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Enabling Voyager 2 Science Data Return During Heliopause Transition with a Low Cost Portable SDR*

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This paper describes a fast-track, low-cost implementation effort that the NASA Deep Space Network (DSN) undertook to support Voyager 2 mission. The result significantly increased science data return for Voyager 2 mission's heliopause detection. The Parkes Observatory 64-m "Murriyang" radio telescope of the Australia Telescope National Facility (ATNF) was used between November 2018 – February 2019 to supplement the DSN tracking of Voyager 2. One key equipment that made such a support possible was the Record & Playback Assembly (RPA). It was based on a commercial software defined radio (SDR) that can be procured at low cost and quickly assembled to exhibit new capabilities with public- domain software libraries. The RPA at Parkes captured and recorded the received signal from Voyager. It then sent the digitized samples via the public internet to another RPA at Goldstone, California to be played back into a standard DSN receiver. Bridging the ATNF and DSN equipment across two continents, the RPA enabled data received at Parkes to flow into the Voyager mission operation system as if they came from another DSN antenna. In this paper, we will discuss the design of such a system. We will also describe the system operational concept, and a tight processing timeline necessary to keep up with new data collected daily. Some data management challenges associated with realizing a timely transfer of a large data set over the internet will be discussed. Other performance metrics such as the operating link margin at Parkes antenna, the system loss, the amount of data return to Voyager 2 mission, weather statistics and its impact on data return will be presented.

1. Introduction

In late 2018, it was expected that the Voyager 2 spacecraft will be soon crossing the solar system's heliopause – a boundary where the influence of the solar winds is equal to that of the interstellar particles [1]. The spacecraft had been mostly tracked by the DSN's 70-m antenna at Canberra. The 70-m antenna, being only one asset available at each of the three DSN Deep Space Communications Complex such as Canberra, was required for tracking Voyager 2 due to the large distance between the spacecraft and Earth. Being in the southern inclination, Voyage 2 spacecraft could only be tracked by the Canberra Complex, rather than at the other two DSN sites of Goldstone, California and Madrid, Spain in the Northern hemisphere. That made the Parkes support critically important to Voyager 2 mission [2].

Coincidentally, around the same time in November – December, 2018, the 70-m antenna at Canberra was also needed to support other missions' critical events. For example, Insight mission was about to go through Entry, Descent and Landing as it landed on Mars. The schedule constraint on the Canberra 70-m antenna motivated the use of Parkes antenna to supplement Voyager 2 coverage. Through negotiation between NASA and Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO), the Parkes "Murriyang" radio telescope would provide about 11-hours "daily" tracking to Voyager 2 from November 2018 to end of January, 2019 and a 6-hour "daily" track between February 1-28, 2019. To be precise, "daily" agreement was for 11 passes over 14-day cycle.

Normally, one of the standard DSN receiver would be deployed at Parkes to process Voyage 2 downlink signal. However, due to time constraint and equipment availability, a different approach was taken. JPL has previously developed, for the Artemis 1 mission support, a Playback Assembly (RPA) device that is based on commercial SDR-based capability. For the Voyager 2 support, one RPA was deployed at the Parkes antenna to capture the signal, and another RPA was deployed at Goldstone to replay the captured signal into a standard DSN receiver. This capability enabled the use of Parkes antenna to increase the data return to Voyage 2 mission, helping the mission scientists to better characterize the heliopause boundary.

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In Section 2, we will describe the system design. Section 3 presents the operational concept on the timeline of data processing to ensure that all processing at a particular site (Parkes or Goldstone) would be completed before data from the next day arrive. Section 4 reflects the observed link performance at Parkes, as well as at other DSN antennas. Section 5 provides the results on telemetry data return to Voyager 2 mission.

2. System Design

A key device that made the Voyager 2 support from Parkes possible is the Record & Playback Assembly (RPA). The RPA is based on commercial products that can be quickly procured, assembled, and implemented with desired capabilities leveraging on public domain software library. The RPA, as seen in Figure 1, comprises of three key components: (1) a laptop computer with a very high input/output throughput to enable data transfer between the SDR and disk storage, (2) a high-capacity external data storage (tens of Terabytes) to archive the symbols, and (3) a commercial SDR module that generates an analog RF signal as well as filters and digitizes the input RF. The computer provides a graphical user interface for user to control and configure the signal generation or signal recording that are done by the SDR. In the recording mode, the computer transfers digitized samples from the SDR to the disk storage. In the playback mode, it reverses the digital samples flow, from the disk storage to the SDR. Both the computer and disk storage use a high speed USB3 interface for data transfer. For a 5 MHz I/Q sampling, the data throughput can be as much as 40 MB/s. During the recording or playback, an FFT spectrum generated from the recorded or playback digital samples provide a monitor capability on the signal quality.

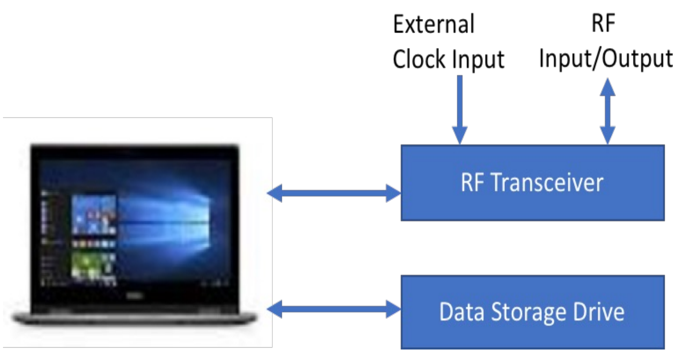

Figure 1: Components of the Record & Playback Assembly

The system can record an incoming RF/IF signal and play back the recorded data as an RF/IF signal, at selectable frequency from 10 MHz to 6 GHz. It was originally developed to support another effort related RF compatibility testing for the NASA Artemis 1 mission with the Japan Aerospace Exploration Agency (JAXA) 34-m antenna at Uchinoura and Usuda, Japan [3]. For Voyager 2 support, the RPA was used as an operational system, rather than a test capability.

The data were first recorded at the Parkes Observatory, then transferred across the internet and subsequently played back into the DSN receiver at Goldstone, California. Bridging the ATNF and DSN equipment across two continents, the RPA enabled data received at Parkes to seamlessly flow into the Voyager mission operation system as if they came from another DSN antenna. The system was operated remotely - recording at Parkes utilized the telescope's remote observing capability, allowing a mixture of on-site and remote operations by personnel, while the data transfer and playback at Goldstone were all remotely supported by the engineering and operation teams at the Jet Propulsion Laboratory, Pasadena, California.

Figure 2 reflects the system configuration, with the top half being what was implemented at Parkes and Goldstone for Voyager 2 support, while the bottom half being the standard configuration when the 70-m antenna at Canberra tracked Voyager. The RPA at Parkes captured and digitized the received signal. Data was then compressed prior to sending over the internet to reduce the latency in data transmission. At Goldstone, the data was decompressed and played back as an analog IF signal into the DSN receiver. The recovered telemetry data was then delivered to Voyager 2 mission operation center.

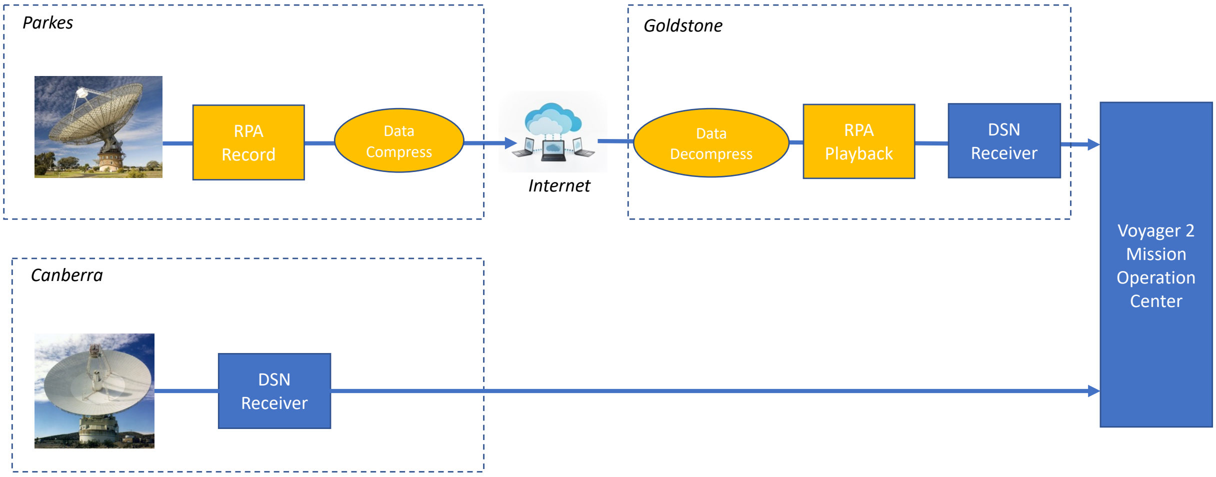

Figure 2: System architecture

The sampling rate of the recording required a special consideration. It was a balance between minimizing the signal to noise (SNR) loss and minimizing the latency of data processing. Voyager 2 was operating with little link margin, requiring the use of 70-m antenna or an array of two 34-m antennas. With the use of Parkes 64-m antenna, care was taken to minimize the loss through the 2 RPAs, and the data compression/decompression. The minimum loss in the RPA would favor a wider bandwidth, and thus higher sampling rate, setting since we observed that the SDR used in the RPA had a much greater loss (1 dB or more) at lower bandwidth settings (2-3 MHz). A high sampling rate of the RPA recording would minimize the SNR loss, but required more time for data transfer from Parkes to Goldstone. Given that there was 11-hour daily pass, plus about one hour preparation time, there was an upper limit of 12 hours available for completion of post-pass activities at Parkes. After much testing, we found that a sampling of 4 MHz best met both constraints.

3. Data Processing

Figure 3 shows a relative timeline of different activities for a tracking pass. The activities started out with a 12-hr tracking at Parkes (1 hr system preparation at start and end of pass, plus 11 hours spacecraft tracking). The data were recorded at a rate of 32 MB/s (4 MHz bandwidth, I&Q sampling, 4 bytes per sample). At the end of the tracking pass, data were compressed to reduce the amount of data transfer by a factor of 4 (4-byte sampling converted to 1-byte format). The decompression typically took about 3 hours. To expedite the data transfer, the file transfer was parallelly initiated one hour after the file compression started. Using the internet connection, the realizable transfer rate was close to 80 Mbps; thus, the data transfer of 12-hr pass from Parkes to the next node of reception at the Jet Propulsion Laboratory (JPL) in Pasadena, California took about 10 hrs. Due to security reason, data first received at JPL was in a buffered zone and then moved into an internal network and routed to the RPA at Goldstone. The data replication process was designed to be in parallel and started about 1 hour after the file transfer. The received data then went through another 3-hr decompression before it was ready for playback. In the playback, recorded data was regenerated as an IF analog signal to serve as an input into the standard DSN receiver. The playback process occurred at the same rate as the recording, which was 12 hrs long.

After the telemetry frames were extracted by the receiver during playback, an additional processing was required to adjust the Earth received timetag (ERT). The timetag of telemetry frames by the receiver were done at the time of playback, rather than at the original ERT the signal was received at Parkes, which was many hours earlier. A time offset was calculated based on the time of the start of recording at Parkes and the time of the start of the playback at Goldstone. This offset, with an accuracy in the order of few seconds, was then used to correct for the Earth received time tags of telemetry data.

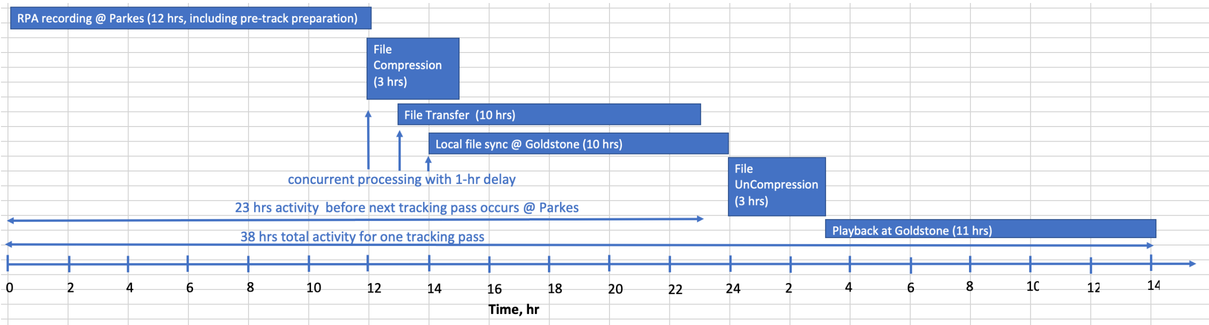

Figure 3: Timeline of data processing

4. Link Performance

Figure 4 presents a comparison of the telemetry symbol SNR of Voyager 2 signal received at the DSN and Parkes antennas. Measurements from various tracking passes were captured. DSN data included various configurations of a single 34-m antenna, an array of two 34-m antennas, and the 70-m antenna. Parkes data included the loss of recording and playback of the two RPAs, which was estimated to be at least 1 dB based on calibration testing in the lab with and without the RPA.

On the average, the received symbol SNR (Es/No) at Parkes, including the recording & playback losses, was about 0.7 dB. Compared to a decoder threshold of -0.7 dB symbol SNR required for successful decoding of the concatenated (7, ½) convolutional and Reed Solomon codes being used by Voyager 2, the link margin was 1.4 dB. This small link margin placed a constraint on the signal processing loss and thus the choice of sampling bandwidth discussed earlier in Section 3.

In terms of relative performance, Parkes data offered a 1.8 dB higher SNR than that of single 34-m antenna. It was 1.6 dB less compared to an array of two 34-m antennas, and 5.6 dB less than the 70-m antenna.

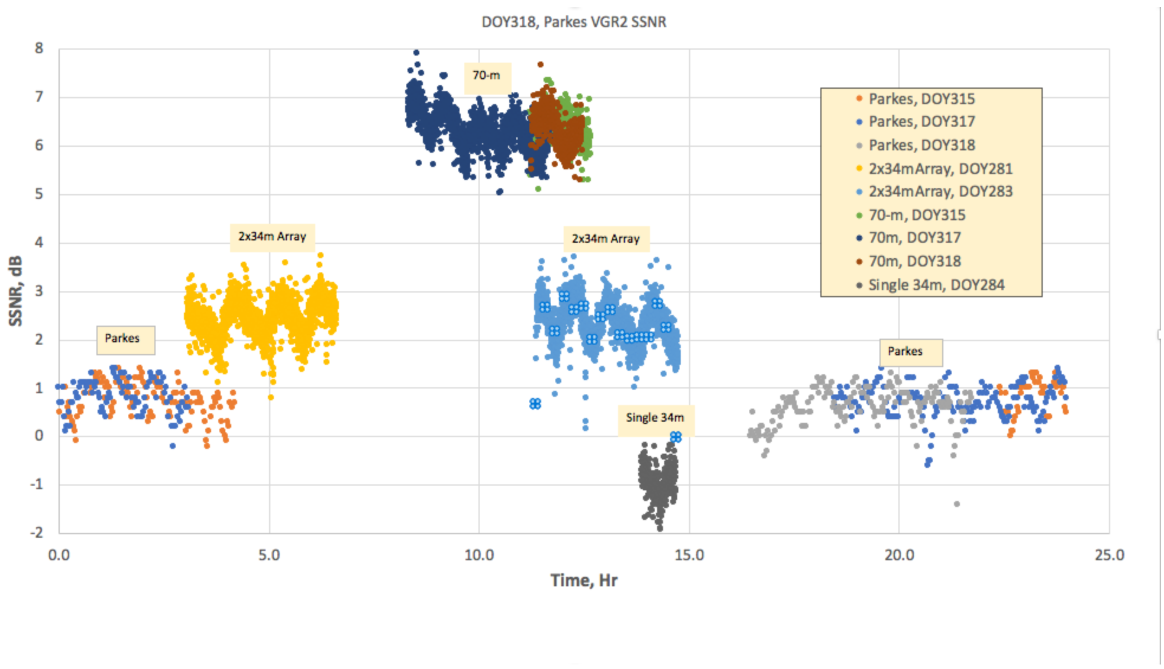

Figure 4: Measured symbol SNR received at Parkes and DSN antennas

5. Data Return

Figure 5 reflects Voyager 2 measurements on the count of the Solar wind and interstellar particles over time, in early part of 2018 to early 2019 [4]. Support from Parkes, started on November 5 as part of engineering testing, with the committed operational capabilities starting on November 8,2018. This turned out to occur right at the cusp of the transition where solar wind particles started dropping off and interstellar wind particles started climbing. The support continued until February 24, 2019 when the transition was completed with the particles counts became stable at the new levels.

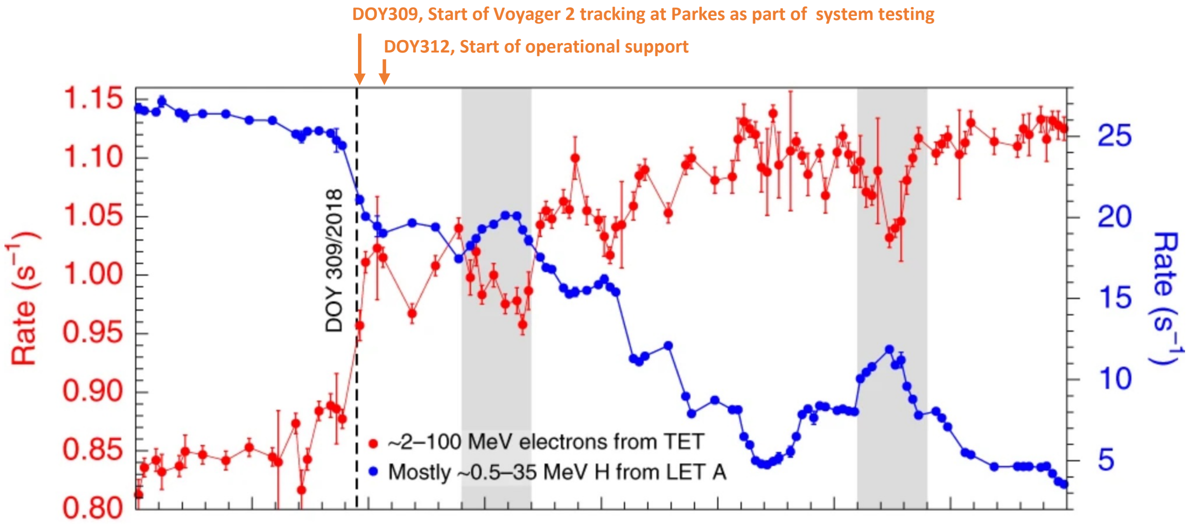

Figure 5.: Start of Parkes support with respect of heliopause transition

Overall, Parkes antenna added 745 hours of antenna tracking to Voyager, spread out over 4 months, as seen in Figure 6. In comparison, the schedule on the Canberra 70-m antenna for VGR2 support during this period was 260 hrs. Thus, Parkes antenna increased the data return by a factor of three, compared to the DSN-only tracking. In November 2018 – January 2019, the station provided about 11 hours of tracking a day. It reduced to 6 hours a day in February due to other obligations. In terms of data return, Figure 7 reflects a daily return of ~800 telemetry data frames a day between November and January, and ~360 frames in February.

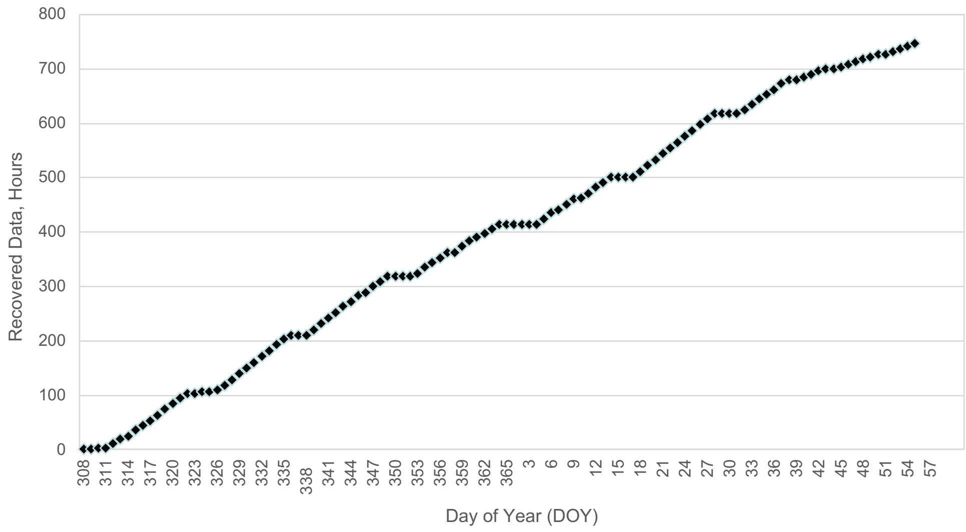

Figure 6: Accumulative number of tracking hours provided by Parkes

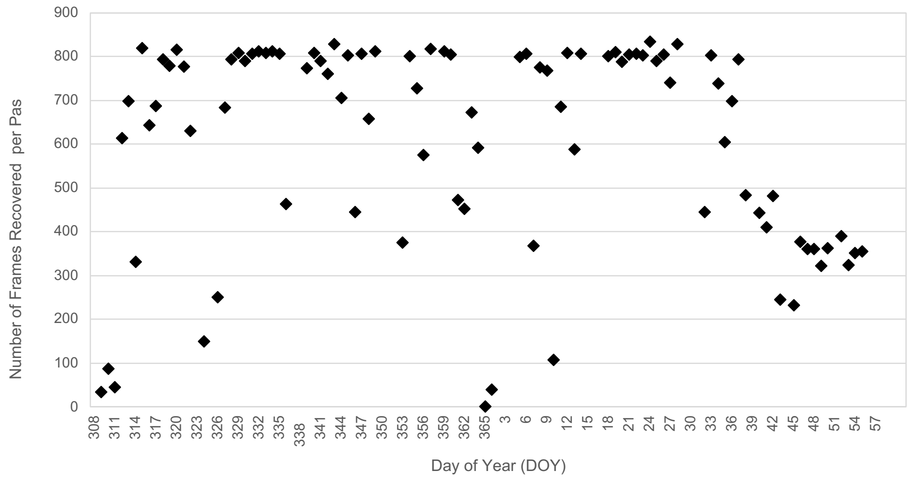

Figure 7: Telemetry data frames returned per tracking pass from Parkes

In term of system reliability, the equipment at Parkes and the receiver at Goldstone proved to be quite robust for this support. The RPAs however encountered issue with hardware (e.g., disk, laptop) on 3 passes, out of 96 total.

In terms of environmental impact, Parkes antenna was exposed to much higher winds, especially in November – December, than what was typically seen with the DSN antennas. Out of 96 passes, 24 passes experienced high winds and 3 passes affected by rain. The high winds resulted in some data outages due to antenna stowing and some performance degradation due to larger pointing error.

6. Conclusion

In this paper, we have described a system that was deployed to enable science data return to Voyager mission. The effort was quite successful in returning significant additional data to Voyager 2 mission during this critical science observation. This implementation had several unique characteristics compared to traditional DSN implementations, e.g., combining COTS products with DSN & Parkes equipment, leveraging on internet connection for data transfer, unique combination of real-time data capture at Parkes and post-pass processing at Goldstone via remote operation at JPL. The record-and-process approach described in this paper was very effective given the fast deployment requirement, as Voyager 2 was entering the heliopause region. In fact, it took only ten days from the notice to the DSN personnel to start of recording at the Parkes antenna. The two key enablers to the speedy implementation were (a) that the RPA that was already developed as a test tool and could be quickly deployed (The RPA was hand-carried to Parkes in a briefcase by the lead author), and (b) the strong prior cooperation between JPL and CSIRO in the use of the Parkes antenna. Overall, the effort increased the Voyager 2 data return three times the amount of data returned by Canberra-only schedule._The success of the effort was attributed to a small team working together across the development and operation teams to help Voyager 2 mission achieved its science objectives.

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