S-Band Low Earth Orbit Reconfigurable Small Satellite System for Space Environment Sensing

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***Abstract*—The applications of additive manufacturing (AM) techniques have rapidly increased in industry sectors in recent years. In combination with the ever-increasing number of new constellations of communications satellites in Low-Earth Orbit (LEO), the innovative technology presents promising qualities for space industry applications, particularly for radio frequency (RF) systems. This paper presents a S-band telemetry and data backup system for space radiation experiments for LEO to analyze the effects of long-term exposure of materials to the harsh space environment. The design presented in this paper is based on Commercial Off-The-Shelf (COTS) components, presenting approximately an average and peak power consumption of 0.8 W, and 1 W, respectively, while transmitting the peak configurable RF output power of 20 dBm. Including an AM radiation shielding, the system can be accommodated in 76 mm x 76 mm x 46 mm. Its modular design makes this system fully configurable, allowing a wide variety of applications. In this work, all the on-board measurements are backed up on an on-board memory card with error correction capabilities, as well as downlinked, enabling the possibility to monitor the total absorbed radiation during the experiment, as well as the communications link impact of the degradation of the on-board RF materials and circuit components. The system can be commanded while in orbit to reconfigure on-board sensor measurements and transceiver parameters.**

***Index Terms*—COTS, LEO, S-Band, Space Radiation**

I. Introduction

The production of nanosatellites intended for LEO has been increasing at a fast pace, and with them, the analysis of new materials to improve their capabilities at an affordable cost. Additive manufacturing (AM) techniques has been explored for a wide range of applications that benefits the space industry, thanks to their specifications, such as the ability to obtain conformal designs that traditional manufacturing cannot achieve. One of the main areas of interest and focus is the RF applications. AM is presenting alternatives to the development of complex systems in a more affordable and low time-consuming manner, enabling innovative systems opportunities [1][2]. The characteristics of the required materials need to be analyzed in the space environment for suitable periods of time, like it has been done in the past with other spacecraft components. The Komplast materials experiment (12 years) and the Long Duration Exposure Facility (LDEF) mission (5.7 years) are examples of long-duration analysis of LEO effects on samples for spacecraft materials and components [3].

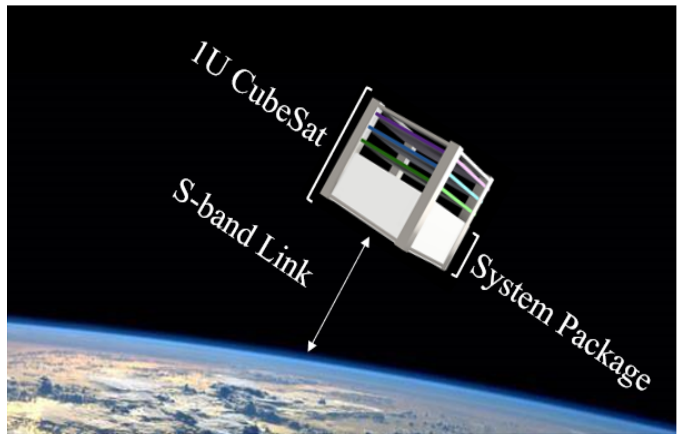

Fig. 1. Application example illustration of S-Band telemetry and backup system on-board a 1U CubeSat, being exposed to space environment effects.

Short-term experiments are conducted nowadays in programs such as the Materials International Space Station Experiments (MISSE), with a total material exposure from 6 months to 1 year. These experiments are externally mounted on the International Space Station (ISS) on platforms where they are exposed to the space environment and retrieved for future analysis [4]. The system presented in this paper is designed to analyze space environment impacts on RF systems and 3D printed radiation shielding. The modular design of the system presents configurability capabilities to be adapted to any application with reduced space and S-band low data transmission requirements. In this case, it is focused on the analysis of the impact of the system degradation. The data generated by the on-board sensors is downlinked as well as stored on-board, enabling the analysis of the communications link impact of the degradation of the materials while the experiment is in orbit. The system includes an AM radiation shielding, which properties are studied as well. A 3D model of one of its applications is presented in Fig. 1.

This paper is divided as follows. Section II presents the main components and specifications of the designed system. Section III presents the design and manufacturing of a prototype of the system. Performance testing and results are depicted in Section IV. Concluding remarks and future work are provided in Section V.

II. System Characteristics

The system presented in this paper consists of a reconfigurable modular radio based on COTS components, for in orbit sensing and communications. The main modules of the system are the transceiver module, the microcontroller, the data backup module, the on-board sensors, and the radiation shielding. A RF port and a power and control port are included for external connections to the antenna for data transmission and reception, and power supply and grounding purposes, respectively. The antenna and any additional RF conditioning to improve the link capabilities are not discussed in this design.

A. Application Considerations

This subsection includes details on the link budget and system dimensions for the small satellites missions or LEO experiments. To ensure a link margin of 6 dB -receiver sensitivity of -135 dBm-, a RF output power requirement of 17 dBm is computed by simulations performed with AGI Systems Tool Kit (STK) as presented in Fig. 2, with the following parameters: (1) transmitter antenna gain of 8 dB, (2) maximum distance from spacecraft to Ground Station (GS) of 900 km and (3) 35.4 dBi GS S-band antenna (see Fig. 3). A maximum size of 89 mm x 89 mm x 50 mm is considered for the entire system, considering its accommodation in small carriers.

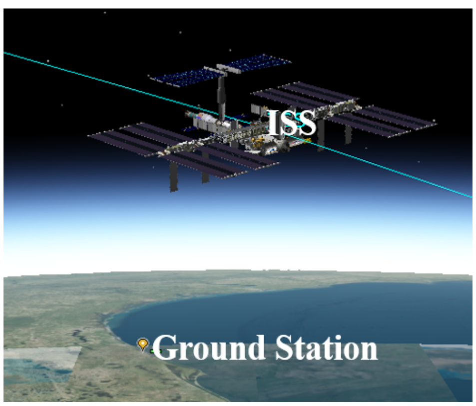

Fig. 2. STK Simulation Environment - Ground station pass of ISS.

Fig. 3. ERAU Facility - S-band ground station.

B. Transceiver and Microcontroller

The design includes a Radiocraft RC2500HP-RC232 2.4-2.483 GHz transceiver module, which combines the Texas Instruments chips CC2510 as the main transceiver and CC2591 as the range extender. The transceiver is a low-power module that has been previously considered for communications systems for small satellite platforms [5][6]. The microcontroller selected is based on the ATmega4809 processor. Conventional nanosatellites have used ATmega models in their on-board subsystems, a low-cost alternative for education and research purposes. The main parameters of the selected components are presented in Table I and II.

TABLE I
RC2500HP-RC232 MAIN PARAMETERS

Parameter	**Values**	
	Minimum	***Maximum***
RF Data Rate [kbps]	1.2	100
Output RF Power [dBm]	-10	20
Sensitivity [dBW]	-91(@100 kbps)	-108 (@1.2 kbps)
Modulations	GFSK, MSK	

TABLE II
ARDUINO NANO EVERY MAIN PARAMETERS

Parameter	**Value**
Clock Speed	20 MHz
Flash Memory, SRAM, EEPROM	48 KB, 6 KB, 256 B
Available Programmable I/O Lines	48 (1x UART, SPI, I2C)

C. Data Backup and On-Board Sensors

The degradation models of the materials are essential to analyze the impact of the space environment. Continuous monitoring of absorbed radiation can improve the accuracy of the models, but all the generated data cannot always be downlinked. The presented system can continuously save on-board measurements, providing a backup system in case of temporary downlink failure. To mitigate the data errors, an industrial-graded microSD card with Bose-Chaudhuri-Hocquenghem error correction codes engine is selected [7]. The system also includes on-board sensors to monitor its functionality -power, temperature- and for experiment purposes -absorbed radiation-. For the absorbed radiation, two ionizing radiation-sensitive metal-oxide-silicon field-effect transistors, Varadis VT02, are placed inside and outside the system's shielding [8]. The components selection is based on flight heritage and results from NASA radiation test databases [9].

D. Radiation Shielding

The system includes a 3D-printed shielding that encloses the main circuit board to protect it against the ionizing radiation found in LEO and for environment sensing and materials analysis purposes. Different materials can be used to provide protection, such as aluminum, and High-Density Polyethylene

(HDPE). When polymers are selected, the impact of the harsh space environment, due to atomic oxygen and vacuum UV among other degradation effects, shall be considered [10], since the required thickness of the material to be able to protect the electronics against external space effects is defined by the material performance against them. For the presented system, a shielding of 0.5 to 1 cm is considered, based on dimensions, LEO specifications, a mission duration of 6 months and radiation degradation levels of the selected materials and components, among other analyzed parameters.

E. Reconfigurability

The system includes several configuration options that can be accommodated to a specific application or changes in mission conditions while in orbit. The transceiver module allows for reconfiguration of power output and frequency channel parameters, as seen in Fig. 4, and RF data rate. It shares the same lines for transmission and reception, and configuration, changing between modes using a single enable line. Therefore, it can be configured with the on-board micro-controller, enabling pre-programmed or commanded in-orbit reconfiguration capabilities.

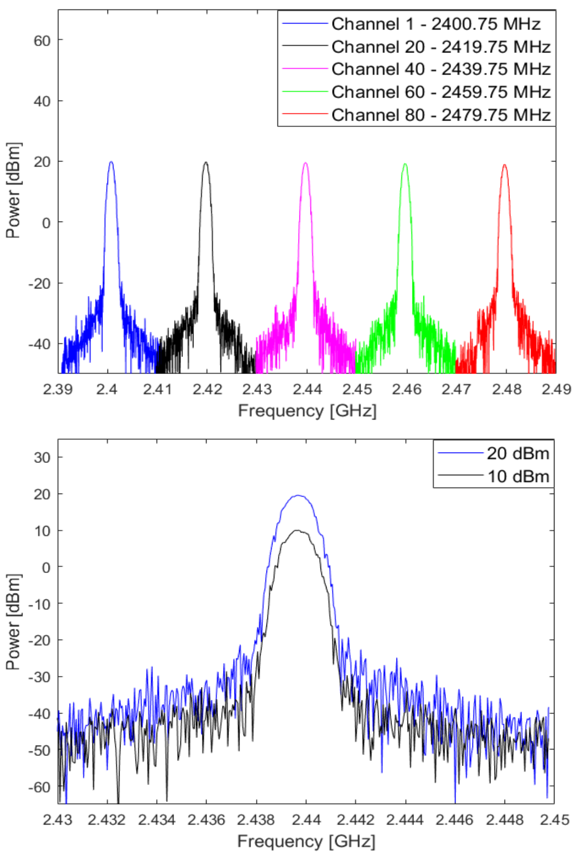

Fig. 4. (T) Signal Spectrum for different configured channels at 20 dBm, (B) Signal spectrum for channel 40 at different power output configurations.

III. Prototyping Design and Manufacturing

To test the telemetry and data backup capabilities of the system, a prototype is manufactured using laser prototyping techniques with a LPKF ProtoLaser U4. The Rogers RO4003C microwave laminate is selected for its electromagnetic, mechanical, and outgassing properties. The thicknesses of the substrate and copper cladding are 1.524 mm and 17 μm, respectively. The microcontroller and the data backup module are mounted on the top and bottom sides, respectively, as it can be seen in Fig. 5. Fig. 6 presents the board with the 3D printed package of 7 mm for radiation shielding. The total dimensions of the system are approximately 76 mm x 76 mm x 46 mm. Wider shieldings can be accommodated, depending on the level of protection required, and the space available.

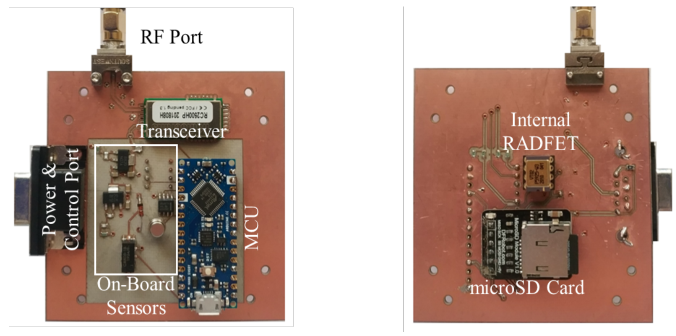

Fig. 5. Manufactured prototype PCB with RO4003C and LPKF U4.

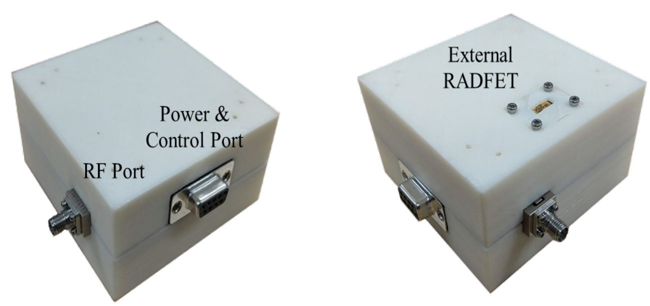

Fig. 6. Manufactured prototype with 3D printed shielding. Mounting holes are included to attach the system to the preferred carrier system.

IV. Tests and Results

To test its performance, the system is configured at 19.2 kbps of data rate and 20 dBm of output power in the 2439.75 MHz channel. For data reception purposes, a PCB with only a transceiver module and open external connections for power and data transferring purposes is manufactured using the same substrate and specifications used to manufacture the system board. During the tests, the two modules are located at approximately 650 m of distance from each other in line of sight (LoS), as shown in Fig. 7, and transmission tests of 10-15 minutes are performed. A power output of 19.5 dBm is measured with the system continuously transmitting data, as seen in Fig. 4. The total percentage of packet losses in those tests is less than 0.05%, successfully maintaining an expected data throughput of 6 kbps, based on the delay between packet transmissions and the number of bytes per packet, as presented in Fig. 8. With this setup, the system is reset to simulate the carrier powering on the system only during specific GS accesses. The data backup system is able to save all the generated data packets on different files with the correct identification and timestamp. The data backup system presents capabilities to keep track of the ground station passes and time for future data analysis based on GS passes. Additional Real-Time Clock (RTC) capabilities can be added as well, if required.

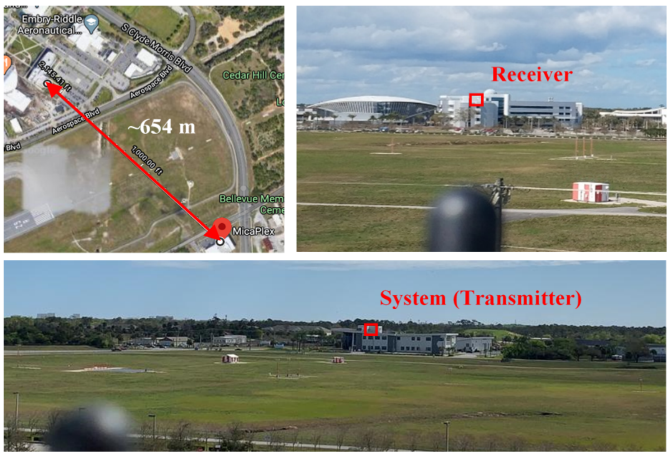

Fig. 7. Communications tests setup: rooftop of two buildings from Embry-Riddle Aeronautical University at approximately 650 meter of distance.

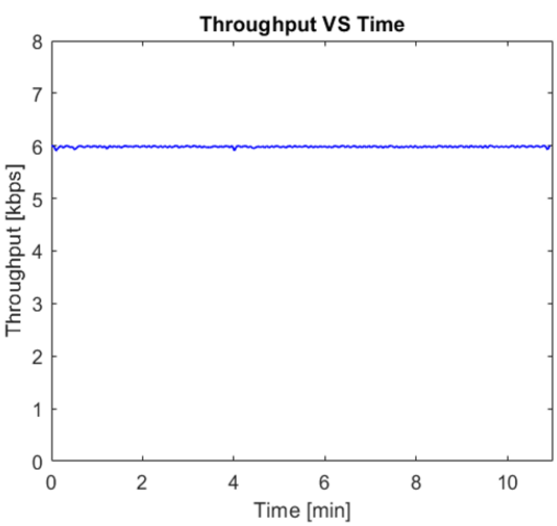

Fig. 8. Communications test results sample: constant/continuous data throughput of 6 kbps for a total transmission time of 11 minutes.

V. Conclusions and Future Work

The design, manufacturing, and testing for a S-band LEO reconfigurable small satellite system prototype for space environment sensing is presented. The low-cost modular design provides a maximum RF power output of 19.84 dBm at 2400.75 MHz and a configurable data rate of up to 100 kbps with a maximum power consumption of 1 W. The system is able to back up all the generated on-board data with GS accesses and time tracking possibilities. The tests performed to date present that the system is compliant with the requirements to be included as an active experiment as part of LEO Space Stations, such as the MISSE experiment. Future work is focused on reducing the overall dimensions, adding capabilities to connect external sensing modules of interest, and radiation testing. The electronics could be embedded/encapsulated using only additive manufacturing techniques. This would present a series of advantages: among others, the space for redundant COTS components to improve the success rate of the experiment, and the capability of in-space manufacturing of the whole system to easily duplicate it and repair it in space.

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