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Development of a Modular Half-Duplex Frequency-Agile X-Band Transceiver for CubeSats and Robotic Spacecraft

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Abstract

The EPFL Spacecraft Team (EST) is working on the CHESS mission, which aims to launch a constellation of two CubeSats in 2025. These CubeSats will study the chemical composition of Earth's exosphere using time-of-flight mass spectrometry. To downlink the collected scientific data, the satellites will utilise a custom X-band transceiver operating in the amateur frequency range of 10.45 to 10.50 GHz, which is presented in this paper. The proposed transceiver architecture employs software-defined radio (SDR) technology and can be easily adapted for different use cases. This modular approach has the potential to be suitable for future spacecraft missions, such as active debris removal or lifetime extension services, where flexible communication systems are required.

1. Introduction

The EPFL Spacecraft Team (EST) is a student team developing two 3U CubeSats for the CHESS (constellation of high-energy Swiss satellites) mission aiming to research Earth's exosphere using time-of-flight mass spectrometry with high-grade scientific instruments contributed by the University of Bern and ETH Zurich. The team consists of around 50 Bachelor's and Master's students, supported by various laboratories of EPFL and other Swiss academic institutions. Throughout the various developments and projects at EST, students are engaged in the full lifecycle of space projects, enabled by rapid prototyping and iterative design procedures, as was demonstrated with the launch of the *Bunny* onboard computer in January 2023, a payload that was developed, assembled, integrated, and tested within a record timeframe of less than half a year.

Given the success of *Bunny* in both educational and technical domains, the EPFL Spacecraft Team is focusing on developing and qualifying the next subsystem for the final CHESS mission through in-orbit demonstration/validation (IOD/IOV). An X-band transceiver has been identified for this purpose, enabling the CHESS CubeSats to downlink the scientific data from their instruments at a higher rate than would be possible using a VHF/UHF system.

1.1 Amateur CubeSat Communication Systems

CubeSat communication systems typically operate in the VHF, UHF, S, X, and Ka bands. The VHF and UHF frequency bands are the most mature for satellite communications and operations in terms of available technology and infrastructure, hence their widely adopted use; however, the data rates remain comparatively low. There has always been a need to increase the data rates of telecommunication systems, which implies higher frequencies and higher bandwidths, with the S, X, and Ka bands being well-suited for high data-rate communications.[9] Specifically for CubeSat RF systems, software-defined radio (SDR) technology is particularly suited, as the required ICs can be procured with short lead times at affordable prices. Furthermore, the main bands of interest (i.e. VHF/UHF/S) are typically covered by standard commercial off-the-shelf (COTS) components.

Amateur radio operations are allowed in the frequency range of 10.00 to 10.50 GHz by the International Telecommunication Union (ITU); in particular, the band from 10.45 to 10.50 GHz is allocated to amateur satellite operations.[6,7]

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Leveraging the amateur satellite spectrum as opposed to frequency ranges attributed to commercial services leads to a significant simplification in the frequency coordination process with other parties. For this particular reason, the team is developing its own transceiver precisely targeted for that frequency range, as no viable commercial solutions are yet available to meet this requirement. Nevertheless, the use of amateur bands for a particular mission must be authorised by the national regulatory agency responsible for radio amateur operations in the satellite's country of origin and the ITU. The use of amateur bands is limited to projects without pecuniary interests and to purely educational and/or scientific purposes.

1.2 Robotic Spacecraft Communication Systems

The trend to move towards software-defined radio (SDR) based communication solutions can also be observed in bigger spacecraft. Companies like Honeywell,[5] Syrlinks, TESAT, GOMSpace and Kongsberg are developing or already offering SDR-based solutions that provide more flexibility in terms of frequency, data rate, and modulation. Most spacecraft applications will benefit from the lower cost and flexibility that these solutions provide; however, it is especially robotic spacecraft designs, for example, in In-Orbit-Servicing (IOS) or Active Debris Removal (ADR) missions, where these advantages are especially important.

One of the main constraints of these missions lies in the fact that the ITU frequency filing process is not very well suited for spacecraft that change their orbit multiple times over their mission lifetime. The orbits where a client or debris object resides, might not even be known at the time of the frequency coordination. This causes the frequency filing to be more complicated than it needs to be and the coordination with ITU member states and other systems to be more tedious. While dedicated spectrum could be a potential solution, it is not achievable in the near-term future. Instead, frequency-agile and modular SDR-based transceivers can help to overcome the operational limitations that one might have to set when coordinating spectrum for an IOS or ADR mission.

The most important frequency bands for IOS/ADR missions that could be covered by a modular SDR-based front-end, like those presented in this paper, are S-band for TMTC, C-band for TMTC and image/instrument data and X-band for image/instrument data. While the IOS/ADR market and its enabling technology are still in its infancy, companies like ClearSpace, Astroscale, and others are already organizing in the Consortium for Execution of Rendezvous and Servicing Operations (CONFERS).[3] CONFERS aims to standardise how rendezvous and servicing operations are performed globally and propose frequency bands and telecommunication solutions for these types of missions.

2. Transceiver Architecture

The proposed transceiver architecture comprises three main components, separated into distinct development boards for the prototyping approach, which are presented below and illustrated in figure 1. Nevertheless, the focus of the final design lies in merging these subsystems into a single custom-developed PCB.

- An Analog Devices AD9364 **RF agile transceiver** is the central component of the system, implementing the main functionalities of a software-defined radio in a single integrated circuit (IC) and therefore linking analogue and digital signal paths.
- A **custom superheterodyne stage** called *Radio Jerry* is used to mix, amplify, and filter the input/output of the SDR transceiver to the targeted frequency range of 10.475 GHz for the radio amateur satellite band.
- A **ZedBoard development kit** based on an AMD Xilinx system on a chip (SoC) is used to implement the required digital signal processing (DSP) routines and interface the transceiver with a host system.

2.1 Radiofrequency Architecture

A superheterodyne architecture generally consists of one or two mixing stages that are fed into an analogue-to-digital converter (ADC) for reception and a digital-to-analogue converter (DAC) for transmission.[4] For the proposed architecture herein, the SDR transceiver internally generates an output signal at a frequency of 2.435 GHz on the transmission side. This intermediate frequency (IF) signal is then mixed with an 8.040 GHz local oscillator (LO) to obtain the desired 10.475 GHz output radiofrequency (RF) signal. Following the signal path after the mixer, the RF signal is filtered and amplified with a gain stage and a subsequent power amplifier. Given these amplification stages, a maximum transmission power of 1.5 W $\approx$ 32 dBm is to be expected. The receiver side represents the inverse of the transmission side: The signal is filtered, amplified and mixed with an 8.040 GHz LO to obtain the same 2.435 GHz IF, which is fed into the SDR component, where the baseband signal is extracted and processed digitally. The key requirements of the superheterodyne architecture are summarised in table 1.

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The presented architecture is a half-duplex transceiver; the transmission (TX) and reception (RX) chains are switched via a single-pole double-throw RF switch to the antenna. For testing purposes, *Radio Jerry* has two separate voltage-controlled oscillators (VCO), which are individually fed into the TX and RX mixers, with the goal of reducing this to a single frequency reference for the next development iteration. Figure 2 summarises the laid-out RF front-end, including the central SDR.

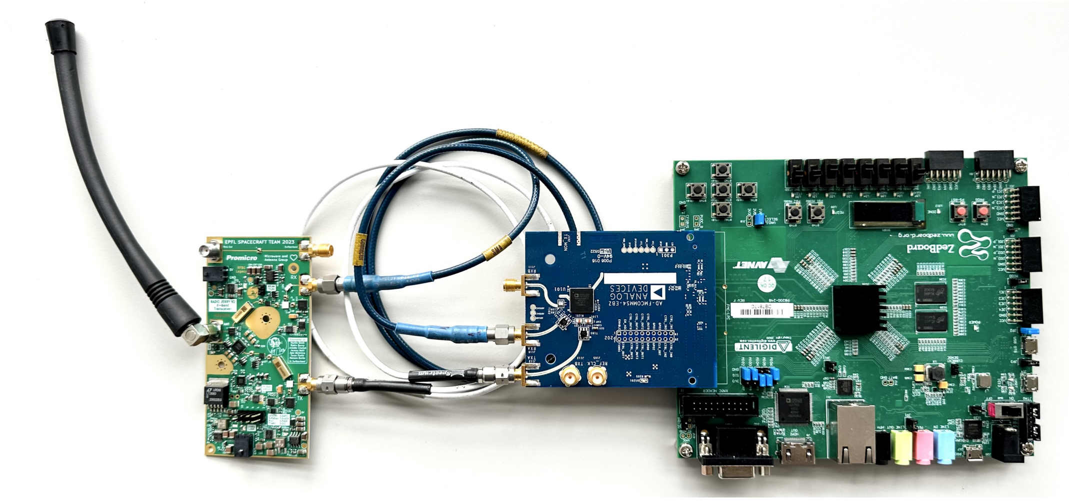

Figure 1: Transceiver architecture development/testing setup

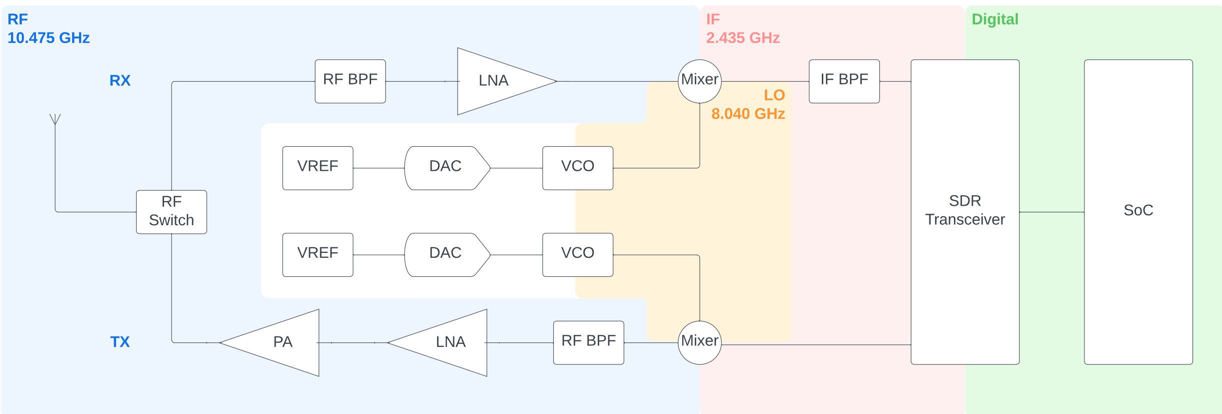

Figure 2: Block diagram of the transceiver architecture

Table 1: Radiofrequency design requirements

Requirement	**Value**
Centre frequency	10.475 GHz
Tuneable range	10.450 – 10.500 GHz
Bandwidth	50 MHz
Intermediate frequency (IF)	2.435 GHz
Local oscillator (LO) frequency	8.040 GHz
Receiver noise figure	1.8 dB
Transmit power	32 dBm
Total power consumption	12 W

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2.2 Software Architecture

The development of the software for the transceiver requires first a selection of a modulation scheme. Indeed, many options are available which do not imply the same implementation complexity, as the SDR-based architecture offers a large degree of flexibility in terms of modulation and coding schemes. For the first iteration of the software, it has been decided to employ quadrature phase shift keying (QPSK), as it has been widely used for space communications and has shown successful usage for such types of communication. Moreover, the channel attenuation is large when transmitting over several hundred kilometres; thus, a trade-off has been made to make use of convolutional encoding to increase the system's robustness as proposed by prior work.[8] Nevertheless, these design choices are to be re-evaluated by the performance of the design in integrated tests, especially with regard to filtering requirements and frequency stability.

Encoding at transmission implies decoding at reception, and finally, some corrections are required to compensate for the channel effect on the signal and possible impairments introduced by the receiver. These corrections are, for instance, to compensate carrier frequency offset and to synchronise the received symbols. To estimate these corrections, some preamble bits are concatenated to the encoded and scrambled data bits, sent, and used for correction estimation at reception.

3. Development Approach

The conception of the transceiver is performed through an iterative approach, meaning that it is preferable to move from theoretical developments to physical prototypes within short timeframes, followed by testing and implementation of identified necessary improvements in a subsequent hardware iteration. Given the current status of the project, hardware development only applies to the *Radio Jerry* superheterodyne stage, as this is the sole component that had to be developed from the ground up. This layout previously shown in figure 1 corresponds to an elegant breadboard (EB) model and, therefore, to a technology readiness level (TRL) of 4. Integration of the SDR transceiver and SoC onto custom PCBs will follow as soon as the design of the superheterodyne stage has been thoroughly validated, leading to an engineering model (EM) at TRL 5. Subsequently, a qualification model (QM) at TRL 6 that can undergo the complete suite of environmental testing is to be designed.

Hereafter follow some further insights into the two hardware iterations of Radio Jerry that have been manufactured so far at TRL 4. The two prototypes are shown in figures 3 and 4, respectively.

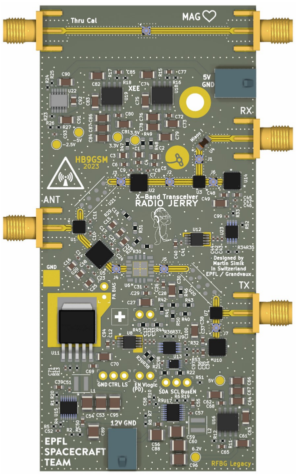

Figure 3: Radio Jerry V1

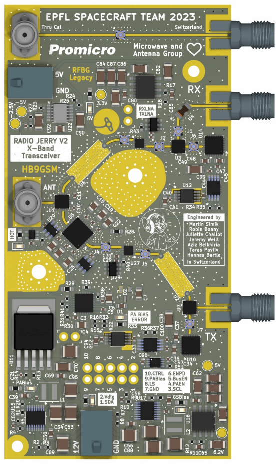

Figure 4: Radio Jerry V2

3.1 First Prototype

The first hardware iteration of *Radio Jerry* represents a proof-of-concept, with the components placed on the PCB to meet impedance and size requirements. Some problems were identified, especially at the end launch SMA connectors and within the power amplifier biasing stability. Most of the board space on the PCB is taken up by the low-noise power supplies that are required for the proper operation of the RF components. Neither thermal nor other environmental constraints were considered at this stage.

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3.2 Second Prototype

Radio Jerry V2 is the second iteration of the X-band superheterodyne stage. The problematic SMA connectors of the previous iteration were replaced with properly matched transmission lines. A closed-loop power amplifier biasing circuit is added to ease the operations and stability of the circuit. Thermal constraints were taken into account and arrangements were made for a 3 mm thick copper slab to be soldered beneath the power amplifier using a low-temperature solder for adequate power dissipation. To conduct the heat from the power amplifier through the PCB to the copper heatsink, the number of buried vias was increased without interfering with the soldering of the IC itself. Furthermore, two digital temperature sensor ICs were added in close proximity to the power amplifier to monitor and turn off the circuit if acceptable temperature ranges are exceeded.

4. Management Aspects

The design of the presented X-band transceiver architecture was accomplished by a small team of Master's students at EPFL with different technical backgrounds, working on this project alongside their student obligations. Given the nature of such a team, a projection of precise project planning schedules is difficult; nevertheless, some important past milestones are presented in table 2, alongside estimates for future developments. The lead times in the procurement of components, especially RF ICs, had a significant influence on the iterative prototyping approach, in some cases requiring adaptations in the design to accommodate the availability of hardware. Furthermore, knowledge transfer remains an ongoing challenge, as some students may not remain members of the team throughout the full project lifecycle. In this particular case, the core members will remain involved with the development of the transceiver, even after their graduation, with the goal of avoiding premature knowledge loss and seeing this component on its way to space.

Table 2: Past and future project milestones

Milestone	**Timeframe**
Development start	October 2022
Main component selection and procurement	November – December 2022
Radio Jerry V1 development	January 2023
Radio Jerry V1 procurement and assembly	February 2023
Radio Jerry V2 development, software development	March – May 2023
Radio Jerry V2 procurement and assembly	June 2023
EM design and development	Q3 2023
EM functional testing and QM development	Q4 2023
Environmental testing campaign, flight model assembly	Q1 2024
Launch	Q3 2024

5. Outlook

Given that the development of the presented transceiver is focusing purely on commercial off-the-shelf (COTS) components, as opposed to radiation-hardened devices, it may pose some challenges when adapting the final design to the constraints of the space environment. Nevertheless, prior research has been performed on SDR solutions employing a transceiver of the same family as the AD9364 presented here, arriving at the conclusion that total ionising doses (TID) up to 25 kRad do not cause any remarkable performance deviations for this particular component.[1]

As soon as the developed transceiver architecture presents a sufficiently high technology readiness level (TRL), it is important to lay out a comprehensive testing plan for space qualification of the assembly. In addition to environmental testing procedures applicable to a hardware radio or similar components, getting an SDR-based architecture ready for the launchpad may require testing beyond the standard thermal vacuum, electromagnetic interference, and vibration testing.[2]

Nevertheless, the goal within the framework of the EPFL Spacecraft Team is to leverage lessons learned from the *Bunny* mission and perform in-orbit demonstration/validation (IOD/IOV) of the presented X-band transceiver as soon as the second half of 2024, demonstrating the team's capability to be the students' fast track to space.

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