive DM trials and 98 negative (nonphysical) trials was implemented in the RRAT TRAP firmware to search up to a maximum $|\mathrm{DM}|$ of 2000 cm^{-3} pc.

The block diagram for the FPGA implementation is shown in Fig. 2 (RRAT process). The FPGA first converts the differential signal and scales the converted signal to the appropriate signal level for the fast Fourier transform (FFT) processor. The FFT processor is a Xilinx FFT core based on a pipelined architecture. The output of the FFT processor is an 80-MHz bandwidth divided into 64 channels. The magnitude squared of the time series from each FFT output is accumulated for 100 μs or 1 ms depending on the desired time resolution (see Table 1). The averaged data are stored in a buffer. The buffer size depends on the longest delay in the selected DMs. The data buffer is implemented using Xilinx's dual port block memory. The size of the block memory is computed offline from the selected DMs. The implemented DMs range from 20 to 2000 cm^{-3} pc.

For each DM, the signal is de-dispersed by delaying the high frequencies relative to the low frequencies. The delay trajectory can be formulated by a polynomial whose coefficients are loaded into the FPGA RAM. The de-dispersion processing starts when the averaged FFT data fill the data buffer. The processing reads the coefficients and computes the data locations in the buffer for each DM. For the incoherent processing, the data only need to be extracted from the buffer and added together, without requiring multiplication mathematics. The FPGA completes the de-dispersion processing for each DM before the next averaged data line of FFT processor is written into the buffer. The buffer acts as a first-in–first-out (FIFO), so the first written data line is read out first.

The firmware outputs two types of data: the raw averaged FFT output data for postobservation analysis, and the de-dispersed data from the real-time FPGA de-dispersion

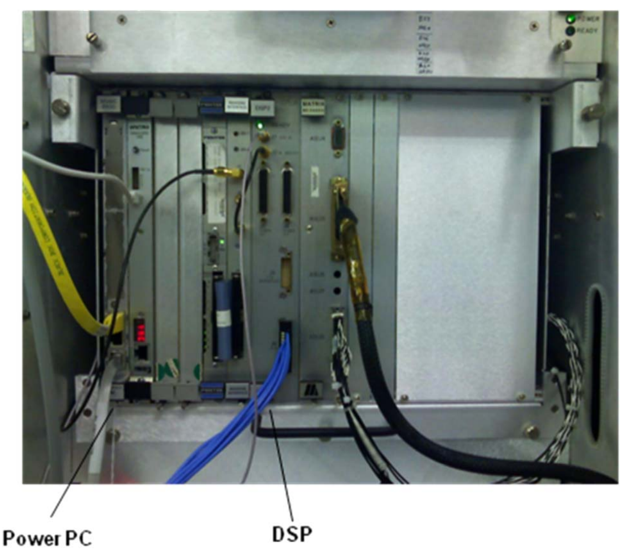

Fig. 1. ***DSN's standard telecom receiver.***

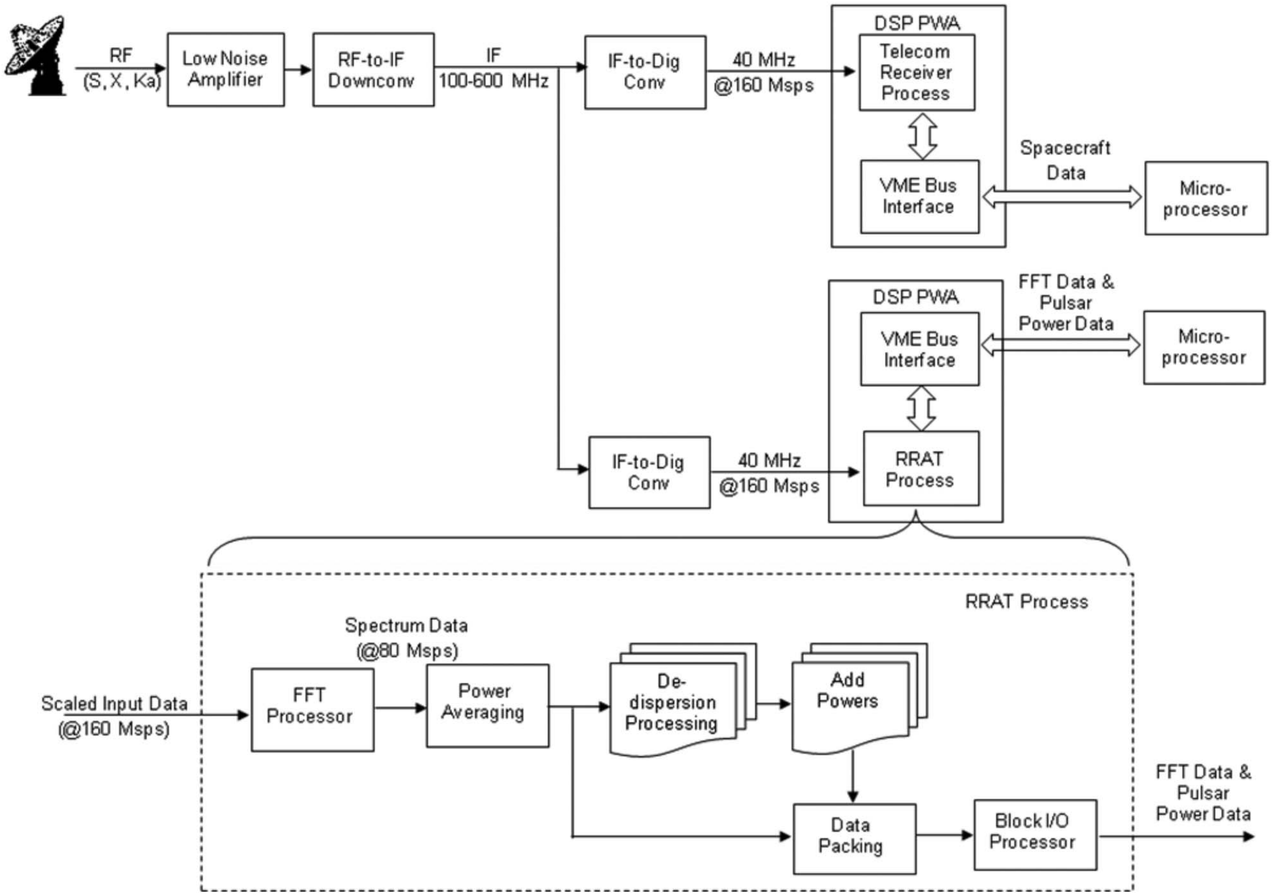

Fig. 2. ***Block diagram of DSP PWA and FPGA design (JPL).***

processor. The data are transferred from the FPGA to the receiver microprocessor through the VMEbus backplane. Although the FPGA can support higher frequency and time resolution, the output data are limited by the VMEbus data transfer rate.

The FPGA design uses CoWare Signal Processing Worksystem (SPW) for algorithm and hardware design, Synplicity Synplify Pro for logic synthesis, and Xilinx ISE for place-and-route. Floating-point and fixed-point models are simulated in SPW to verify the system functional requirements. Postsynthesis and post-place-and-route simulations are performed to verify that the output of each stage is functionally equivalent to the fixed-point model. Timing analysis is also performed after place-and-route to ensure that the timing constraints are met.

Software development was conducted in parallel with the FPGA work. The filterbank's detected power and DM output data from the FPGA are transferred to the receiver microprocessor using 32-b block transfer (BLT) protocol. The primary requirements of the software are to acquire the data, provide double buffering to avoid data gaps, and store the data to disk. The block diagram for the software implementation is shown in Fig. 3. The collected data are then converted from packed binary to text for offline analysis. Software was also developed by UTB using eight-core parallel code to de-disperse and search for bursts. This near-real-time capability (for up to 256 channels) was not tested in the field due to time constraints. The software design uses C language for data acquisition, and Python for data sorting and conversion to text. Software configuration and management is done through Trac, an open source web-based project management tool.

The software design for the embedded controller (see Fig. 3) in the receiver was kept very simple. Two tasks were implemented: one to read data from the FPGA across the VME bus and a second to write the collected data to an external hard drive via NFS over Ethernet. A double buffer was used to facilitate continuous transfer of data between the two tasks. Before testing in the field, we ran extensive tests in the lab to ensure that the FPGA/software performance would be adequate to capture all data with no gaps.

The resulting data files were stored as interleaved raw and de-dispersed data packets. Software was written to run on a Unix system that handled de-interleaving the two data streams based on packet header fields. This software also

Table 1 RRAT TRAP Parameters

attribute	value
RF center frequencies	2.3 GHz and higher (note 1)
Antenna aperture	34m and 70m
System temperature	≈25K
Analog bandwidth	80 MHz
Sampling interval	12.5 ns
Hardware (FPGA)	Xilinx Virtex-4 FPGA (P/N XC4VSX55-12FF1148C)
De-dispersion method	Incoherent [8]
Number of filterbank channels	64
Frequency resolution	1.25 MHz
Time resolution	100 μs or 1 ms (note 2)
Search negative DMs?	Yes (note 3)

Note 1: DSN frequencies are S-band (≈2.3 GHz,) X-band (≈8.4 GHz), and Ka-band (≈32 GHz).
Note 2: During testing we switched between 100 or 1000 μs time resolution, with the former being useful for testing on low-dispersion pulsars.
Note 3: "Non-physical" (negative) dispersion measures – i.e. those associated with a pulse sweeping from lower-frequency, earlier time to higher-frequency, later time – were searched in post-processing. In addition to giving an "off-source" to estimate noise-only statistics, any confirmed detection of a negative DM pulse would be interesting; if exotic RFI could be excluded it would suggest an intentional signal of extraterrestrial origin.

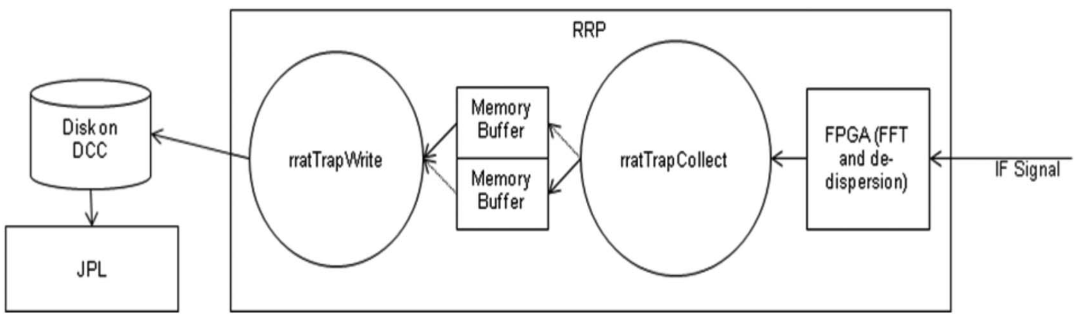

Fig. 3. ***Block diagram of software design (JPL).***

converted the binary data packets to ASCII for transfer to other team members for analysis. ASCII was selected for the data format to avoid confusion on record formats and byte ordering. This software took advantage of the "struct" module supplied with the Python interpreter to unpack the binary packets for processing.

III. FIELD TESTING

We tested RRAT TRAP at S- and X-bands (≈2.3 and 8.4 GHz) using DSS15 (a 34-m antenna at the NASA/DSN Goldstone tracking complex in Southern California) for several hours on each of April 25 and June 2, 2009. For these tests, we recorded and saved for postprocessing the accumulated power measurements. We observed continuum sources to calibrate system sensitivity and pulsars (B0531+21, B0329+54, B2351+61) as sources of low, known-dispersion pulses. B0329+54 was detected with high signal-to-noise ratio (SNR) at both S- and X-bands and with the expected period, verifying timing. B2351+61 was detected with the expected period and high SNR at S-band. We noted in all recordings a persistent signal at 1.2 Hz and its harmonics, apparently of instrumental origin and possibly associated with the cryogenic cooling of the front end. We processed the B0531+21 data, implementing incoherent pulse de-dispersion, to verify postprocessing performance on a source with known DM. Fig. 4 shows an individual "giant pulse" from B0531+21, clearly showing dispersion (power arriving

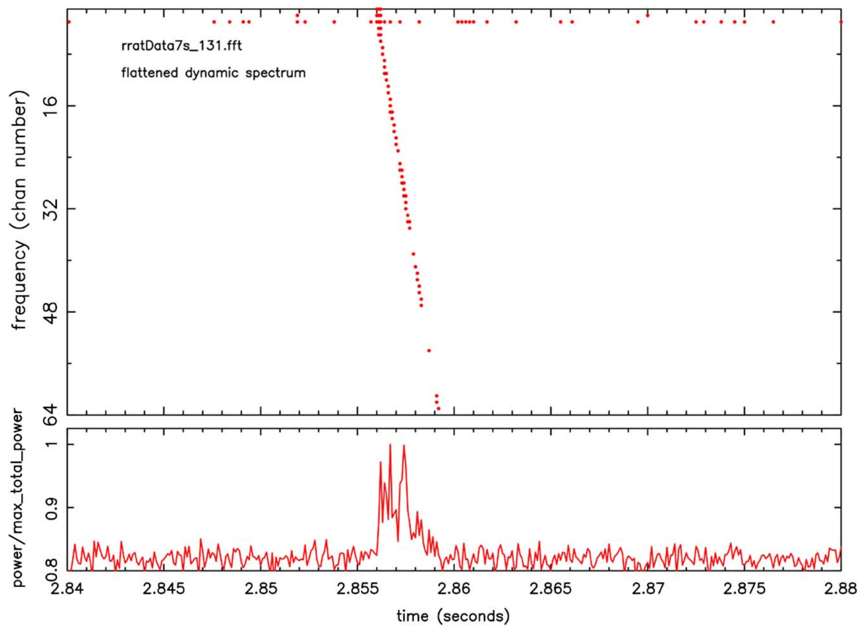

Fig. 4. ***Dynamic spectrum and time series of total power in the 80-MHz band for observations of a giant pulse from B0531+21 observed on June 2, 2009 (DSS15; S-band; 100-μs time resolution). The power in the dynamic spectrum has been clipped to better show the dispersed pulse (signal arriving first at higher radio frequency and later at lower radio frequency).***

first at higher radio frequency and later at lower radio frequency). The slope across the 80-MHz band is correct for this pulsar's known DM $\approx$ 56.8 cm^{-3} pc. Fig. 5 shows another section of the B0531+21 data where the power in a weaker pulse is smeared by dispersion to be invisible within the noise. It is subsequently clearly detected after our dispersion correction.

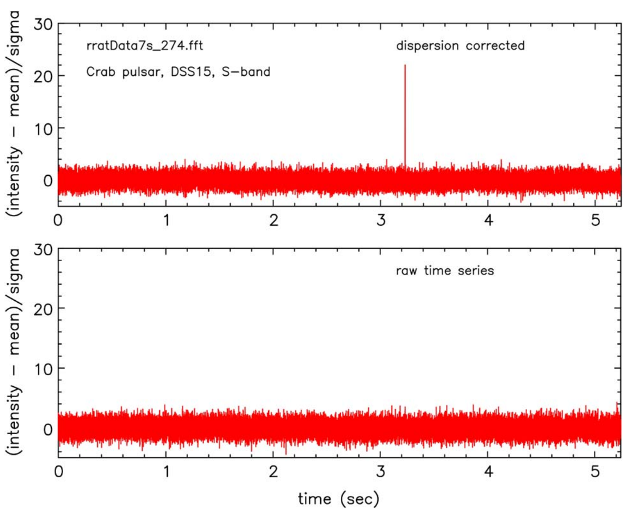

Fig. 5. ***Example of a pulse recovered with signal-to-noise $>$ 20 after de-dispersion (upper panel), but within the noise of the raw time series (lower panel). Data were taken June 2, 2009 on B0531+21 at S-band using station DSS15 with RRAT TRAP's 100-μs time resolution.***

IV. CONCLUSION

This work demonstrated that, via a different FPGA firmware load, an operational DSN hardware receiver could be reconfigured as a filterbank/pulse searcher. RRAT TRAP could be used in parallel with any existing DSN spacecraft track to continuously monitor the background radio sky for dispersed pulses. This has impact on the scientific use of the NASA/JPL DSN: because the DSN tracks continuously with low noise, wide bandwidths, and many apertures, an operational RRAT TRAP could significantly increase the total observing time (thus the statistics) for rare radio events. Reconfiguration of DSN telecom receivers as RRAT detectors could be automated so that idle receivers would connect to an IF signal from a spacecraft track and monitor for RRATs in the same beamwidth.

More work is needed to make the RRAT TRAP operational, including handling of radio-frequency interference (RFI), and implementing a real-time trigger to store data around the detected event, which allows for selective data to be recorded to minimize disc space usage. Another potential task is to search in pulse width and shape, since our work assumed that pulses were effectively bandwidth-limited delta functions. ■

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