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S-Band Transponder Multi-Network Compatibility, Space Environment and Radiation Testing

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ABSTRACT

This paper presents the development and testing of the Software Define Radio (SDR) transceiver to meet the emerging needs for SmallSat communication and navigation. Vulcan Wireless and NASA Goddard Space Flight Center (GSFC) collaborated in testing the Vulcan Wireless S-band SDR engineering model. Apart from testing, communication link analysis was performed for a Low Earth Orbit (LEO) 400 km scenario. The results of the compatibility, radiation, environmental testing, and link analysis are presented. Also, this paper reviews a set of SmallSat missions under development at NASA GSFC.

INTRODUCTION

As CubeSats/SmallSats increasingly become the low cost option of doing science, it is necessary to ensure that the CubeSat/SmallSat communication hardware is standardized and compatible with NASA Near Earth Network (NEN) and Space Network (SN). Today, there is a lack of standard NASA SN/NEN compatible CubeSat/SmallSat transceivers available, either developed by NASA or industry. Software Define Radio (SDR) transceiver is the key device for future CubeSat/SmallSat communication and navigation needs. The SDR transceiver will allow one radio platform to be re-configured and function across multiple operational characteristics such as data rate, modulation type and coding scheme and allow reducing payload mass, cost, and power for SmallSat missions. NASA GSFC and Vulcan Wireless Inc. are collaborating to develop and test a NEN and SN compatible SDR for the communication needs of current and future LEO, GTO, L1/L2, Lunar and Planetary missions. This paper will discuss (i) high level performance parameters of the Vulcan Wireless S-band SDR engineering model, (ii) current and future mission set, (iii) NEN and SN compatibility testing, (iv) Radiation testing and analysis, (v) environmental testing, and (vi) high level RF link analysis, of the Vulcan Wireless S-band SDR engineering model.

This radio will support both direct communications with the NASA Near Earth Network ground terminals, as well as the Space Networks Tracking and Data Relay Satellite's multiple access data link (TDRS- MA). The TDRS-MA capability will allow for missions that require real time access to the ground system through the TDRS-MA geosynchronous data network. Having both waveforms integrated into one radio would provide a major advantage for size, weight and power for small satellite applications. Further the antenna system is also capable of supporting both frequency bands thus only one antenna is required for both waveforms.

CURRENT MISSION SET

The NASA Goddard Space Flight Center Small Satellite missions currently under development include PetitSat, SNOOPI, GTOSat, BurstCube, and DIONE.

Table 1 - Current NASA GSFC CubeSat Missions

Mission	Orbit	Lunch Date	COMM Network	Downlink Data rate	Uplink Data rate
PetitSat	LEO	6/21	NEN	4Mbps	62.5Kbps
SNOOPI	LEO	9/21	NEN	4Mbps	62.5Kbps
GTOSat	GTO	10/21	NEN/SA	4Mbps/ 1Kbps	62.5Kbps/ 1Kbps
BurstCube	LEO	2/22	NEN/SA	4Mbps/ 1Kbps	62.5Kbps/ 1Kbps
Dione	LEO	8/22	NEN	4Mbps	62.5Kbps

An overview of the NASA GSFC portfolio has been captured in Table 1 while details into the payloads and science goals are below. These missions share a common baseline of components to maximize re-use across the missions. Due to payload constraints, these missions each have different physical layouts inside the standard 6U, 60cm x 20cm volume.

PetitSat

The PetitSat mission [1] is a 6U CubeSat designed to examine the link between MSTIDs and plasma enhancements. The mission will provide in situ measurements of the plasma density, 3D ion drift, as well as ion and neutral composition. The instrument suite includes a combined retarding potential analyzer and cross-track drift meter and an ion-neutral mass spectrometer. This instrument suite will provide comprehensive information about the fluctuations in plasma, as well as changes in the neutral profile. PetitSat will launch into a 51 degree inclination orbit at 400 km (consistent with an International Space Station deployment), allowing for numerous conjunctions with the Boston University All-Sky Imager network over the mission lifetime.

SNOOPI

SNOOPI is a 6U spacecraft flying a reflectometer to demonstrate complex (magnitude and phase) reflection coefficient measurements of land surface reflections in P-band from space. SNOOPI will be launched from the ISS with an orbit of 420 km altitude and an inclination of 51.6 deg. SNOOPI measurements will enable future satellite missions for remote sensing of Root Zone Soil Moisture (RZSM) and Snow Water Equivalent (SWE), priority variables in the Earth Science and Applications from Space (ESAS) 2017 Decadal Survey produced by the National Academies of Sciences, Engineering and Medicine (NASEM, 2018) with critical roles in hydrology and water management.

GTOSat

GTOSat's primary science goal is to advance our quantitative understanding of acceleration and loss of relativistic electrons in the Earth's outer radiation belt. From a low inclination Geosynchronous Transfer Orbit (GTO), GTOSat will measure electron spectra and pitch angles of both the seed and the energized electron populations simultaneously, using a compact, high-heritage Relativistic Electron Magnetic Spectrometer (REMS), a customized version of the MagEIS-Medium instruments from NASA's Van Allen Probes mission. A boom-mounted Fluxgate Magnetometer (FMAG) will provide 3-axis knowledge of the ambient local magnetic field. These high-quality particle and field measurements enable direct measurement of spectral and pitch angle evolution of the outer radiation belt and calculation of physically significant quantities, such as phase space density (PSD) and its radial gradients, which are necessary to discriminate between radial transport and in-situ modes of electron energization.

BurstCube

BurstCube [1] is a 6U CubeSat with a 4U instrument package. The mission's objective is to detect and characterize short Gamma-ray Bursts (sGRBs) that are counterparts of Gravitational Wave Sources. BurstCube will automatically detect Gamma-ray transients onboard (astrophysical, solar, and terrestrial), and send rapid alerts through the Tracking and Data Relay Satellite System (TDRSS) to the ground to enable follow-up observations. The 4U instrument package is a wide field-of-view scanning instrument looking for simultaneous rate increases above background in two or more detectors on timescales from milliseconds to seconds. BurstCube is currently in development and will launch through the early 2020's.

DIONE

Dione is a 6U LEO cubesat which will help us understand the Ionosphere-Thermosphere (IT) responses to Magnetospheric forcing. Energy from the sun is first transferred to the magnetosphere. It's transferred to the IT where the magnetic field lines reconnect, near the north and south poles. Dione is going to measure electromagnetic and kinetic energy at the poles, as well as IT responses, such as temperature, density and composition (number of neutrals and ions).

MULTI-NETWORK RF COMPATABILITY

Network Overview

The Vulcan Wireless' NSR-SDR-S/S software defined radio is a multi-waveform radio designed to support multiple communications missions. Two waveform modes have been tested for network compatibility to the National Aeronautics and Space Administration (NASA) Near-Earth Network (NEN) and the Space Network (SN) standards. Both networks utilize the unified S-Band frequencies and are operated in full duplex mode.

The NEN network path is used for direct space to earth communications and is used for high data rate communications and control functions of the space vehicle. The NEN network can only be used when the space vehicle is in direct line of sight of the ground terminal. This constrains the ability to communicate with the vehicle to the periodic windows of communications where the vehicle is in view of the ground station in use. The limited contact times necessitates mission planning of the science mission and large delays between contacts.

The SN consists of a series of three regions: Atlantic, Pacific and Indian Ocean Regions. The SN provides continuous coverage for a satellite over a wide range of LEO, MEO and HEO orbits. The SN is designed for multiple simultaneous space vehicles communicating through the network. The SN waveform allows for multi-user access with a wideband spread spectrum code division access. The specific mode that is implemented is the Tracking and Data Relay Satellite System-Multi-Access (TDRSS-MA). This waveform is significantly more complex that the NEN waveform due to the synchronization and dispreading feature. The TDRSS-MA satellites are parked in a Geosynchronous Orbit (GEO) with a one-way range of greater than 42,000Km, so due to this great range the data rate for the TDRSS-MA is constrained. Due to the link budget limitation of the TDRSS-MA the practical user data rate is constrained to ~10Kbps.

With this background, let's describe the verification process undergone to confirm that the waveform implementation and Radio Frequency (RF) interfaces are compatible with the NEN and SN infrastructure. This is the critical step to verify that the radio will be interoperable on orbit. The compatibility testing is conducted for each specific waveform that the communications device intends on using during the satellite mission. The primary goal of the testing is to ensure the quality and reliability of the communications device over the full regime of RF performance criteria.

NEN Waveform Compatibility Testing

The NEN waveform is used for controlling the space vehicle in a full duplex data link. This link performance is critical to the command, status and control of the vehicle. This testing will validate the radios uplink and downlink performance over a wide range of tests. In lab testing will focus on characterizing the physical RF waveform performance using statistics such as Bit Error Rate (BER) over the perceived Doppler and amplitude variation that is expected on orbit.

NEN Physical Layer Testing

The test configuration consists of integrating the Vulcan radio with a simulated ground station and hardware to emulate the physical channel. Transmitter testing consists of frequency range, programmable power levels, modulation characteristics, forward error correction, symbol rates, and virtual channels. Receiver compatibility testing consists of a range of tests that include maximum and minimum input powers, diverse Doppler variations to emulate satellite motion impairments during acquisition and tracking, modulation quality, data formatting, protocol formatting, and the specifics of the Command Link Transmission Unit (CLTU).

SN TDRSS-MA Return Waveform Compatibility Testing

The SN waveform is a Direct Sequence Spread Spectrum (DSSS) waveform. The information rate supported for the return link is determined by the link budget margin and is expected to be in the 1 Kbps to 20 Kbps range. The TDRSS-MA return link is spread over a 3 MHz chipping rate and the TDRSS-MA satellite system has a 6 MHz bandwidth. Testing of this link will mirror the testing of the NEN waveform with the exception that the TDRSS-MA waveform has a spreading factor.

SN Physical Layer Testing

The SN test configuration, like NEN, also consists of integrating the Vulcan radio with a simulated ground station and a physical channel emulator. A test suite is performed that is similar to the tests done with NEN but modified for the SN waveform.

Space Environment Testing

The environmental testing campaigns differ between each mission. This is due to the fact that the missions are typically performing analysis at the spacecraft level before proceeding directly to testing, skipping the individual components except for those that are a major concern. A majority of the components in use, such as the Vulcan Radio, either have flight heritage or have undergone a component level campaign in the past that is being leveraged. Each mission will be tailoring the examples provided to align with mission requirements, cost, schedule, and risk posture.

Ground Support Equipment

The ground support equipment (GSE) is composed of four major components. These include the mission operations center (MOC), GSE rack, harness, and spacecraft as seen in Figure 1. The GSE Rack provides all the necessary equipment including servers and the Q-Radio SDR necessary to communicate with the spacecraft. The harness includes a coupler to enable duplex support while the attenuators are used to correct the power level. The spacecraft itself contains the Vulcan Radio, a command and data handling (C&DH) on-board computer, and the instrument payloads.

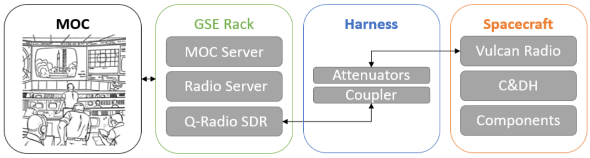

Figure 1 - Ground Support Equipment Overview

The GSE is utilized throughout the life of the mission beginning at the integration and test phase. This starts with initial component checkouts and continues until an entire comprehensive performance test (CPT) can be done at the spacecraft level. The CPT is performed before and after each major test planned to ensure no damage to the spacecraft occurred.

Vibration Testing

Following the standard "test as you fly" mentality, the vibration test typically occurs first in the environmental test campaign. This is because the vibration test emulates the forces seen on the spacecraft during its launch into space. For SmallSat missions it is typical to perform a random vibration test to levels required from the launch provider. Additional analysis is performed using these results to prove that the requirements for shock and acoustic were met.

Thermal Vacuum Testing

A typical NASA thermal vacuum or TVAC test campaign includes a hot and cold balance, survival cold soak, twelve cycles, and a bake out to be performed in a thermal vacuum chamber after final integration. A streamlined CPT is typically performed during each period, or straight line as seen in Figure 2, to ensure functionality and monitor performance through the test.

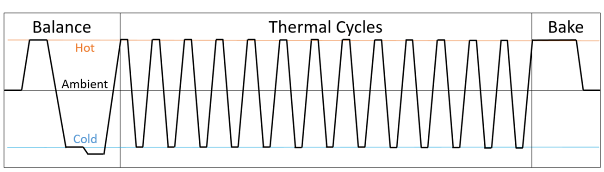

Figure 2 – Standard Thermal Vacuum Test Campaign

RADIATION EFFECTS AND ANALYSIS

The GSFC radiation effects and analysis group has assessed the radiation concerns for the NSR-SDR-S/S communication system, taking a tailored approach to radiation hardness assurance (RHA). The parts list will be reviewed and analyzed for Total Ionizing Dose (TID) impacts, which may determine parts selection criteria, second is the Single Event Effects (SEE) which can impact the temporal operation and reliability of the NSR-SDR-S/S. In certain device types like opto-electronics, the additional impact, if any, through Total Non-Ionizing Dose (TNID) was also addressed. Radiation effects in general are highly dependent on device process parameters, the application and bias of a device, and the intended natural space radiation environment that they are going to. Two different orbits varied only by inclination can have entirely different radiation requirements for mission success.

Wear-out like effects: TID Effects are concerned with the buildup of charge within the semiconductor at interfaces and within device oxides or passivation layers. This process dependence can lead to a lot of variation to radiation response for a given part type. Charge buildup in these structures have negative effects to the performance of the device, and therefore the design. As charge builds up semiconductor parametrics become degraded causing higher bias current leakage, gain degradation, and overall degradation of the integrated circuits. In most modern CMOS, oxides have become thin and have high yield allowing for better radiation performance than those with thicker oxides, beware field oxides and isolation oxides. In linear devices the threat remains prevalent and dose rate can show a sensitivity not seen in accelerated ground-based testing. TNID, adversely impacts the semiconductor lattice, and has a similar wear-out or early degradation signature as well as device, application.

Instantaneous and Random effects: Single Event Effects are caused by a single high energy particles which deposits charge into susceptible semiconductor structures, these are referred to as sensitive volumes or locations that have the ability to upset the nominal operation of a device. Energetic particles can cause data faults (single event upsets (SEU), multi-bit upsets (MBU), single event transients (SET)), functional faults (single event functional interrupts (SEFI)) and in some cases destructive effects (single event gate rupture (SEGR), single event burnout (SEB), or single event latchup (SEL)). The metric used in order to compare device characterization (cross-section) to energetic particles in the environment is called the linear energy transfer (LET), which is the charge deposited per unit path length in a given material.

The principles and practices of RHA, take into account the instantaneous and the deleterious effects that degrade performance, weighing what mitigations or trades are necessary for a given design in a given environment. Shown below are the two most influential environment models for parts impact during nominal operation, the dose-depth curve (showing dose behind a given amount of shielding for solar particles and trapped particles) and the spectra of energetic particles that contribute to the SEE (GCR, Solar protons, trapped particles). These values were calculated using the modeling suite within Spenvis. Figures 3&4 show the representative missions radiation analysis.

LEO Environment

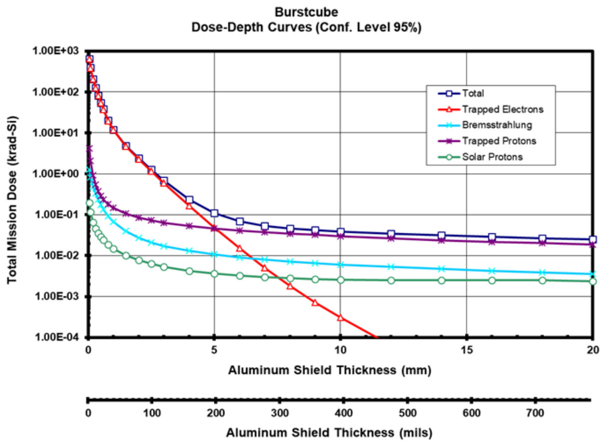

Figure 3: Representative missions Radiation Analysis

MEO Environment

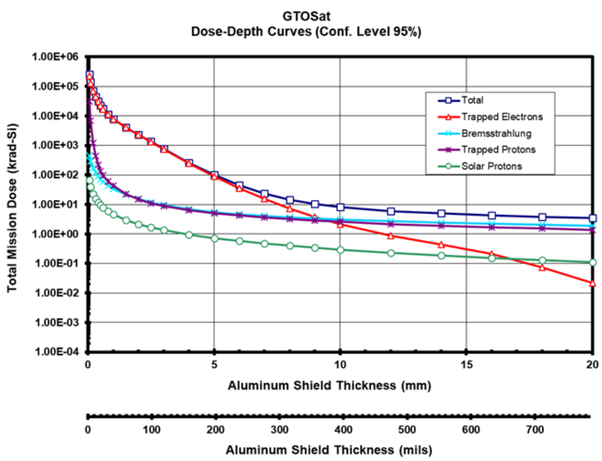

Figure 4: Representative missions Radiation Analysis

RADIATION TESTING

Candidates and rationale for testing

Based on the radiation hazard for the given environments, selective testing of components is being pursued in order to verify the design's robustness and to identify any impact to availability or reliability for operational considerations. Where possible, applicable or representative data have been leveraged to make worst case assumptions for radiation impact to system functionality. For any given part or device where there were truly unknown radiation characterizations, and therefore an unknown consequence criteria, testing is suggested and is driven by the physical mechanisms and possible outcomes.

Heavy Ion Beam Testing

Radiation testing comes with its own challenges of measurement and preparation. SEE testing is done at facilities that are able to accelerate charged particles and bombard the devices under test. The ions that are accelerated at radiation test facilities can be varied in species, energy, and flux/fluence. It is important to test devices over a range of all of these variables in order to characterize over a wide range of LET, so that the data may be used to predict on-orbit rates of upset. In some instances where parts are being screened for a particular consequence rather than a likelihood, knowing the onset threshold of an energetic particle's LET to cause that effect is valued information. This may help to determine if a particular outcome will be "rare" on a given mission.

RF Link Analysis

The coverage and Loading Analysis studied the link budgets for the mission profiles. There are two communications modes that individually be analyzed. The first mode is the NEN mode and second is the SN mode. There are standard tools used that input the appropriate technical parameters such as waveform characteristics, forward error correction, data rate, transmitter power, antenna gain and receiver sensitivity.

Table 2 - Vulcan/NEN WG1 S-Band Link Margin Summary at S/C LEO Altitude of 400km

Links	Rate (Mbps)	S/C EIRP or G/T (Note 3)	Margin @ Viterbi Decoder (Note 1 & 2)	Margin @ BER=10^{-5} (Note 1 & 2)
S-band Uplink via 11.3-m WG1	--	-21.1 dB/K	--	63.3 dB
	--		--	54.2 dB
	--		--	48.2 dB
S-band Downlink via 11.3-m WG1	0.830	13.0 dBW (4 Watts TX)	29.7 dB	31.5 dB
	1.660		26.7 dB	28.5 dB
	3.320		--	22.3 dB
	0.830	7 dBW (1 Watt TX)	23.7 dB	25.5 dB
	1.660		20.7 dB	22.5 dB
	3.320		--	16.3 dB

Notes:

1. Margin is relative to required BER for each scenario and does NOT include any required performance margin

2. For the S-band uplink, the margin was calculated BER of 10-5 for Uncoded. For the S-band downlink with Rate ½ Conv. & RS coding, the NEN can perform RS decoding; however, the NEN requires a BER of 10-

5 at Viterbi decoder, which will produce a BER much better than 10-5 at RS decoder. For the S-band downlink with RS coding, the link margin was calculated BER of 10-5 at the output of the RS decoder.
3. The S/C Minimum Required EIRP or G/T listed includes pointing loss, if applicable.

Table 3 - Vulcan/SN S-Band MA Link Margin Summary at S/C LEO Altitude of 400km

Links	Rate	S/C EIRP or G/T (Note 3)	Margin @ Viterbi Decoder (Note 1 & 2)	Margin @ BER=10^{-5} (Note 1 & 2)
MAF (1st Gen.)	0.977 ksps	-21.1 dB/K	--	6.9 dB
	3.907 ksps		--	0.9 dB
	7.813 ksps		--	-2.1 dB
MAR (1st Gen.) DG1 Mode 2 Noncoherent	0.810 kbps	13.0 dBW (4W TX)	11.4 dB	13.2 dB
	3.242 kbps		5.4 dB	7.2 dB
	6.485 kbps		2.4 dB	4.2 dB

Notes:
1. Margin is relative to required BER for each scenario and does NOT include any required performance margin.
2. For MA forward link, the link margin is related to BER of 10^{-5} for Uncoded. For rate ½ and RS MA return, the link margin is related to BER of 10^{-5} @ Viterbi decoder. The SNG or MOC can perform RS decoding; however, SN requires 10^{-5} at Viterbi decoder, which will produce a BER much better than 10^{-5} at RS decoder.
3. The S/C Minimum Required EIRP or G/T listed includes pointing loss, if applicable.
Per SNUG, the minimum channel data rate for MAR DG1 Mode 2 is 1 kbps. The SN is not guaranteed the support performance for this mode.

The coverage and Loading Analysis studied the link budgets for the mission profiles. There are two communications modes that individually be analyzed. The first mode is the NEN mode and second is the SN mode. There are standard tools used that input the appropriate technical parameters such as waveform characteristics, forward error correction, data rate, transmitter power, antenna gain and receiver sensitivity. Table 2 shows Vulcan/NEN WG1 S-band Link Margin Summary at S/C LEO Altitude of 400 km. Table 3 presents Vulcan/SN S-band MA Link Margin Summary at S/C LEO Altitude of 400 km.

SUMMARY AND CONCLUSION

Vulcan Wireless Inc. and NASA NASA Goddard Space Flight Center (GSFC) are collaborating in testing the Vulcan Wireless' NSR-SDR-S/S software defined radio for compatibility and operation with NEN and SN. Two waveform modes have been tested for network compatibility to the NASA NEN and the SN standards. This radio is designed to support direct communications with the NASA Near Earth Network ground terminals. High speed data can be transmitted during a 10 minute pass over a tracking ground aperture. Data rates are as high as 4Mbps for different coding and modulation schemes and maintain the spectral mask required by the ITU. A wide range of data rates are available ranging from 1Kbps to 4Mbps. The second mode of operation is the Space Networks Tracking and Data Relay Satellite's multiple access data link (TDRS-MA). This capability will allow for missions that require real time access to the ground system through the TDRS-MA geosynchronous data network. Having both waveforms integrated into one radio provide a major advantage for Size, Weight and Power for small satellite applications. Further the antenna system is also capable of supporting both frequency bands thus only one antenna is required for both waveforms.

Radiation analysis and testing is in progress to ensure NSR-SDR-S/S meets radiation hardness assurance for on-orbit operation. The parts list is being reviewed and analyzed for Total Ionizing Dose (TID) impacts. Also, various tests are planned to test Single Event Effects (SEE) like SEU, MBU, SET, SEGR, SEB, and SEL.

The environmental testing campaigns for the radios vary between each mission. The environmental testing being done for the NSR-SDR-S/S includes the thermal vacuum (TVAC) and the vibration test.

Successful testing of the NSR-SDR-S/S software defined radio will pave the way for the next generation NEN and SN compatible communication systems to address the current and future LEO, GTO, L1/L2, Lunar and Planetary missions.

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