Leveraging Commercial Software-Defined Radio for Low Cost Deep Space Testing

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***Abstract* – In a typical space mission development life cycle, there is a stage where the spacecraft needs to test against the ground station for interface compatibility to ensure that the spacecraft will be properly tracked after launch. This testing normally requires the spacecraft team to bring their flight equipment to the ground station facility. While recognizing that testing with actual flight or engineering module is the most preferred option because of maximum fidelity, there are occasions when the use of actual flight hardware is a logistical challenge because of constraints in spacecraft development schedule. Having another test tool that can emulate the spacecraft signal – by recording the signal transmitted by the spacecraft and later regenerating a radio frequency (RF) signal for ground system testing - would be very useful. It is even more beneficial if such spacecraft emulator is inexpensive and highly portable. In this paper, we describe a new approach that enables ground station testing in support of deep space missions. This is very different from the traditional approach used in the Deep Space Network (DSN) where test equipment is custom designed and built, with much more capability in generating signal of different characteristics, but also at a much greater cost. The new approach, which can be used in complement with the traditional DSN test signal generator or with spacecraft flight radio equipment. The new test capability involves a very low-cost and light-weight recorder/playback assembly (RPA). This equipment leverages on the commercially available Software-defined Radio (SDR) and public-domain software. The RPA, thus far, has been used to support two missions under the National Aeronautics and Space Administration (NASA). One effort is to validate that the Uchinoura 34-m tracking station of the Japanese Aerospace Exploration Agency (JAXA) can track the upcoming NASA Exploration Mission 1 (EM-1) spacecraft, scheduled for launch in 2019. The RPA helps the EM-1 team keeps their flight system for other development/testing needs. The second effort is to help with the testing certification of the 21-m antenna ground station at the Morehead State University (MSU) in Kentucky, United States, prior to the time when the NASA Lunar IceCube spacecraft is ready for actual compatibility testing. The RPA also enables MSU student/staff training on the operations of the new ground station. This low-cost test signal generator allows the MSU team to save money and effort by not having to develop a full-scale self-generated telemetry test signal source.**

Keywords - SDR; RF Test Capability; Uchinoura; Morehead State University Ground Station.

I. INTRODUCTION

In a typical life cycle of deep space mission development, there is a period prior to spacecraft launch when the flight communications system needs to be tested for interface compatibility against the ground station that will be later tracking the spacecraft. The compatibility testing normally requires the spacecraft team to bring their flight radio to the ground station test facility. The tests would exercise various modes of spacecraft operation, e.g., different data rates, coding schemes, signal levels, to ensure that the signal can be properly processed by the ground station. Under the philosophy of "test as you fly", this is a good practice to ensure the compatibility between flight and ground system; however, there are occasions when such a test poses logistic problem to the flight team, e.g., their equipment may be tied up with other development effort. Having a test instrument that can serve as a substitute for flight equipment – a tool that records the signal transmitted by spacecraft and recreates an RF signal for injection into the ground station under test - would offer more flexibility. The benefits are even greater if such a spacecraft emulator is very affordable and highly portable, as in this case, because it reduces the financial burden on the mission and simplifies the shipping logistics when conducting tests.

Section II of this paper discusses a design and capability of the Recorder/Playback Assembly (RPA), developed at the Jet Propulsion Laboratory in support of NASA missions. The benefits of the equipment are captured in Section III. Some possible future improvements to the equipment operations, gained from our testing experiences, are offered in Section IV. Support to the EM-1 mission testing is described in Section V, followed by a similar discussion on test support at the Morehead State University in Section VI.

II. DESIGN ARCHITECTURE

The Recorder/Playback Assembly offers a complementary capability to the test equipment typically developed in the NASA Deep Space Network. Up to now, the test equipment is custom designed and built to the specifications so it can generate test signals that emulate various characteristics of spacecraft that require DSN support. Such development requires significant effort, both in terms of financial resource and time. The new SDR-based equipment described in this paper leverages on commercial products; thus, enables a quick development at low cost. The RPA can be used in complement with the DSN test signal generator by recording its signal and replicating at another facility; thus, enables the test capability at the new site without much cost and effort.

The RPA, as seen in Figure 1, comprises of three key components: (1) a laptop computer with a very fast input/output (via USB3 connections) to enable data transfer

 ISBN: 978-1-61208-624-8

from the transceiver to a disk storage, (2) a high capacity data storage (~3 Terabytes or greater), and (3) a commercial SDR RF transceiver. The computer provides the graphical user interface for user to control the signal generation or signal recording. It configures and controls the setting of the transceiver. In the recording mode, the computer transfers a 10-MHz digitized samples from the transceiver to the disk storage. In the playback mode, it reverses the digital sample flow, from the disk storage to the transceiver. In addition, the laptop also generates a Fast Fourier Transform (FFT) spectrum of the recorded or playback signal, using the digitized samples. The second component – the disk storage - archives the samples. Both the computer and disk storage use a high speed USB3 interface for data transfer. For a 10 MHz I/Q sampling, the data throughput can be as much as 80 MB/s.

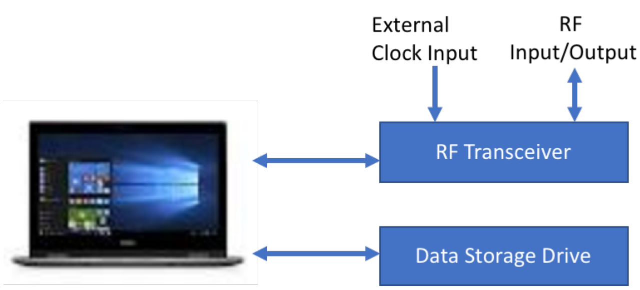

Figure 1. Components of the Recorder Playback Assembly

The most crucial element of the RPA is the RF transceiver [1]. On the recording, it is equivalent to a heterodyne receiver where the RF signal is first down-converted to an IF frequency and then digitized. On the playback, the functions are reversed. The particular commercial unit we employed in the RPA can digitize an RF signal input up to a rate of 20 Msps, I/Q sampling. To enable the recorded data possibly used by other SDRs (e.g., for future upgrade), we chose to have the digitized samples written in the standard 32-bit format. This prompts a high I/O rate (80 MB/s) and a large data storage capacity. Our particular chosen SDR supports an input/output RF frequency range of 1 MHz - 6 GHz. This allows the signal recording, or playback, directly at S-band frequency (~2.3 GHz) that the ground station expects to be receiving from the EM-1 spacecraft. For the Morehead State University testing with the Lunar IceCube spacecraft, since the spacecraft RF transmitted signal will be at X-band (8.4 GHz) which is beyond the capability of the transceiver, the recorded and playback signal are done at an intermediate frequency (IF) around 300 MHz. In the ground system under test, this signal injection point is after the first RF/IF downconversion and prior to the carrier and symbol demodulation.

The SDR transceiver can operate with an internal clock or be synchronized to an external 10 MHz reference. Since the SDR expects a Low Voltage Transistor Transistor Logic (LVTTL) input level for the frequency reference, we needed to build an adapter to convert a typical sinusoidal reference (+13 dBm) to that of LVTTL. This adapter essentially is a resistor-capacitor-diode network to level shift and it clamps the signal level to the 0-volt minimum and 3.3-volt maximum, as required for LVTTL compatibility. The use of an external frequency reference from a highly stable clock, such as those produced by a Hydrogen maser at both ground stations of JAXA and MSU, produces a significantly more stable signal, which is critically important to our test objectives. Performance of the signal stability with and without the external reference is later discussed in section VI.

The transceiver control software is leveraged on public-domain software available from the gnu library. This is another benefit for using the commercial SDR. We developed two modes of operation, either recording or playback. Figure 2 shows a sample of the graphical control interface for data recording. By specifying the local oscillator frequency, typically a few MHz off from the actual carrier frequency, we can position the signal to be sampled away from the dc component. Figure 3 shows a similar control window for the playback where one can specify the selection of the data file and output frequency, along with other detailed configuration parameters such as the setting of RF, IF and baseband gain. In both recording and play back modes, an FFT spectrum, as seen in Figure 4, is provided to aid with signal monitoring.

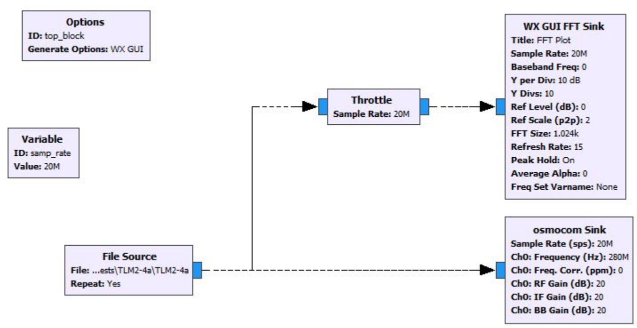

Figure 2. Control Interface for Recording

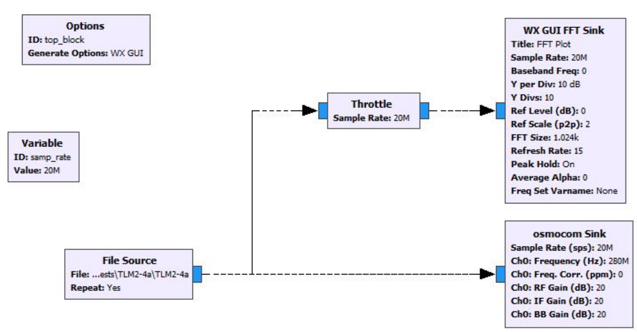

Figure 3. Control Interface for Playback

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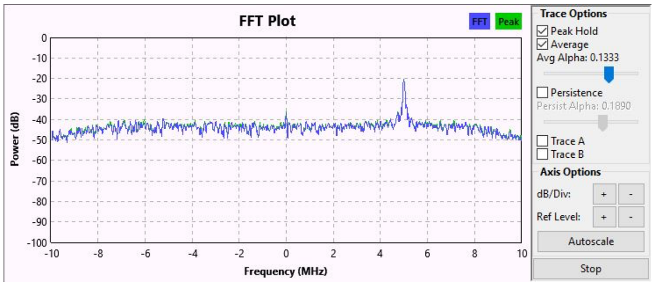

Figure 4. Spectral monitor of recorded/playback signal

These control interface windows make it easy to operate the system. Typically, only a few parameters such as the input/output filename and the signal frequency need to be changed when running different tests.

III. Benefits

From our experience, below are some key benefits of the RPA.

(1) *Low Cost* - In application where one needs to replicate a test signal source that is only available from other high-end equipment, this low-cost recorder/playback capability is an attractive option. The hardware cost, purchased in 2016, is around $2K. About 1 month of effort is required to assemble and test the monitor & control software, leveraging on the programming codes available to the public.

(2) *Portability* - Another feature we highly value is the equipment portability. The whole RPA weighs just a bit heavier than a common laptop, less than 7 lbs., making it very easy to hand carry to a distant test site.

(3) *Upgradability* - Since the SDRs are commercial products and supported by a large user community who also provide many standard interfaces and functionality, as more powerful products become available, the system could be easily upgraded without much effort.

(4) *Flexibility* - The wide range of frequency supported by the transceiver provides much flexibility with testing. It allows us to inject the test signal directly into the front-end of ground system at S-band frequency (the same signal path traveled by spacecraft signal during operational phase), or at some intermediate frequency in mid-stream of the system. The ease of setting the carrier frequency makes it easy to simulate different spacecraft signals under test.

(5) *Efficiency* - The RPA can generate test signal with the data-repeat option. It can continually regenerate the signal with only a small set of recorded data; thus, reduces the need for a large data storage or a long recording session.

IV. Future Improvements

Although the RPA sufficiently supports our testing needs, there are certain features we could pursue in the future that would improve its operability:

(1) *Gain setting* - The gnu library allows for the gain setting of three stages: baseband, IF and RF. By setting these gains in midrange, we are able to capture and regenerate the signal at nominal power level and with good quality (i.e., without distortion). Having a better understanding on how various combinations of gain setting work would help toward creating a signal of different power levels that is best suited for various operating conditions.

(2) *Trimming of recorded data* – Some of our recorded data files started earlier than the actual data segment of interest. Under the current capability, the entire data file is replayed, resulted in some wait time before reaching the segment of interest. Having utility to trim the data file to just segments of interest would increase the efficiency of testing.

(3) *Higher frequency* – As more commercial products become available with greater capability, we would consider upgrade the SDR to those operating at X-band (8.4 GHz) and beyond. This would further enhance testing capability for X-band, as well as Ka-band (26-32 GHz), missions.

V. EM-1 Mission Support

One objective of the RPA development is to provide test support to the Exploration Mission 1, currently scheduled to be launched in late 2019 [2]. The EM-1 spacecraft will be on a three-week trajectory that takes it to the Moon, stays in the parking orbit for a few days, and then returns to Earth. EM-1 is intended to demonstrate the operation of a new spacecraft system, along with the new Space Launch System, prior to the Exploration Mission 2 that will be carrying the astronaut crew. In support of future crewed mission, precise navigation and spacecraft orbit determination, especially for the Earth return segment, are important. For EM-1, most of the tracking during the mission three-week operations will be provided by the NASA Deep Space Network; however, in the interest of getting supplement tracking data during the critical phase of the mission, e.g., Earth return, additional 3-way Doppler data from the JAXA antenna is deemed beneficial to mission navigation.

The focus of JAXA support is mainly on tracking EM- 1 carrier signal and providing 3-way Doppler data to the mission navigation. 3-way refers to a mode of operation where the receiving antenna tracks the spacecraft signal is coherent to the uplink of another transmitting antenna. In our case, the DSN antenna would provide an uplink to the spacecraft and JAXA antenna will track the spacecraft downlink, in concurrent with the DSN tracking. No telemetry data processing is needed from JAXA Uchinoura station.

Normally, we could leverage a spacecraft currently in flight that has the same signal format to test the ground system compatibility with future spacecraft. However, EM-1 signal format is different from other lunar missions currently in operation, such as the Lunar Reconnaissance Orbiter (LRO). EM-1 telemetry data is directly modulated onto the carrier. In contrast, the LRO telemetry data is first modulated on a subcarrier, prior to the carrier modulation. To ensure that Uchinoura system can track the EM-1 signal, it was decided that a replica of EM-1 signal – being recorded and played back by the RPA – should be used to check out the compatibility of the flight and ground interface. The main objective is to demonstrate that the receiver at the Uchinoura station can track the carrier in the presence of telemetry modulation, and to provide good, stable Doppler data.

 ISBN: 978-1-61208-624-8

A preliminary test was recently conducted using the RPA to characterize the Doppler data tracked by Uchinoura station [3]. The RPA previously recorded the EM-1 RF test signal during its compatibility testing with the Deep Space Network. The recorded data were then used to generate a duplicated EM-1 signal at 2.3 GHz (S-band). The RPA output was injected into the front end of the Uchinoura station, in front of the low noise amplifier. The Uchinoura receiver successfully locked to the RPA signal and produced Doppler data (measured carrier frequency) as shown in Figure 5. Testing was done for several EM-1 configurations of different telemetry data rate ranging from 72 ksps to 2 Msps. The test also demonstrated that it could track EM-1 signal with both the Costa loop (relying on telemetry symbols only, not carrier) and the standard phase lock loop (relying on the residual carrier buried underneath the telemetry spectrum).

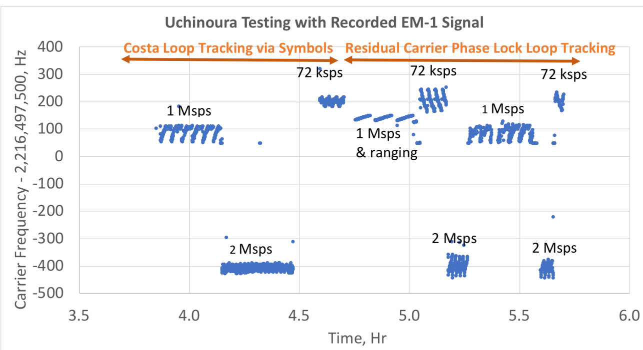

Figure 5. Uchinoura test with EM-1 signal, 2017-12-01

One may observe that there is a cyclic pattern within each data rate configuration. This is caused by the data repeat feature in the play back mode discussed earlier in Section III.

VI. MSU SUPPORT

The 21-m antenna system at the Morehead State University is being upgraded to support the Lunar IceCube mission, and likely also for other CubeSats launched on the EM-1 mission along with the Lunar IceCube [4][5]. This system will be capable of deep space tracking at X-band (8.4 GHz). The system has some DSN-replica digital equipment that are specialized in telemetry, tracking and command in deep space environment. Due to limited budget and time constraint, the 21-m system does not have a full-scale test equipment that can simulate the Lunar Ice Cube signal. The RPA helps to fill this gap. It first recorded a test signal of Lunar IceCube characteristics that was generated by a more capable DSN Test Signal Generator. The signal was then recreated and injected into the MSU ground station. Through this effort, the RPA helps verifying the ground system components and building up the confidence that the MSU ground system would be ready to support further interface testing with the actual Lunar IceCube flight system when it becomes available.

The recorded Lunar IceCube test signal comprises of a suppressed carrier modulated by telemetry data which are encoded with Turbo code, rate 1/6. The preliminary test results demonstrated that the MSU equipment can successfully demodulate and decode the Lunar IceCube telemetry data at 64 ksps. Further testing is needed to demonstrate similar performance at 384 ksps where Lunar Ice Cube is expected to operate.

During the MSU testing, we were also able to characterize the performance of the RPA with and without the 10 MHz reference obtained from the on-site hydrogen maser clock. Figure 6 shows the measured frequency stability of the test signal, as detected by the receiver. With the 10 MHz reference input, the carrier signal was very stable. The frequency variation was within 20 mHz over short term and 70 mHz over a period of 2.5 hrs.

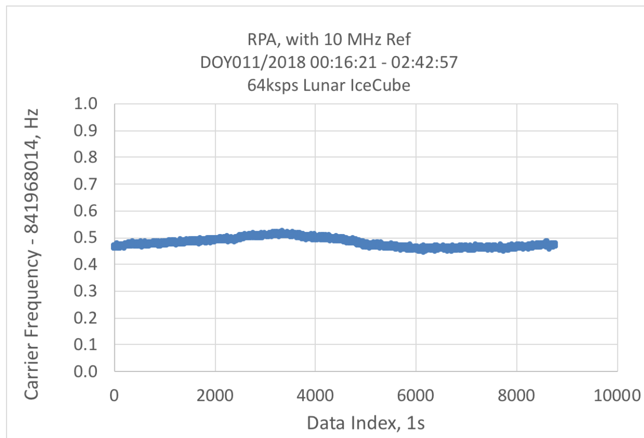

Figure 6. Stability of the test signal, with external reference.

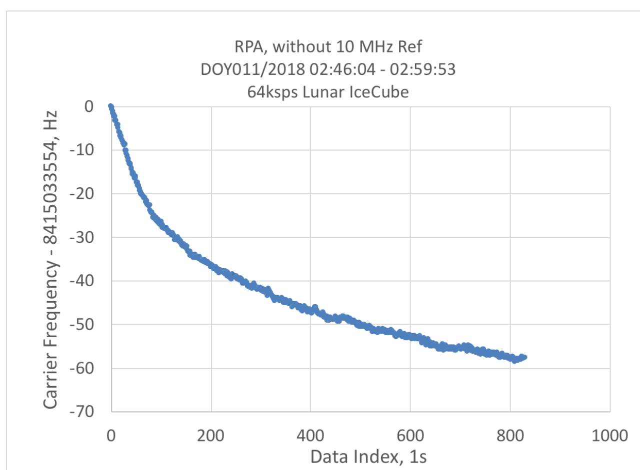

Figure 7. Stability of the test signal, with internal clock.

When generated with the transceiver internal clock, the carrier frequency drifted as much as 60 Hz just over 14 minutes, as shown in Figure 7. With such variation, while it is possible to track the carrier with a wider bandwidth, it would be difficult to maintain symbol demodulation with the maximum bandwidth allowed by the receiver. Our assessment is that in order for the RPA to support telemetry data testing, it needs to be synchronized to a stable external frequency reference.

VII. Conclusion

In this paper, we discussed the use of a commercial software-defined radio in our testing effort at the JAXA Uchinoura and the Morehead State University ground stations. This test tool allows us to record, and later play back, the EM-1 signal generated by the spacecraft under development, and the emulated Lunar IceCube generated by the DSN Test Equipment. The test capability is of low cost, both in term of hardware procurement and software development, thanks to the available commercial products and public domain SDR software. One most valuable feature is the portability of the system. Its light weight makes it very easy to transport and conduct test at other distant ground station, without a need for transportation shipment or on-site installation.

Both preliminary testing at Uchinoura and MSU have been successful. At Uchinoura, the ground station demonstrated it could track the recorded EM-1 signal. At the Morehead State University, the RPA enabled demonstration of functionality of the ground station, where telemetry data emulating the Lunar IceCube mission was successfully demodulated and decoded. From our testing, we learned that it is critical to have the RPA using an external atomic frequency reference – instead of relying on the internal clock - in order to achieve the necessary frequency stability needed for Doppler and telemetry processing.

Acknowledgment

The work described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. We would like to thank Hiroshi Takeuchi and Atsushi Tomiki at JAXA for their indispensable assistance with the Uchinoura testing. Support in conducting additional tests at the Morehead State University by Sarah Wilczewski and data extraction by Jason Liao are much appreciated.

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 ISBN: 978-1-61208-624-8