ESA's OPS-SAT Mission: powered by GNU Radio

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Abstract

OPS-SAT is a mission by the European Space Agency that is aiming to establish an open hardware and software innovation platform in Low Earth Orbit. The purpose of this paper is to illustrate the beginnings of the OPS-SAT operational phase and how it was made possible by the GNU Radio project. A GNU Radio reference implementation published by the Flight Control Team resulted in beacon reports from Radio Amateurs shortly after satellite deployment. OPS-SAT operations were initially carried out through the dedicated stations in Ireland and Austria, which fully or partly rely on GNU Radio for the signal processing backend. The Launch and Early Operations Phase (LEOP) has been completed and platform commissioning is in progress.

1. Introduction

OPS-SAT is a mission by the European Space Agency aimed at breaking down borders that prevent innovation in the space operations domain. The 3-Unit (3U) spacecraft was launched on December 18th 2019 with an Arianespace Soyuz launcher as part of mission VS23. Many innovative experiments in the fields of smart satellite operations and on-board autonomy have been submitted and are actively being developed. OPS-SAT hosts various advanced payloads including a fine Attitude Determination and Control System (ADCS), High-Definition camera, optical receiver and a Software Defined Radio that experimenters can interact with in order to fulfill various scientific goals within their experiments. These can be used to devise experiments and test out innovative concepts within the space operations domain. Experimenters on OPS-SAT cover a wide spec-

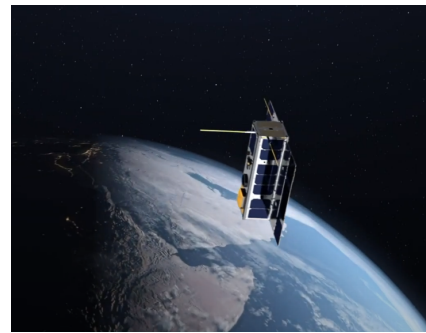trum from small start-ups to established space-players, as well as research groups from academia.

Figure 1. 3D render of OPS-SAT in orbit (ESA Medialab)

2. Reference Implementation in GNU Radio

2.1. Overview

OPS-SAT communications are carried out in the S and Ultra-High Frequency (UHF) bands. Since OPS-SAT was approved to use the amateur radio spectrum, prior to launch the Flight Control Team published the specifications of the UHF downlink of OPS-SAT of which the main parameters are given by Table 1.

Table 1. OPS-SAT UHF donwlink parameters

Parameter	Value	Unit
Downlink frequency	437.2	MHz
Modulation	GMSK	/
Symbolrate	9600	Baud
Hardware	Nanocom AX100	/

The publication was done to ensure that radio amateurs were informed in a timely manner and to enable the community to experiment and develop their own applications to receive OPS-SAT. In addition to publishing the protocols in

use, a GNU Radio reference implementation was also developed and made available (Fischer & Mladenov, 2019). The published GNU Radio reference implementation consists of a receiver application, a demodulator/decoder flowgraph and a Graphical User Interface (GUI) application. The tracking software G-Predict is used to pass the absolute receive frequency to the receiver flowgraph taking into account the Doppler-shift. The receiver application passes a filtered complex baseband stream to the demodulator and decoder which in turn yields the high-level Cubesat Space Protocol (CSP) packets that are exchanged on the UHF-link. The concept is illustrated by Figure 2.
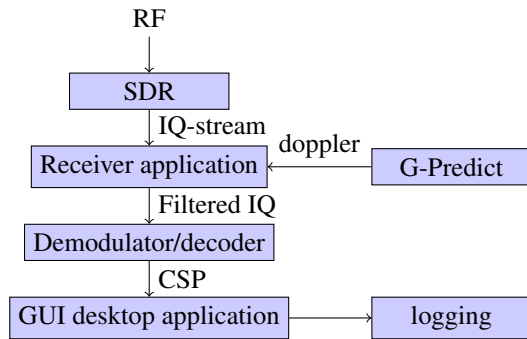

Figure 2. GNU Radio reference implementation overview

2.2. Receiver application

The receiver flowgraph carries out the essential signal conditioning steps prior to demodulation. These consist of a simple thresholding (squelch), lowpass filtering and mixing to baseband and finally downsampling. The full flowgraph is illustrated by Figure 3. The absolute receive frequency taking doppler into account is fed to the flowgraph via a block from the gr-gpredict module.

Both File and hardware IQ sources are supported. The receiver tuning is performed 40 kHz offset to the nominal frequency of 437.2 MHz. This is done to prevent degradation of the signal by DC-offsets caused by IQ imbalance that is inherent to some SDR receivers. A frequency translating Finite Impulse Response (FIR) filter with center frequency equal to the offset sampling frequency and with low pass filter taps brings the filtered signal to baseband. Afterwards the IQ stream is resampled to a fixed lower samplerate. Finally, the samples are published via a ZMQ-PUB socket to to the demodulator application.

2.3. Demodulator and Decoder

The demodulator and decoder flowgraph which is illustrated by Figure 4 receives the filtered IQ samples from the receiver flowgraph via a ZeroMQ ZMQ-SUB socket. Since the UHF downlink is frequency modulated, a quadrature demodulation block is used. To improve performance, a filter is used in the form of a Decimating FIR filter with a modulation-matched profile by using Gaussian taps. Finally, symbol recovery is performed by a Mueller and Müller Clock Recovery block configured with appropriate settings for the gain, initially estimated samples per symbol, and allowed symbolrate deviation. The produced soft symbols by the Clock Recovery block are converted to hard symbols by using a binary slicer. The AX100 UHF transceiver of OPS-SAT is configured to use mode 6, which indicates an AX.25 header is attached to the data frames and encapsulated in an High-Level Data Link Control (HDLC) frame. The core frame is a Cubesat Space Protocol (CSP) packet. The CSP standard is a lightweight routing protocol designed for use specifically on small satellites (GomSpace, 2009). The frame level structure is illustrated by Table 2. The values between brackets depict the number of bytes occupied by each field and a variable length field is indicated with 'v'.
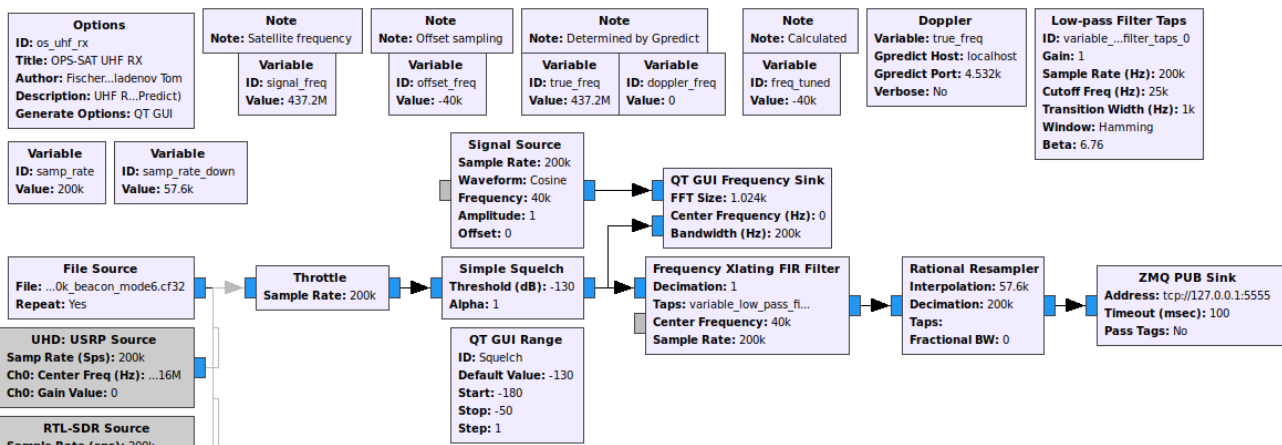

Figure 3. OPS-SAT GNU Radio receiver flowgraph consisting of downsampling, shifting to baseband and lowpass filtering
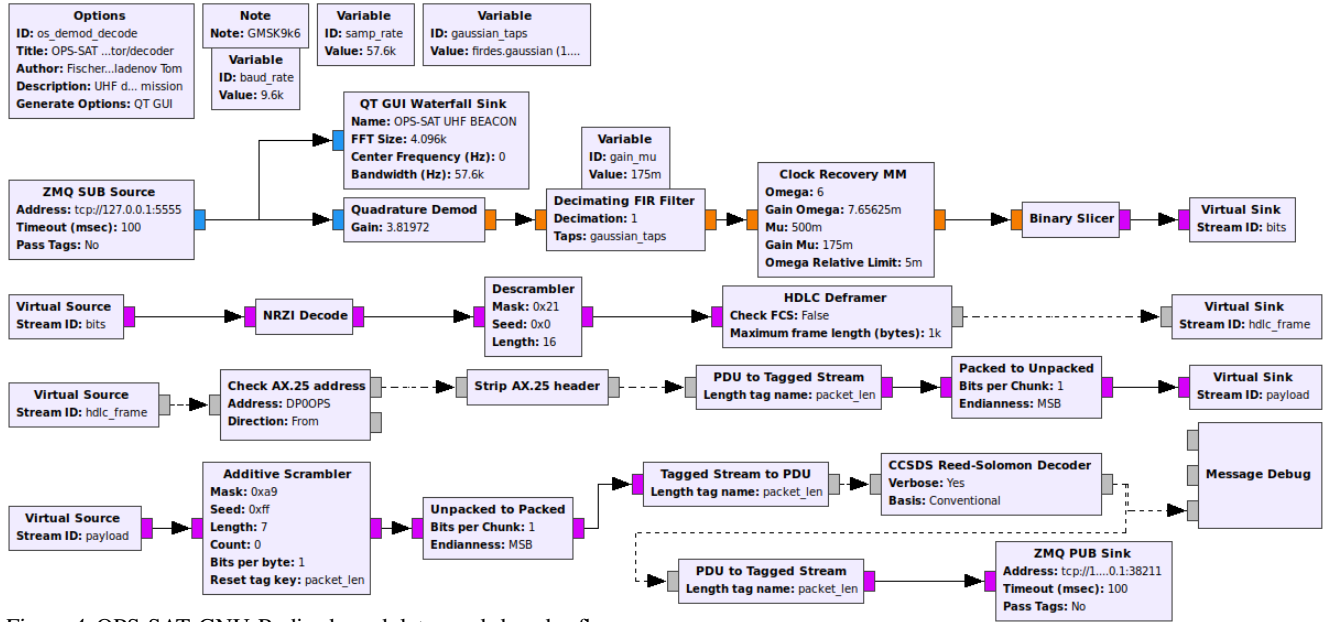
Figure 4. OPS-SAT GNU Radio demodulator and decoder flow-graph

Table 2. OPS-SAT UHF HDLC Frame Encoding

Flag (1)	AX.25 HDR (16)	CSP (v)	FCS (2)	Flag (1)

The HDLC encapsulated frames are G3RUH scrambled with the polynomial (Miller, 1996):

$$p(x) = x^{17} + x^{12} + 1 \qquad (1)$$

which yields the descrambling mask of 0x21 to be used in the GNU Radio descrambler block. The descrambled bits are then passed to an HDLC deframer which checks for the HDLC flags (0x7E) that separate subsequent AX.25 frames and outputs the frames as a standalone Protocol Data Unit (PDU). The AX.25 frame is then checked for the source address if equal to the used callsign by OPS-SAT which is DP0OPS. The AX.25 header is stripped off and converted to a PDU which represents a CSP-packet. The CSP-packets of OPS-SAT consist of a 4-byte header with routing information as well as 32 Reed Solomon error correction bytes. The CSP-payload is accompanied by a 2-byte CRC-32C checksum. The content structure of the CSP-packets are given by table 3.

Table 3. CSP Data field encoding

CSP HDR (4)	Payload (v)	CRC-32C (2)	RS (32)

The 32-bit header structure of a CSP-packet is illustrated by Table 4. The most important values are the priority field (Pri.), the source (Src.) and destination (Dest.) fields. The source and destination fields indicate from which subsystem the CSP-packet originates. OPS-SAT has various subsystems such as an Electrical Power System (EPS), solar array conditioning units, on-board computer (OBC) and UHF radio, each with a unique source (node) number which is reflected in the CSP-packet header.

Table 4. CSP Header structure

Pri.	Src.	Dest.	Dest. port	Src. port	R	Flags
(2b)	(5b)	(5b)	(6b)	(6b)	(4b)	(4b)

The CSP-packets illustrated by Table 3 are still scrambled according to the CCSDS scrambling polynomial:

$$p(x) = x^8 + x^7 + x^5 + x^3 + 1 \qquad (2)$$

Descrambling in the flowgraph is done by using an additive (synchronous) scrambler block with the initial state set to all ones and length equal number of bit shifts necessary in the 8-bit shift register which is equal to 7 (CCSDS, 2017). Finally, Reed-Solomon decoding is performed and results in the decoded CSP-packet which is sent to a secondary application via a ZeroMQ (ZMQ) socket. The used HDLC, AX.25 and CCSDS decoder blocks are part of the gr-satellites project (Estévez, 2020).

2.4. GUI Desktop Application

In order to view the data in engineering values, a desktop application in Python3/PyQt5 has been developed that receives the PDUs from the demodulator/decoder flowgraph by subscribing to a ZeroMQ PUB socket. The received byte sequences are used to instantiate high-level Python CSP objects. If the CSP-header values match the criteria for a beacon, the payload will be parsed and displayed in engineering values. A screenshot of the application is illustrated by Figure 5.
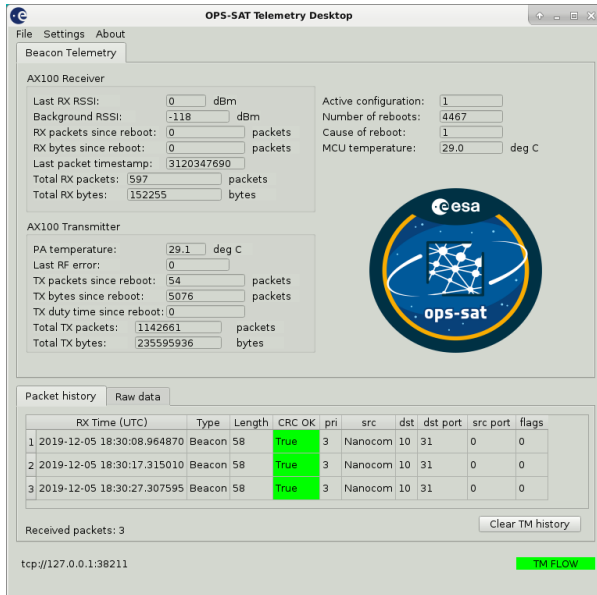

Figure 5. OPS-SAT GUI application for Radio Amateurs receiving beacons

The 4-byte CSP-header is parsed and destination/source devices as well as ports are displayed in the packet history table at the bottom of the application.

3. The OPS-SAT Ground Segment

This section briefly covers the operational ground segment in use by ESOC and highlights where GNU Radio is playing a supporting role.

3.1. ESA

The OPS-SAT ground segment consists of 2 UHF stations in Ireland and Austria as well as a dedicated S-band antenna located on the ESOC premises in Darmstadt, Germany. The station in Ireland is provided by LeafSpace and fully relies on a GNU Radio stack in combination with an SDR modem to facilitate the communications with OPS-SAT. The station in Austria is operated by the OPS-SAT main industry partner Technische Universität Graz (TUG) and is based on a hybrid approach using a USRP and GNU Radio for the downlink path and a commercial modem for the uplink path. The stations in Ireland and Austria are mainly used for spacecraft configuration and preparation, while the S-band station in Germany is used for high-rate communications and file-based operations. The OPS-SAT ground segment provides coverage from 40 degrees West to 40 degrees East, covering roughly 34 million square kilometres of sea- and landmass. A degraded link performance on UHF was confirmed by long term measurements of the UHF background noise. Significantly higher values were observed over central-Europe while contact windows over the North Atlantic often offered better performance. The long term measurements are illustrated by Figure 6.
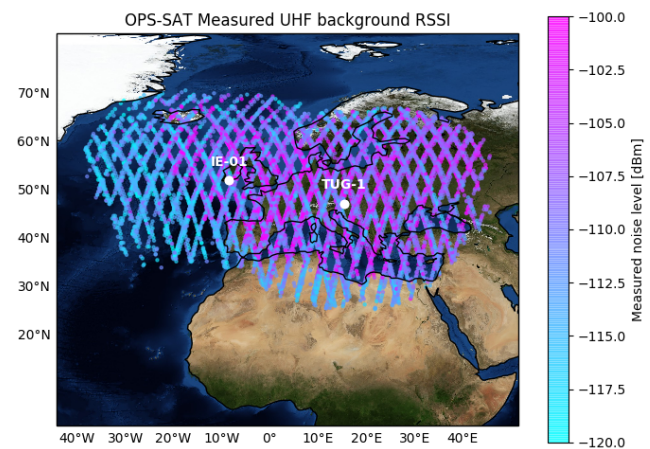

Figure 6. Geographical plot of the UHF background RSSI beacon values received through the ESA stations in Ireland and Austria. The heatmap shows a significantly increased background noise over central Europe and lower levels over the North-Atlantic and African regions.

3.2. Radio Amateur Support

The early information and outreach by the OPS-SAT team allowed also the radio amateur community to prepare for the OPS-SAT mission. As a result, OPS-SAT was entered early in the SatNOGS database with a preliminary TLE . The Satellite Network Operated Groundstations (SatNOGS) project is an open source project by Libre Space Foundation that connects amateur satellite-tracking antennas and stations worldwide in a single network (SatNOGS, 2020). This resulted in beacon reception reports shortly after the UHF transceiver of the spacecraft started transmitting. As of 21/06/2020, 454183 UHF telemetry packets have been received and forwarded to the SatNOGS database. The extra telemetry coverage has been of great importance and was in many cases useful during the LEOP as well as the commissioning phase.

4. Conclusion and Outlook

Due to a safety issue with the S-band transponder, the LEOP phase of OPS-SAT relied entirely on the UHF-link and therefore the GNU Radio based stations in Ireland and Austria were crucial to the early operations. The LEOP phase of OPS-SAT is completed and the commissioning phase is currently underway. The spacecraft is in daily contact with ESOC via S-band and UHF and several in-orbit software updates have been successfully carried out. The commissioning phase is dedicated to checking out the various advanced payloads within power, thermal and communications aspects.

5. Acknowledgements

The OPS-SAT Flight Control Team received excellent support from the radio amateur community throughout the mission as a result from the outreach that was initially done through early publishing of details, developing software and reaching out to the correct individuals.

The OPS-SAT team would also like to thank the GNU Radio project and its contributors for continued efforts in improving the software and making it freely available, further enabling cutting edge space missions in the future.

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