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High Speed, Low Cost Telemetry Access from Space Development Update on Programmable Ultra Lightweight System Adaptable Radio (PULSAR)

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ABSTRACT

Software Defined Radio (SDR) technology has been proven in the commercial sector since the early 1990's. Today's rapid advancement in mobile telephone reliability and power management capabilities exemplifies the effectiveness of the SDR technology for the modern communications market. In contrast, the foundations of transponder technology presently qualified for satellite applications were developed during the early space program of the 1960's. Conventional transponders are built to a specific platform and must be redesigned for every new bus while the SDR is adaptive in nature and can fit numerous applications with no hardware modifications. A SDR uses a minimum amount of analog / Radio Frequency (RF) components to up/down-convert the RF signal to/from a digital format. Once the signal is digitized, all processing is performed using hardware or software logic. Typical SDR digital processes include; filtering, modulation, up/down converting and demodulation.

NASA Marshall Space Flight Center (MSFC) Programmable Ultra Lightweight System Adaptable Radio (PULSAR) leverages existing MSFC SDR designs and commercial sector enhanced capabilities to provide a path to a radiation tolerant SDR transponder. These innovations (1) reduce the cost of NASA Low Earth Orbit (LEO) and Deep Space standard transponders, (2) decrease power requirements, and (3) commensurately reduce volume. A second pay-off is the increased SDR flexibility by allowing the same hardware to implement multiple transponder types simply by altering hardware logic – no change of hardware is required - all of which will ultimately be accomplished in orbit. Development of SDR technology for space applications will provide a highly capable, low cost transponder to programs of all sizes. The MSFC PULSAR Project results in a Technology Readiness Level (TRL) 7 low-cost telemetry system available to Smallsat and CubeSat missions, as well as other platforms.

This paper documents the continued development and verification/validation of the MSFC SDR, called PULSAR, which contributes to advancing the state-of-the-art in transponder design – directly applicable to the SmallSat and CubeSat communities. This paper focuses on lessons learned on the first sub-orbital flight (high altitude balloon) and the follow-on steps taken to validate PULSAR. A sounding rocket launch, currently planned for 03/2015, will further expose PULSAR to the high dynamics of sub-orbital flights. Future opportunities for orbiting satellite incorporation reside in the small satellite missions (FASTSat, CubeSat. etc.).

INTRODUCTION

Software Defined Radio (SDR) is an industry term describing a method of utilizing a minimum amount of radio frequency (RF) analog electronics before digitizing the signal. Upon digitization, all other functions are performed in software or hardware logic. There are as many different types of SDRs as there are data systems.

NASA Marshall Space Flight Center (MSFC) has an SDR transponder test-bed using "hardware-in-the-loop" methodology for:

- Evaluating and improving SDR technologies;
- Testing and assessing emerging technologies in terms of reliability, and re-configurability; and
- Achieving ever increasingly higher data through-put.

NASA's fourth generation SDR, PULSAR, hardware/software design and development has been fueled using technology advancements funding. During Fiscal Year (FY) 2013, the PULSAR project team developed, procured, bench tested, and flew a unit on a balloon gondola. The "hardware-in-the-loop" bench test, at the middle of August, was the climax from two years of design and nine months procurement.

TECHNICAL APPROACH

The PULSAR Project leverages the lessons learned during the prototype system (version 2.2) development, which used NASA funds from FY2012. The most recent version (2.3) incorporates the lessons learned from the balloon gondola flight in 09/2013 (more details in Performance Section). Non-radiation tolerant hardware (but with a path to radiation tolerance) were procured in order to keep development costs low.

Technical Description

The PULSAR base design has five selectable decks – power deck, processor deck, S-Band receiver deck, and S- and X-Band telemetry transmitter decks (Figure 1). Mission applications determine the final configuration, thus the number of decks.

Power Deck

PULSAR operates electrically isolated from the satellite bus. PULSAR (version 2.2 & 2.2a) requires an external power source providing an input range of +16 to +50 volts direct current (VDC). Version 2.3 power deck distributes up to 30 watts depending on configuration stack up (version 2.2 resulted in higher than expected power usage, see Performance Section).

The power deck contains two separate direct current (DC) power converters. One converter generates 5.2 VDC, while the other generates 15 VDC. The receiver and processor deck are always on while the transmitters power on and off with uplink commands, receiver deck commands, or Flight Computer (FC) commands. At the introduction of power, the transmitters remain off and the receiver powers on. This design methodology allows for commanding ON/OFF, as well as warm and soft reboots from external sources.

The power deck mitigates any unintentional generation, propagation, or reception of electromagnetic energy.

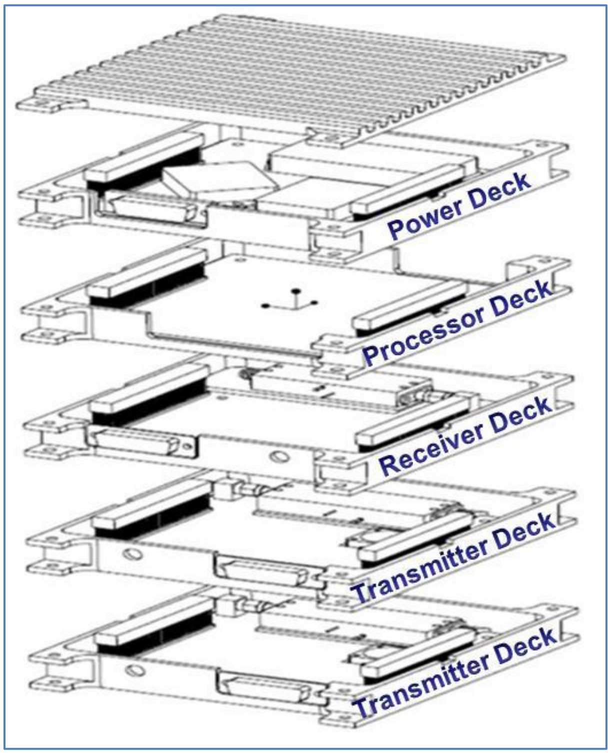

Figure 1: PULSAR contains five main component decks.

Processor Deck

The processor deck utilizes an ARM M1 (Advanced RISC Machine) processor. The processor deck runs a field programmable gate array (FPGA) inside a radiation tolerant housing. The FPGA performs ancillary operations as dictated by mission requirements.

PULSAR utilizes VHDL rather than software. VHSIC hardware description language, VHDL, provides a logic circuit within the FPGA. The VHDL does not change throughout the life cycle of each PULSAR application. Future designs will permit configuration changes during mission operations. The PULSAR Project plans to first demonstrate the technology, and then incorporate more capabilities.

Receiver Deck

The receiver deck connects to two external components: the radio frequency (RF) antenna port (via sub miniature version A - SMA) and the high density DB37 flight computer (FC) interface for the uplink command stream.

The S-band receiver deck processes up to a maximum 300 kilobits per second (kbps) uplink data rate - based on ground station limitations; therefore the limit could increase as the ground station technology improves. The receiver deck demodulates binary phase-shift keying (BPSK).

The receiver deck technology boasts a noise figure of 0.6 dB. The receiver technology also eliminates the need for ranging tones. Instead, PULSAR uses Doppler Shift ranging.

Telemetry Transmitter Decks

The telemetry transmitter decks produce up to a 2 watt (W) radio frequency (RF) output (1W each). The RF output power tailors to many missions. If greater output power is desired, then PULSAR would utilize an external Solid State Power Amplifier (SSPA) to increase the output power to the desired level. The telemetry transmitter decks connect to two external components: the RF antenna port (via SMA) and the high density DB37 Flight Computer (FC) interface for the downlink telemetry stream.

The telemetry transmitter decks stream data with quadrature phase-shift keying (QPSK) at a maximum data rate of 150 Mega-samples per second (Msps). Just as in the receiver deck, the ground station limits the data rate.

The transmitted data uses Low Density Parity Check (LDPC) Forward Error Correcting (FEC) coding. The improved coding gain adds an order of magnitude increase in telemetry through-put. Exemplifying flexibility, PULSAR transmits using LDPC, Reed-Solomon (223/255), or convolutional (Rate ½) FEC based on mission requirements.

PERFORMANCE

PULSAR completed functional checkouts in the SDR transponder test-bed using "hardware-in-the-loop" methodology. The same PULSAR unit completed a high altitude balloon flight (see Figures 2 & 3).

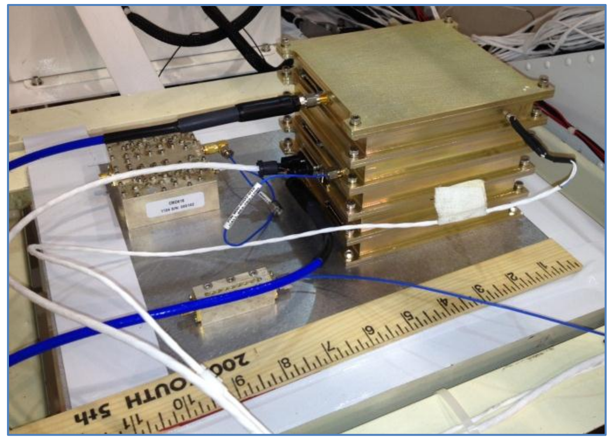

Figure 2: PULSAR installed on balloon gondola.

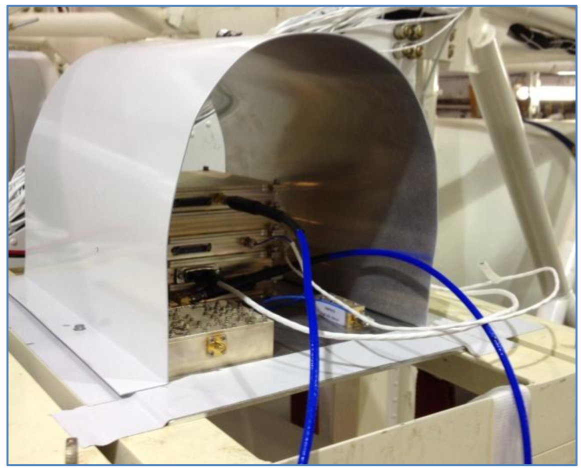

Figure 3: PULSAR with solar shield.

Market Comparison

Table 1 shows a market analysis of industry transponders and differentiates their features compared to PULSAR. In comparison, the NASA-MSFC SDR incorporates the latest in Forward Error Correcting (FEC) codes and utilizes State-of-the-Art electronic components which give PULSAR the capability to achieve much higher Bits-per-Watt (the industry standard benchmark showing data rate versus power).

In Table 1, there are three units listed as Satellite Communications and Navigation (SCaN). These are NASA third generation SDRs installed on the International Space Station (ISS) as part of the SCaN test-bed. At the time of this publication, the telemetry verification and downlink data rates were not published. The data rates listed are the telemetry classes for which the SDRs are categorized. The remaining units were gathered using the data sheets available on the company websites or published in brochures available on the internet.

Demonstration Update and Chronology

During the 2013 Small Satellite Conference, one team member continued performing bench testing while other members attended the conference. The PULSAR prototype unit would not transmit more than 90 Mega-symbols per second (Msps) with the I and Q channels interleaved (X-Band Deck only), although the goal of 150 Msps was met with dual channels non-interleaved.

Due to time constraints for balloon gondola installation, PULSAR was installed (late 08/2013) knowing the current state of the receiver deck would not lock to a carrier. On the other hand, the S- and X-Band Transmitter decks were generating good data patterns with 5 Msps interleaved and 150 Msps non-interleaved, respectively. (Note: The 5 Msps demonstration on S-Band was due to the National Telecommunications & Information Administration (NTIA) bandwidth limit, not a hardware limitation.) Installation and integration tests were performed on site at the Columbia Scientific Balloon Facility in Fort Sumner, New Mexico.

Table 1: Market Analysis of typical industry telemetry transponders

Maker	Unit	Freq. Band	Downlink Data Rate, Msps	Mass, kg	Bench-mark, b/W
NASA-MSFC	PULSAR	S-, X-	150	2.1	10e6
L3 Comm[2]	Cadet	S-	100	0.215	8.3e6
Innoflight[3]	SCR-100	S-	4.5	0.25	3e6
L-3 TW[4]	CTX-886	X-	400	3.85	66e6
Space Micro[5]	µSTDN-100	S-	4	2.1	0.7e6
Harris Corporation[6,7]	SCaN	Ka	100	19.2	2.5e6
General Dynamics[6,7]	SCaN	S-	10	-	1.0e6
Jet Propulsion Laboratory[6,7]	SCaN	S-	10	6.6	1.0e6

PULSAR exceeds most of the other units in term of the industry benchmark. The L-3 TW CTX-886 exceeds PULSAR in data rate, but PULSAR has less mass (2.1 versus 3.85 kg) and uses less power (42 versus 75 watts – not shown in table).

Originally, the non-critical PULSAR experiment (i.e., PULSAR was not the primary telemetry system) was encased in an igloo cooler for environmental thermal protection. Preflight compatibility tests revealed that the chassis temperature was greater than anticipated. PULSAR was removed from the igloo cooler and installed with a solar shield instead (see Figure 3). Compatibility testing on 09/06/2013 continued to show good data patterns. PULSAR On 09/22/2013, the HEROES balloon gondola launched from Fort Sumner. Team members remotely monitored PULSAR and the ground receiver from Huntsville, Alabama. Shortly after launch, both the X-band and S-Band signals decayed to indistinguishable levels. Thermal couple data verified that PULSAR was still operating (i.e., generating heat). A nearby mobile S-Band ground receiver confirmed that PULSAR was transmitting on S-Band (see Figure 4). Ultimately, the HEROES project still carried out its mission and loitered at an altitude between 34 and 40 km (111,500 and 131,200 feet), giving PULSAR exposure to the near vacuum and thermal variations of space environment.

Post flight inspections found the S-Band ground antenna coax cable severed. The PULSAR team concluded that the X-Band failure was the result of a nearby lightning strike prior to launch day and/or elevated temperatures on the X-Band deck. External X-Band chassis temperatures exceeded 60C multiple times during ascent. The power supply was cycled to mitigate overheating, although it may have been insufficient to protect sensitive board components.

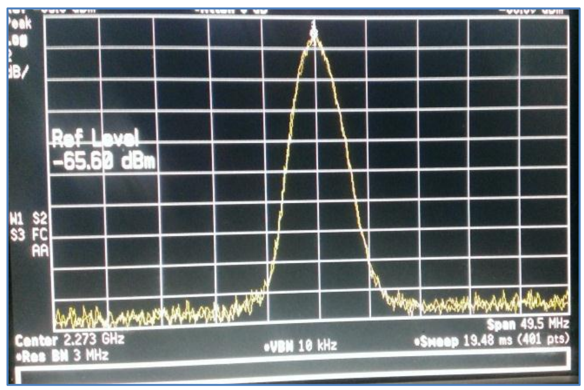

Figure 4: Spectrum Analyzer view of PULSAR S-Band signal.

With year-end activities and federal government shutdown, post flight bench testing was not performed until after 10/31/2013. The telemetry performance had significantly degraded. Data could only be pushed through using an external local oscillator. After a month of investigating, the PULSAR prototype (version 2.2) was declared unsalvageable and procurement began on new hardware (version 2.2a). The most likely failure scenario is that the hardware exceeded recommended component temperatures, but contributing sources were also considered from preflight rework modifications imposing stress on the components and/or boards, and the electromagnetic atmospheric activity (lightning) just days before the flight.

In addition to the circuit board changes for version 2.2a, a chassis redesign changed the coating from alodine to black anodized. Thermal analysis concluded the new coating would significantly improve radiant heat exchange, thus reducing the internal/board temperatures. For example, thermal analysis (5 hour transient models of alodine and black anodized) shows the maximum board temperature drops 82C when comparing chassis temperatures.

ALIGNMENT

NASA is called, at the direction of the President and Congress, to maintain an enterprise of technology that aligns with missions and contributes to the Nation's innovative economy. NASA has been and should be at the forefront of scientific and technological innovation. In response to these calls, NASA generated a plan (NASA Strategic Space Technology Investment Plan[8]) to advance technologies and nurture new innovation that will feed into future missions. PULSAR aligns primarily with the Technology Area (TA) 5 – Communication & Navigation – but has connections to other TAs in which lightweight structures, power efficiency, and communication reliability and through-put are the focus.

Orbital Telemetry licenses PULSAR technology and markets units for increasing capabilities of commercial and academic groups.

STATUS AND SCHEDULE

All PULSAR (version 2.2a) circuit boards are printed, populated, and received. This procurement represents minor design changes compared to the unit flown on the HEROES balloon gondola. The latest units also include a procurement technique modification. The circuit boards were populated using machines rather than component hand placement, referred in the industry as "pick and place". The technique reduces the procurement time and the potential errors from hand placement.

Functional checkouts have been performed on the power deck, processor deck, and S-Band transmitter deck. The S-Band receiver deck checkouts are nearing completion (estimated at 70% completion). The X-Band transmitter deck checkouts will begin after the receiver deck checkouts are completed.

The chassis have been stripped and modified to black anodize coatings.

Future plans include environmental testing conducted on a PULSAR unit in 09/2014. Vibrational testing will subject a PULSAR unit to simulated sounding rocket loads. Thermal vacuum and Electromagnetic Interference and Compatibility (EMI/EMC) testing will expose a unit to simulated space environment (dates are to be determined – TBD).

A proposal was accepted to ride on a sounding rocket as a secondary experimental payload. The flight is currently scheduled for 03/2015. Integration and preflight tasks begin in 12/2014.

CONCLUSION

SDR Industry Future

Studies were performed in 2006 and 2011 to evaluate the adoption of SDR technologies in various markets.[9] One finding shows that once the SDR technology clears the "chasm", it will become mainstream where adopters will select it because of the successful application. PULSAR is bridging that "chasm" in the satellite telemetry realm.

PULSAR Goals Met

PULSAR leverages existing Marshall Space Flight Center SDR designs and commercially enhanced capabilities to provide a path to a radiation tolerant SDR transponder. These innovations will

(1) Reduce the cost of NASA Low Earth Orbit (LEO) and Deep Space transponders,
(2) Increase data through-put,
(3) Decrease power requirements, and
(4) Reduce volume.

Also, PULSAR increases flexibility to implement multiple transponder types by utilizing the same hardware with altered logic – no hardware change required – all of which will eventually be accomplished in orbit. The five PULSAR decks offer many capability permutations – 14 possible combinations of processing, receiving, and transmitting. The flexibility permits CubeSat and SmallSat programs to select only what they need for their mission.

PULSAR project team achieved the targeted procurement cost of less than $100,000 for the SDR. The actual cost will be determined by licensee (Orbital Telemetry) and any required verification and validation efforts.

PULSAR offers high capability, low cost, transponders to programs of all sizes. The final project outcome will be the introduction of a low-cost CubeSat to SmallSat telemetry system.

PULSAR Future

PULSAR will obtain a Technology Readiness Level (TRL) 7 – suborbital – with the sounding rocket flight in 03/2015. PULSAR Project Team is pursuing flight opportunities to advance the technology to a TRL 8 or 9.

NASA Johnson Space Center (JSC) will use a PULSAR unit to validate the Integrated, Power, Avionics, and Software (iPAS). JSC is building the capability to perform "hardware-in-the-loop" testing of avionic components.

The PULSAR Roadmap includes adaptation into a ground based system, upgrading the receiver from S-Band to X-Band, and transmitter options such as C-Band and Ka-Band. These technologies are planned for continued development in FY2015.

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