Space Operations Engineering

Through the eyes of an Electronics Engineer

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UHasselt/KU Leuven alum ‘18

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European Space Operations Centre

Goal of this presentation

- An example of what you can do as an Electronics Engineer at ESA
- Technical overview of the project I am currently working on
- Draw parallels with things you know
- Illustrate everyday problems we encounter
- Show the different aspects of a space mission
- Some things I learnt along the way

Overview

- My path to space
- Current project at ESA
    - ✓ What is OPS-SAT?
    - ✓ Space Segment
    - ✓ Ground Segment
- Operating a satellite in orbit
    - ✓ Tools we use
    - ✓ Operations concepts
    - ✓ Examples of everyday problems
- Launch and Mission status
- Outlook

My path to space

My path to space

- MSc. Electronics-ICT FIIW UHasselt/KUL 2017-2018
  - OSCAR/BEXUS project
  - Thesis at KUL about CubeSat development

- Instrumentation Engineer at KUL Institute of Physics and Astronomy (9 mo.)
  - Development of telescope imaging/control systems
  - CubeSat design and development
  - Electronics design

- Spacecraft Operations Engineer at ESA, YGT* (~1,5yrs.)
  - High-calibre training programme
  - Pre-launch testing, automation and operations of a space mission

*https://www.esa.int/About_Us/Careers_at_ESA/Graduates_Young_Graduate_Trainees

ESA in a nutshell

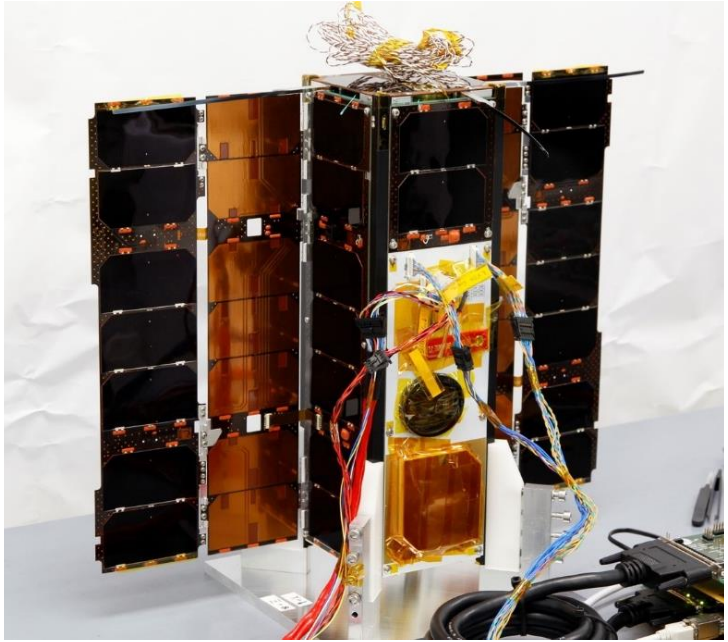
- European Space Agency
- Intergovernmental agency with 22 member states
- Headquartered in Paris
- €14 bn. budget for 2020
- Funding through member state contributions
- Contribution back into member states through contracts with Industry

- Strong focus on
  - ✓ Navigation (Galileo)
  - ✓ Earth observation (Copernicus)
  - ✓ Science/Astronomy missions

Current project at ESA

What is OPS-SAT?

- 3U CubeSat (ESA's first)
- Dedicated to executing hardware/software experiments in Low Earth Orbit
- 100+ companies from 17 countries registered experiments
- Academia, start-ups and large corporations are looking to innovate on OPS-SAT
- Launched 18th Dec 2019 at 05:54:20 from French Guyana (VS23) in a 515km orbit
- Experiments range from telemetry compression algorithms to experimental IP-cores on the FPGA
- Most powerful computer ESA has flown on a satellite



Space segment (1/2)

- EPS (Electronic Power System)
  - ✓ Solar arrays
  - ✓ Array conditioning units
  - ✓ Power regulation
  - ✓ Power storage
- Communications
  - ✓ Radio transceiver
  - ✓ Telecommand decoder / Telemetry encoder
  - ✓ On-board computer & communications buses
- Attitude control
  - ✓ ADCS (Attitude Determination and Control System)

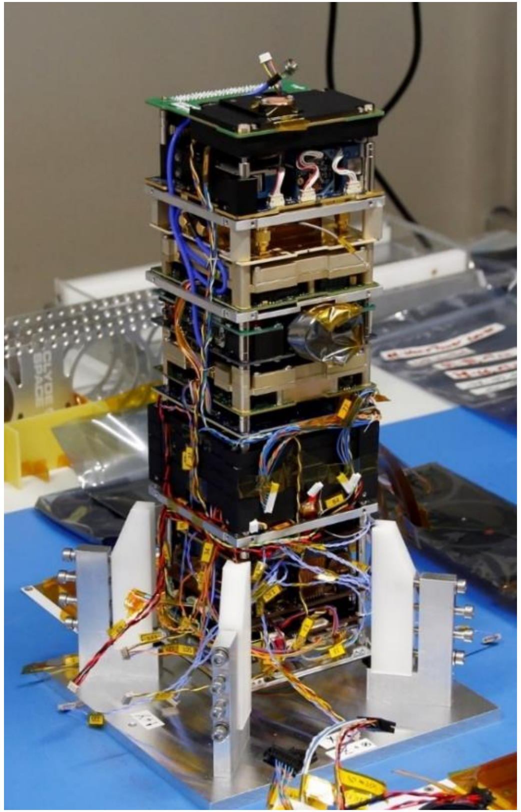
Space segment (2/2)

Satellite **bus** (necessary to run the satellite):

- Gomspace UHF AX100 radio + EPS/ACU
- Nanomind A3200 OBC (On-board computer, AVR32)
- S-band (2.2 GHz) TRX TMTC encoder/decoder (256kbps↑ 1Mbps↓)
- GNSS receiver

Satellite **payloads** (experimental systems):

- HD-camera (Nadir-facing)
- Advanced iADCS (Attitude Determination & Control Sys.)
- Optical receiver (data uplink via laser)
- Software Defined Radio (LMS6002D)
- 2x Altera Cyclone V SoC (Dual Core ARM Cortex-A9 + FPGA fabric)
- X-band transmitter (8 GHz, 3-50MBit/s)



SEPP

- Satellite Experimental Processing Platform, designed by TU Graz
- Cyclone V, Dual Core 800MHz ARM Cortex-A9 (HPS)
- Running embedded Linux 32bit (Ångström)
- Connected via CAN-bus (can0 network interface)

- Nanosat MO Framework (NMF*)
  - ✓ Free open-source ESA SDK on-board to develop applications
  - ✓ Abstracts payloads, *camera.takePicture(exposure, gain)*

- Software is uplinked and installed in the form of IPK files
  - ✓ Open package manager (opkg)
  - ✓ Simple to manage; *opkg install*, *opkg remove*, …

- FPGA portion has IO connections to TMTC encoder/decoder
  - ✓ Currently in development for high-speed file transfer

*https://nanosat-mo-framework.github.io

Software Defined Radio

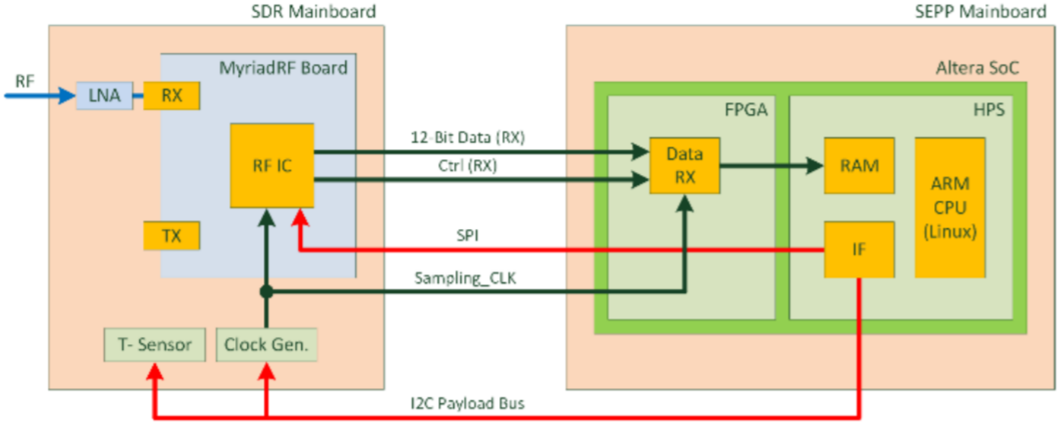
- Based on LMS6002D
- 300MHz – 3.8GHz
- Receive only on OPS-SAT with UHF monopole antenna

HPS:

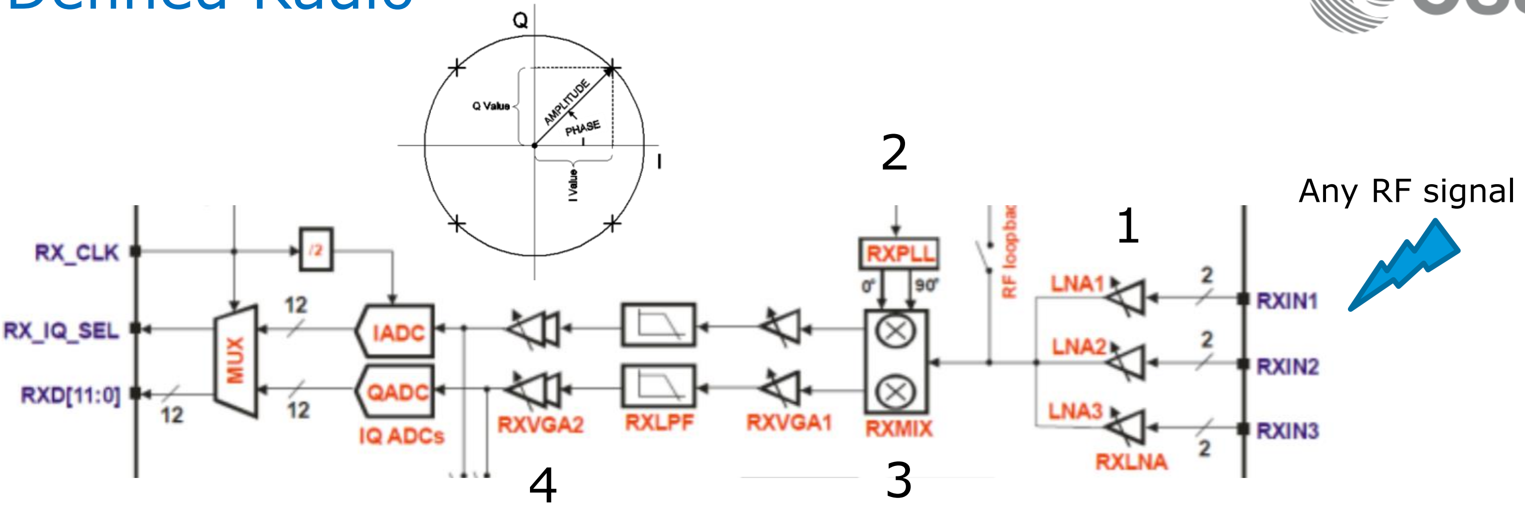
- Board Monitoring & Configuration via I2C Bus

FPGA:

- RFFE Monitor & Control via SPI Bus
- Data I/O via Parallel IO (FPGA)
- 12 bit I/Q samples



Software Defined Radio

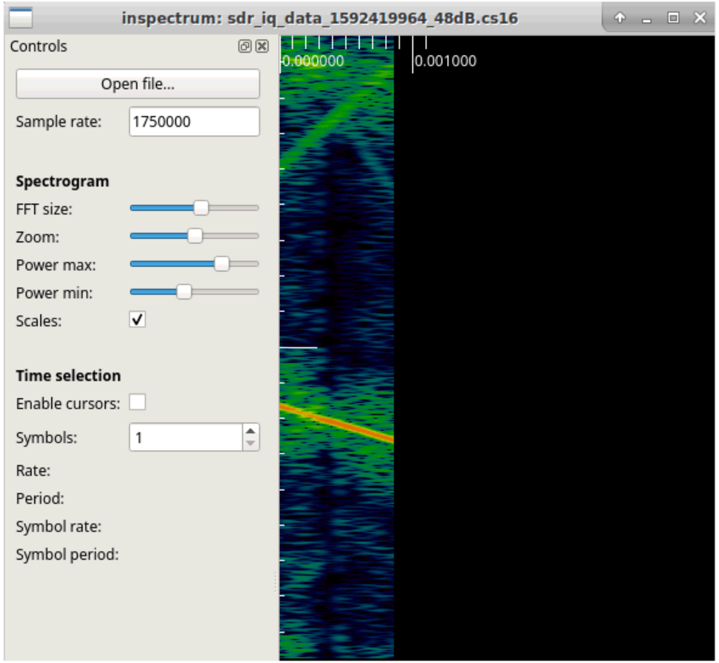


1) Amplify signal with Low Noise Amplifiers
2) Set center frequency fc (RXPLL)
3) Mix with fc and fc – (pi/2) to get I and Q components (downconversion)
4) Filter and digitize I and Q components
5) Use FPGA IP core to get 12-bit IQ data into RAM/FIFO via HPS bridges

Software Defined Radio

```
-rw-r--r--    1 root     root          8000 Jun 16 04:32 sdr_iq_data_1592281979_24dB.iqdat
-rw-r--r--    1 root     root          8000 Jun 16 04:33 sdr_iq_data_1592281981_30dB.iqdat
-rw-r--r--    1 root     root          8000 Jun 16 04:33 sdr_iq_data_1592281984_36dB.iqdat
-rw-r--r--    1 root     root          8000 Jun 16 04:33 sdr_iq_data_1592281986_42dB.iqdat
```

1) Application to write IQ samples to a file (or stream them)
2) Analyse frequency components of RF signal
   FFT(sqrt(I^2+Q^2))



IQ data recorded on-board the satellite while uplinking carrier:

Ground segment (1/3)

- Communications
  - ✓ Receive telemetry (TM)
  - ✓ Send telecommands (TC)
- Planning
  - ✓ Sequences to execute
  - ✓ Software to run
  - ✓ Manoeuvres to make
- File operations
  - ✓ Downlink/uplink of files
  - ✓ Uplink of updates

Ground segment (2/3)

SMILE LAB at ESOC

ESOC1 3.7m S/X dish

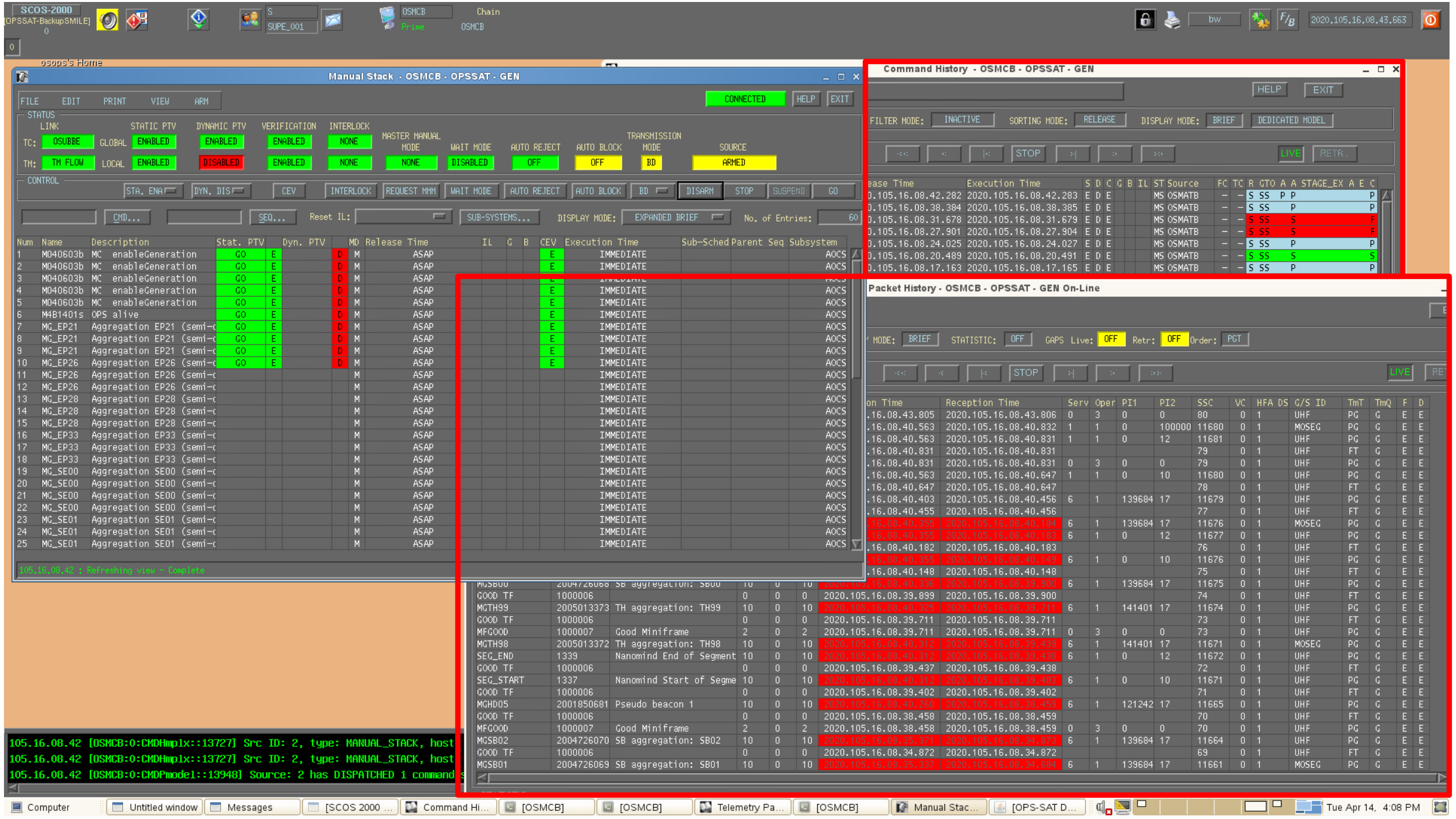
ESOC-2 UHF antenna

- SMILE = Special Mission Infrastructure Laboratory Environment
- All operations automated
- Spacecraft commissioning currently performed remotely due to COVID
- 3 frequency bands:
  - ✓ UHF (437 MHz)
  - ✓ S-band (2.3 GHz)
  - ✓ X-band (8.1 GHz)

Ground segment (3/3)

- Core servers run legacy ESA ground software SCOS2000 (used 20+ years)
- Automated using new ESA software (MATIS - Mission Automation System)

Ground segment (3/3)



Telecommands

- Activity tracking
- Colours indicate status

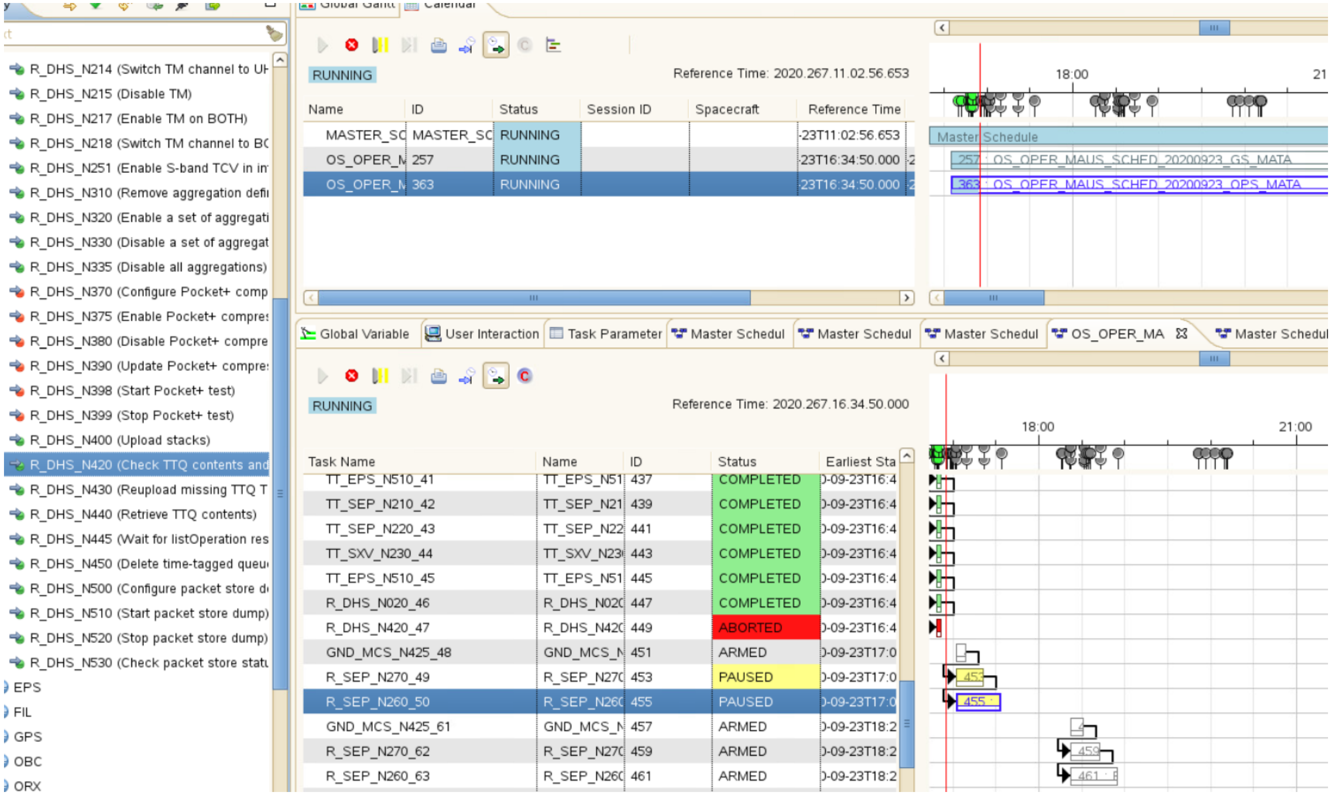
Telemetry

- Sensor values
- System registers
- Warnings
- Log entries

Ground segment (3/3)

- Automation of procedure runtime
- Schedules in XML form
- Sending TCs
- Checking TM
- Generate reports
- Send e-mails
- ECSS-E-ST-70-32C

European Cooperation for Space Standardization



Operating a satellite in orbit

Operating a satellite in orbit

- Operating a satellite is similar to being a system administrator

With the differences:

- Your target machine is in space
- Limited window of contact per day (7 minutes per pass, 4 passes per day)
- No debug console(s)
- Hardware failures are fatal
- Limited power available
- Bitflips, latchups and magnetic storms cause software to behave strangely
- Decisions have to be made in minutes

Operating a satellite in orbit

Do I trust this sensor value?

✓ Understand the route a sensor value goes through in a space mission

Operating a satellite in orbit

Do I trust this sensor value?

✓ Understand the route a sensor value goes through in a space mission

1. A sensor value is acquired over the I2C bus (with possible CRC) -> acquisition
2. The value gets aggregated in a memory location (Datapool) -> caching
3. Telemetry process assembles binary payloads from memory locations -> fetching
4. Headers/trailers/CRCs are attached to form CCSDS Space Packets -> packetization
5. Space packets are sent on the main CAN-bus to the TM encoder -> forwarding
6. Convolutionally encode the packet into a bitstream -> encoding
7. An RF-transceiver modulates bitstream onto RF-carrier -> transmitting
8. The signal travels ~500-1000km through space -> propagation
9. Ground receives and decodes the RF-signal -> demodulation
10. A modem decodes the symbols into packets -> decoding
11. Packets are interpreted by the MCS and values extracted -> interpretation

Operating a satellite in orbit

Reception of occasional close approach alerts by US Space Control

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The United States 18th Space Control Squadron has identified a close approach between OPS-SAT
(SCC # 44878) and SCC # 23358

Time of Closest Approach: 2020/06/25 13:36:19.000(UTC)
Probability of Collision (Pc):  0.000997596
Overall miss distance:  80.0m
Radial miss distance (RELATIVE_POSITION_R):  37.2m
In-Track miss distance (RELATIVE_POSITION_T):  57.1m
Cross-track miss distance (RELATIVE_POSITION_N): -42.6m.
```

Normal ESA missions:

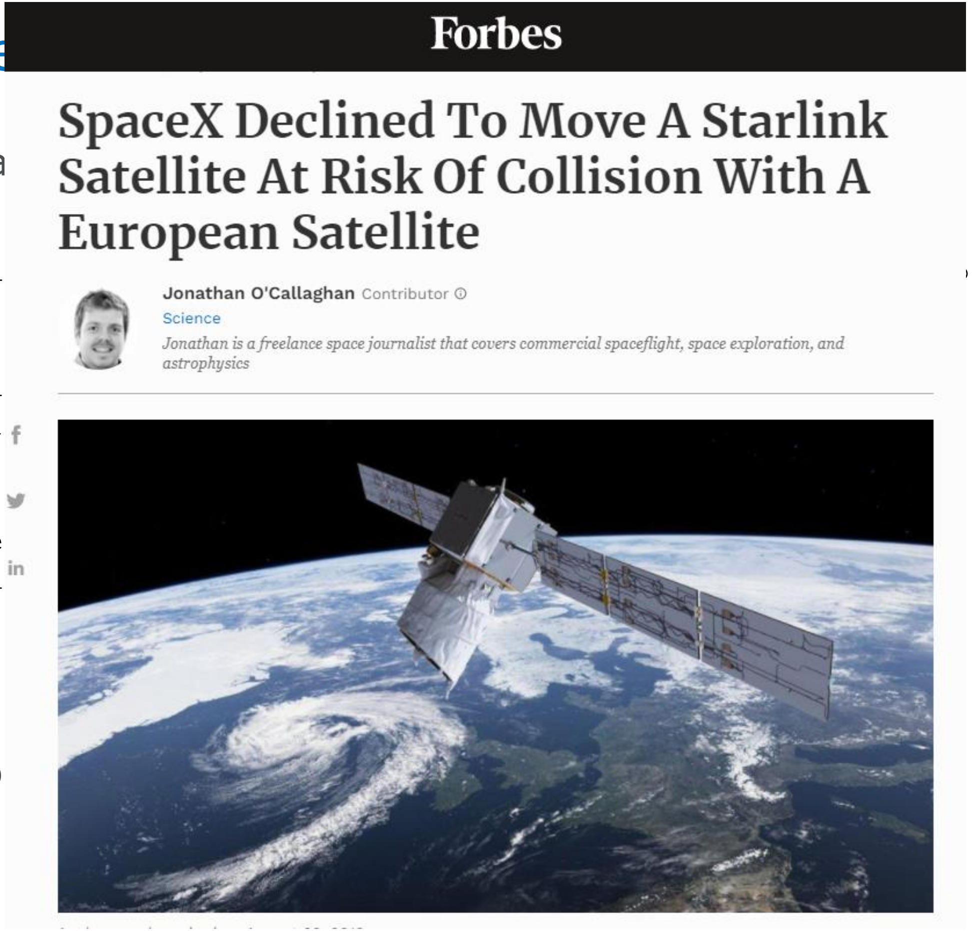
- Check with Flight Dynamics if manoeuvre needs to be made

Operating a sate

Reception of occasiona

The United States 18th   roach between OPS-SAT
(SCC # 44878) and SCC

Time of Closest Approa
Probability of Collisi
Overall miss distance:
Radial miss distance (
In-Track miss distance
Cross-track miss dista



Forbes

SpaceX Declined To Move A Starlink Satellite At Risk Of Collision With A European Satellite

Jonathan O'Callaghan Contributor

Science

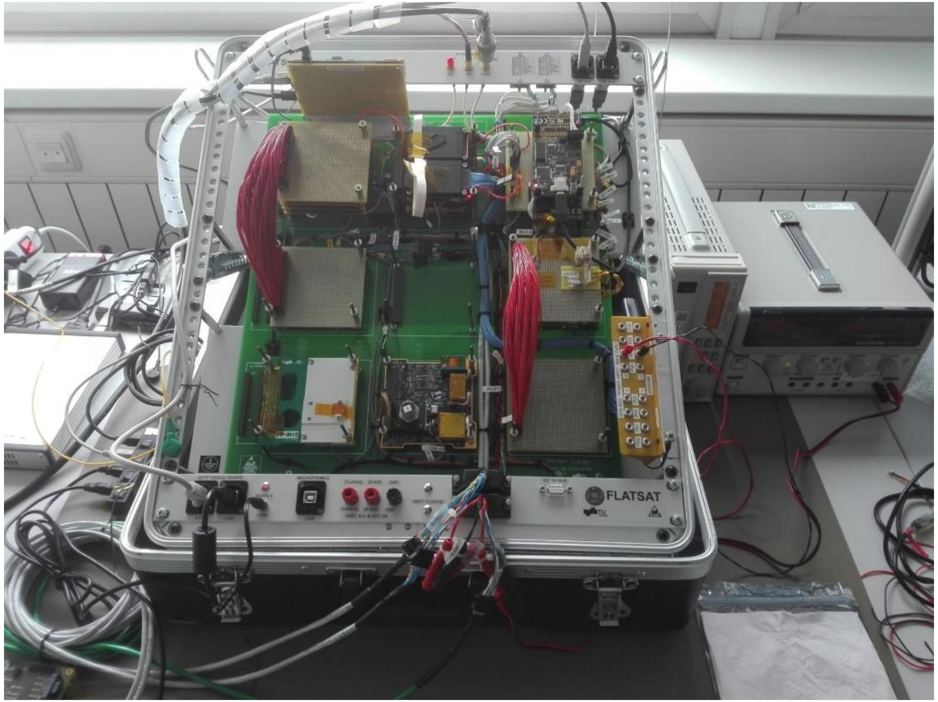
Jonathan is a freelance space journalist that covers commercial spaceflight, space exploration, and astrophysics

Normal ESA missions:

- Check with Flight D

Operating a satellite in orbit

- Procedures, software, sequences and patches are always tested
- Tests happen on ground on the Engineering Model (EM)
- Once validated, a slot is allocated on-orbit



Operating a satellite in orbit

During visibility (in contact with ground):

- Critical checks are performed to quickly check if all systems are nominal
  - ✓ Battery voltages and currents
  - ✓ Temperatures
  - ✓ Spin rates

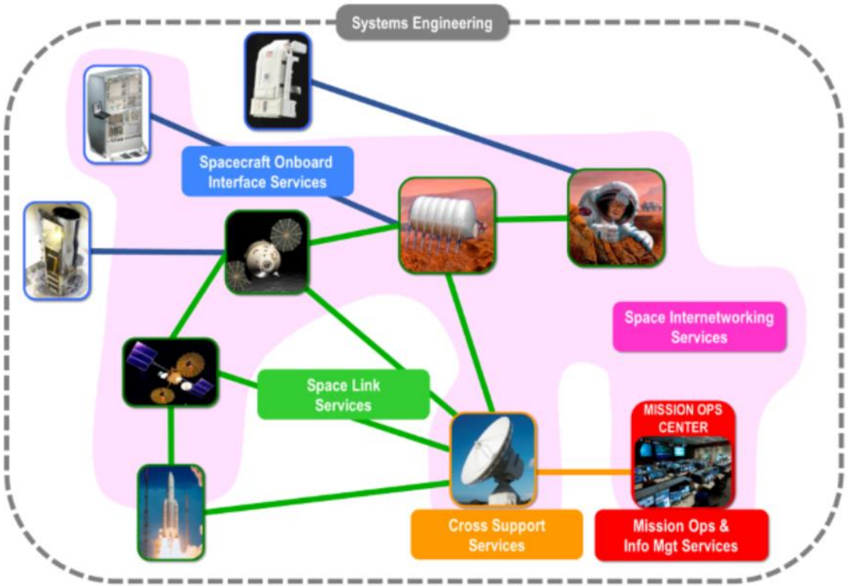
- Hundreds of commands are uplinked with execution times outside of visibility
  - ✓ ‘Programming’ a timeline
  - ✓ 90% of activities happen outside of coverage

- Files are downloaded and software is uploaded

Operating a satellite in orbit

CCSDS standards

- Definition of telemetry/telecommand formats
- File transfer protocols
- Published as colour coded books



Consultative Committee
CCSDS
for Space Data Systems

Operating a satellite in orbit

- Typical ‘Blue book’
- Description of packet fields

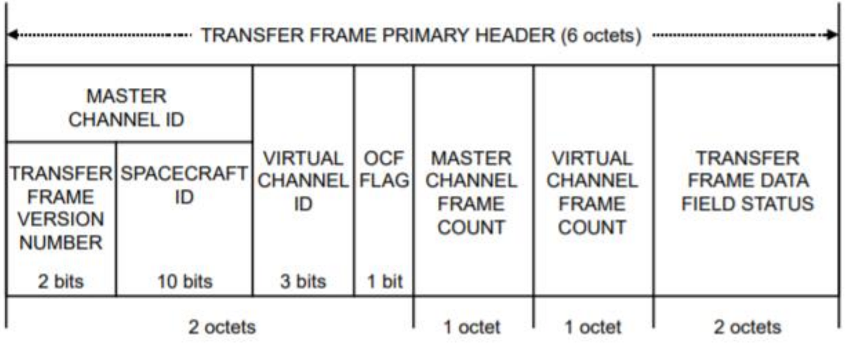


Figure 4-2: Transfer Frame Primary Header

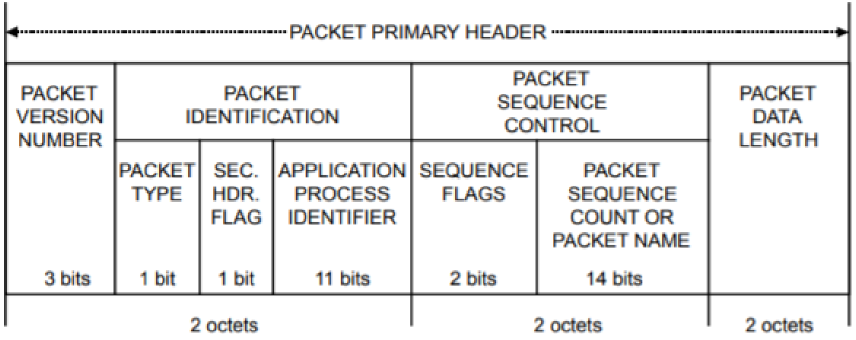


Figure 4-2: Packet Primary Header

Example problems

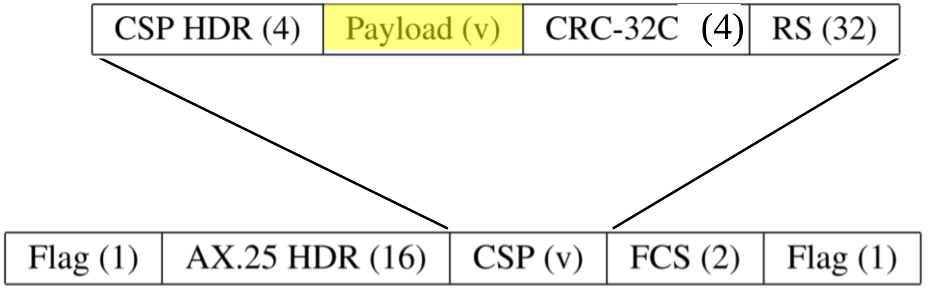
Example problem 1

Statement: Due to an error in requirements, the backup UHF ground station for launch support is not compatible with the RF communication protocol used by the satellite

Solution: Implement and test an SDR modem for the ground station that supports the protocol

UHF link

- CubeSat Space Protocol* (CSP) packets + AX.25 + HDLC (nr of bytes)

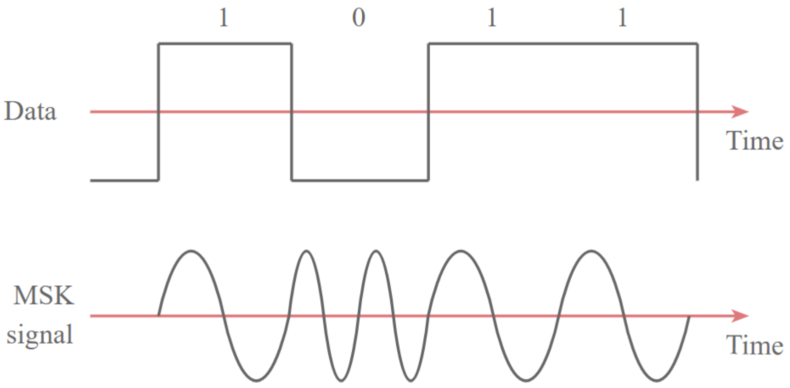


- Add error correction bytes to the payload
- HDLC uses ‘Flags’ (0x7E) to indicate packets in a byte sequence
- Bit stuffing ensures this sequence does not occur inside the packet
- Bytes are scrambled using a PRN sequence (scrambler) to ensure enough transitions 0<->1 take place, improves symbol recovery

*https://github.com/libcsp/libcsp

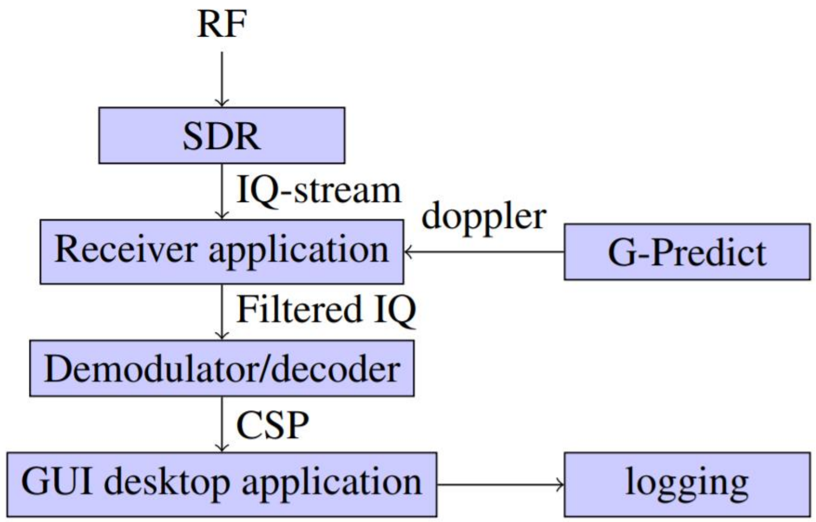
UHF link

- Scrambled bits (now called symbols) are radiated
- GMSK (Gaussian Minimum Shift Keying) @ 9.6kBaud, f=437.2 MHz
    - Bandwidth efficient
    - No phase discontinuities -> less bandwidth than normal FSK

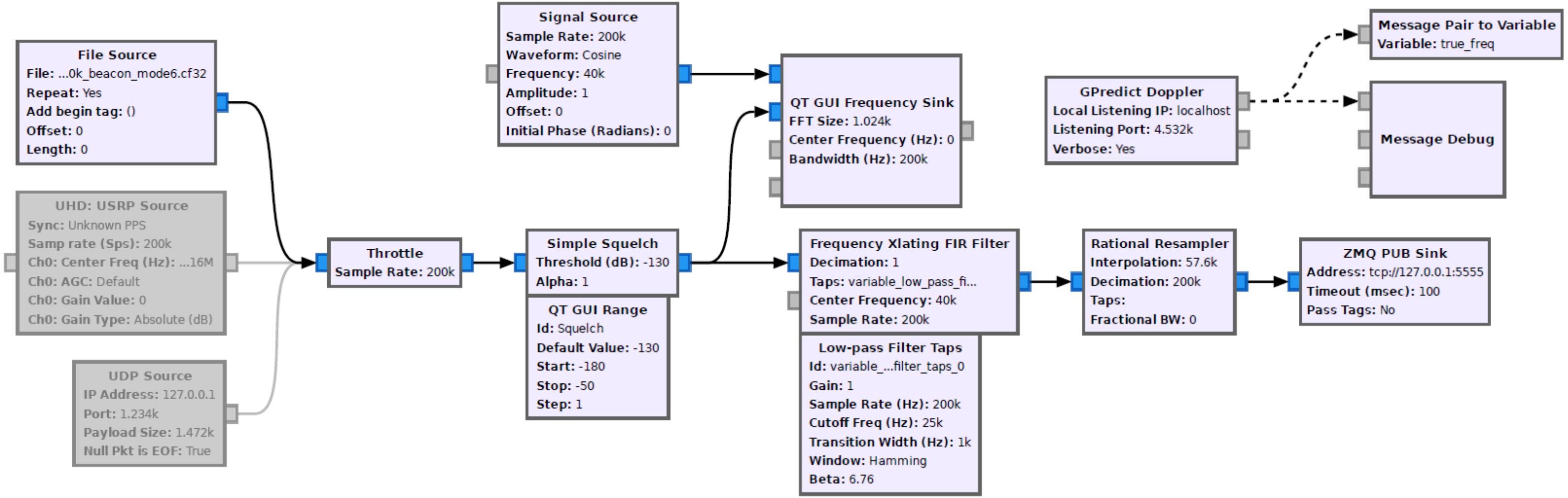


https://www.electronics-notes.com/images/minimum-shift-keying-msk-concept-01.svg

Implementation in GNU Radio

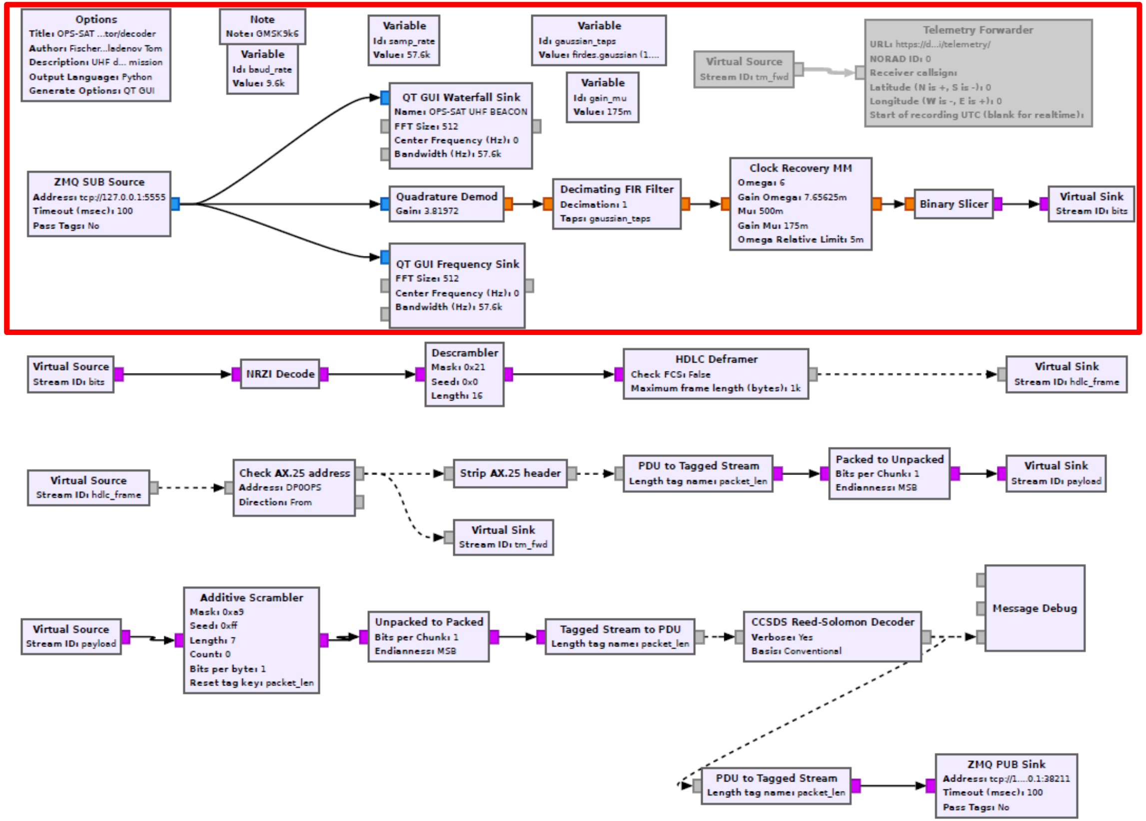


Receiver

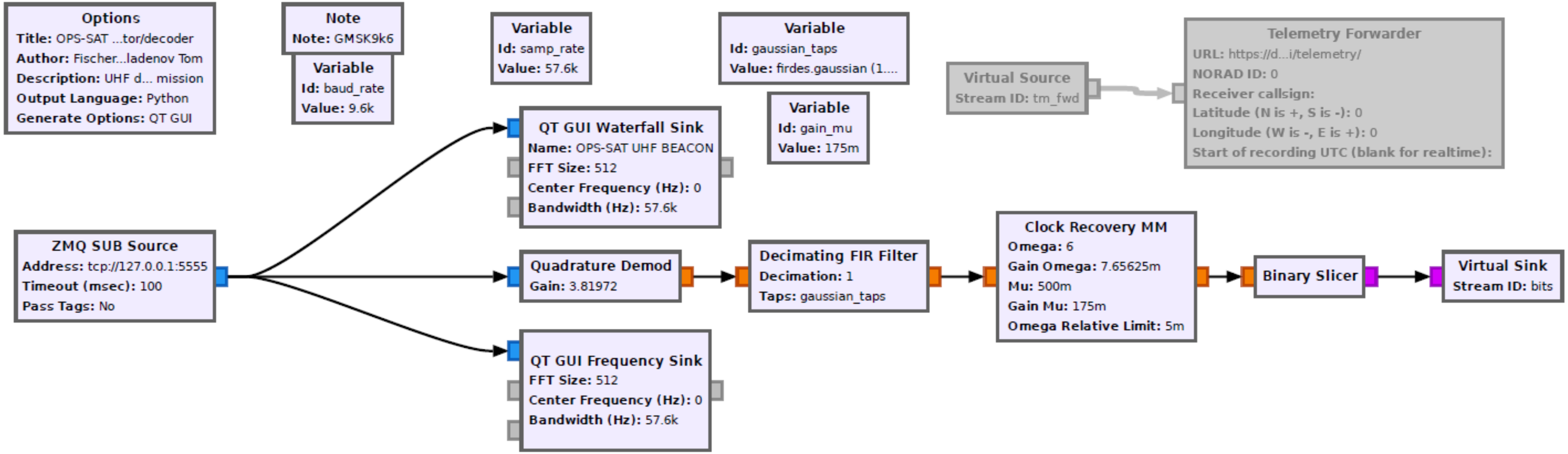


- Simple receiver application
  - Acquire IQ samples (HW f_c set to f_{nom} - 40 kHz)
  - Use relative Doppler frequency (40 kHz + f_{Dopp}) for Xlating FIR filter f_c
  - Resample to fixed rate for demodulator/decoder flowgraph
  - Send filtered IQ samples to ZMQ PUB sink

Demodulator/decoder

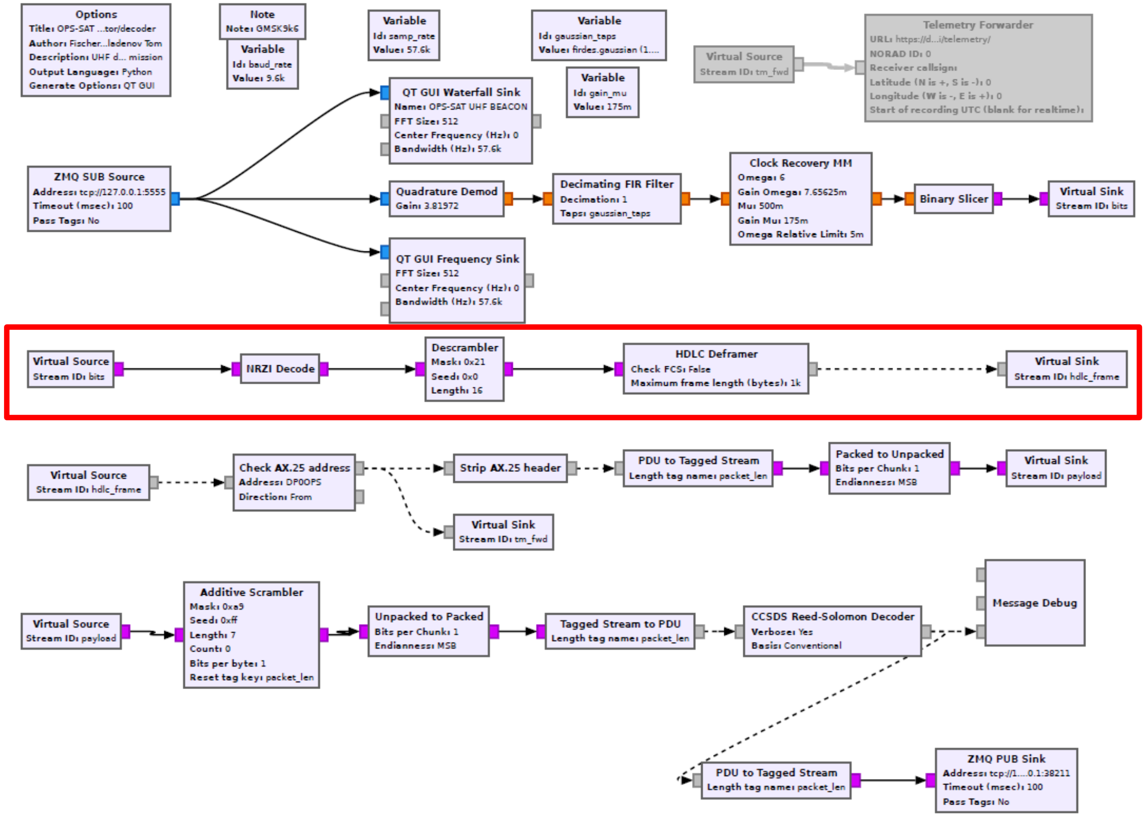


Demodulator/decoder (1/4)

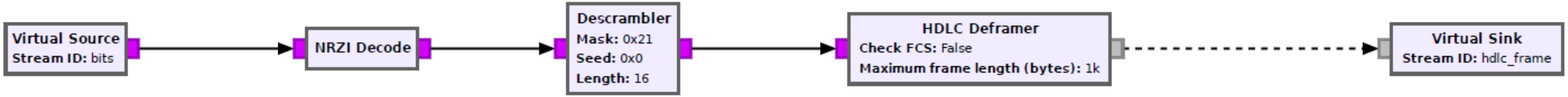


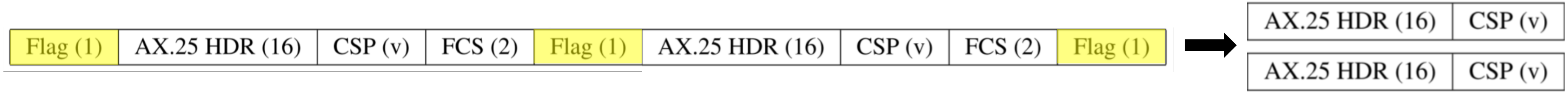
- Quadrature Demod G=2*(samp_rate/baudrate)/pi + Gaussian FIR filter
- Clock Recovery MM + Binary Slicer -> hard symbols

Demodulator/decoder



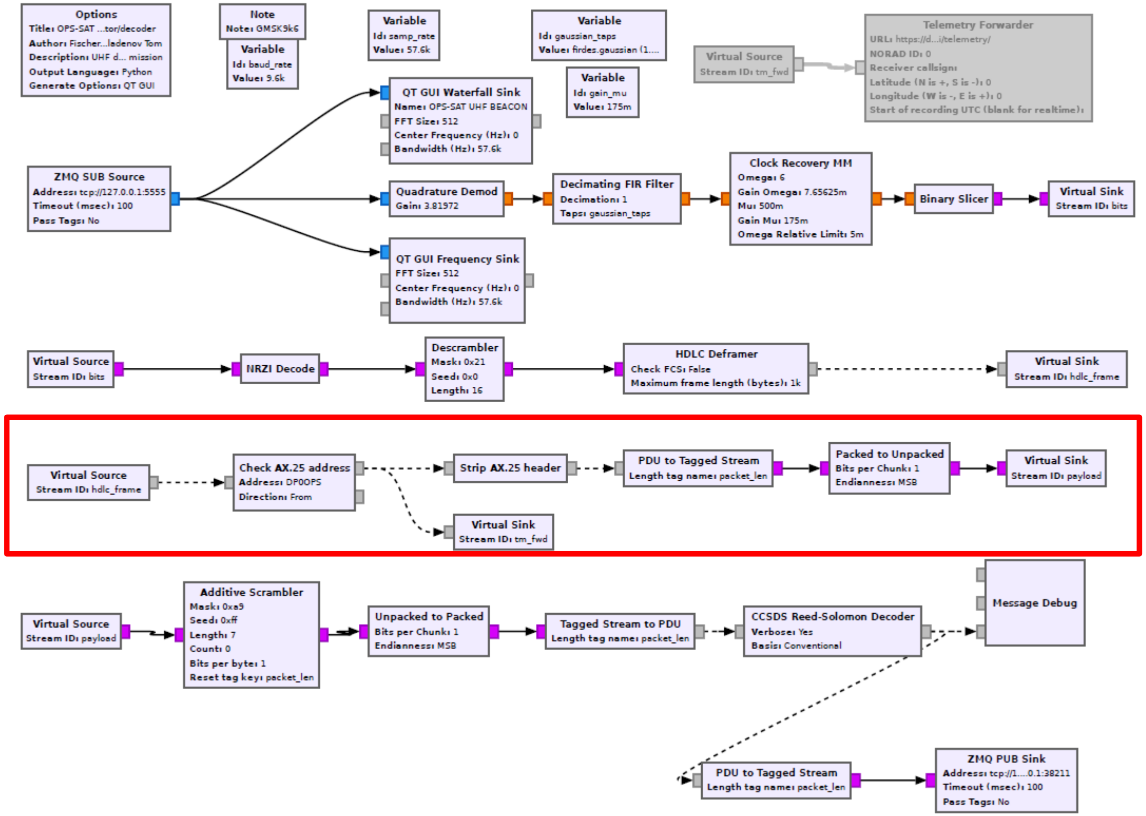
Demodulator/decoder (2/4)



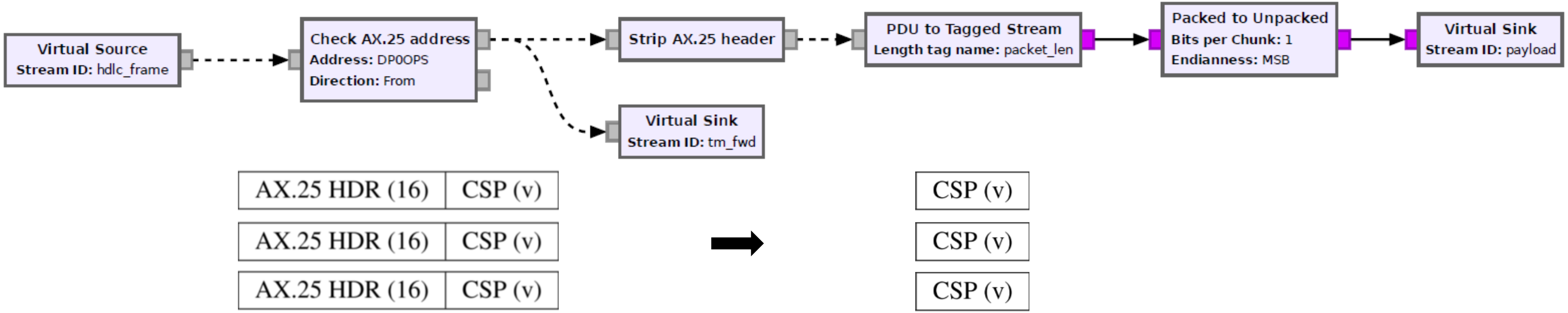


- NRZI decode + G3RUH descrambling of bitstream
- Deframe ‘flagged’ HDLC payloads into packetized AX.25

Demodulator/decoder

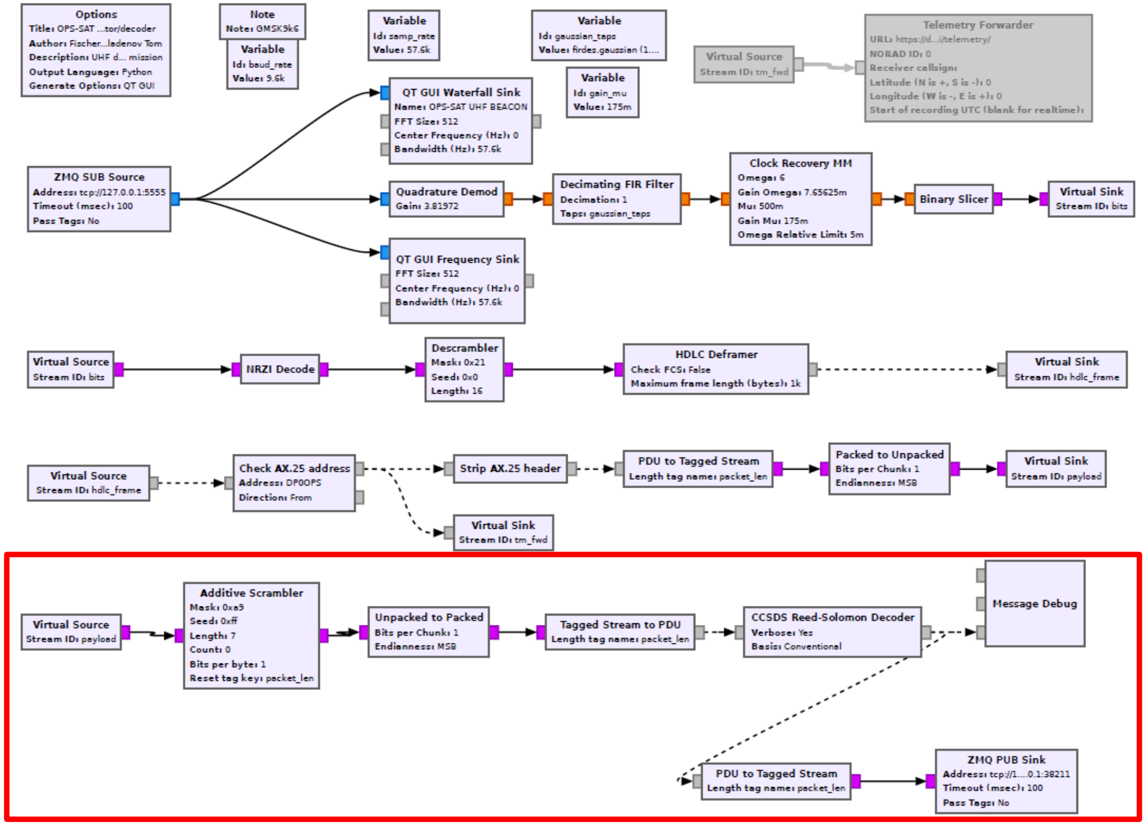


Demodulator/decoder (3/4)

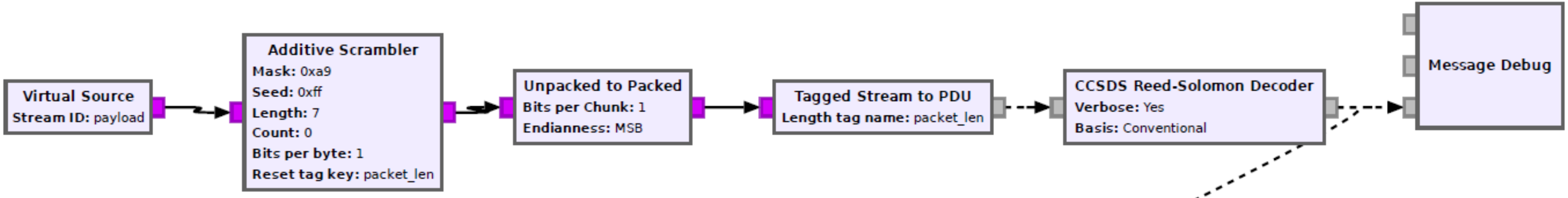


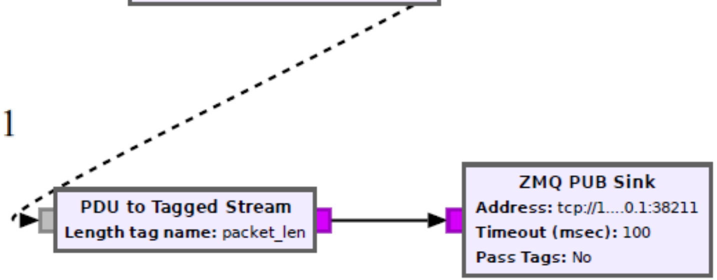
- Strip AX.25 header and convert to bitstream
- Prepare for decoding of CSP packet

Demodulator/decoder

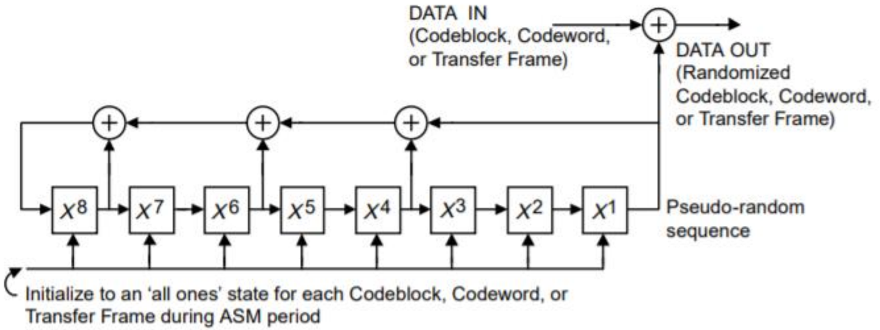


Demodulator/decoder (4/4)





- CCSDS descrambling according to $h(x) = x^8 + x^7 + x^5 + x^3 + 1$

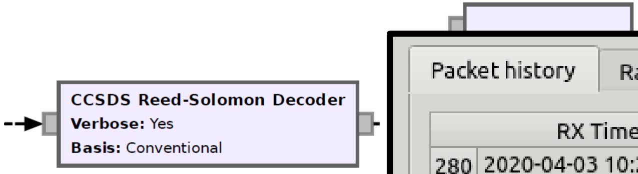


CSP HDR (4)	Payload (v)	CRC-32C (4)

- Reed-Solomon decoding of packet

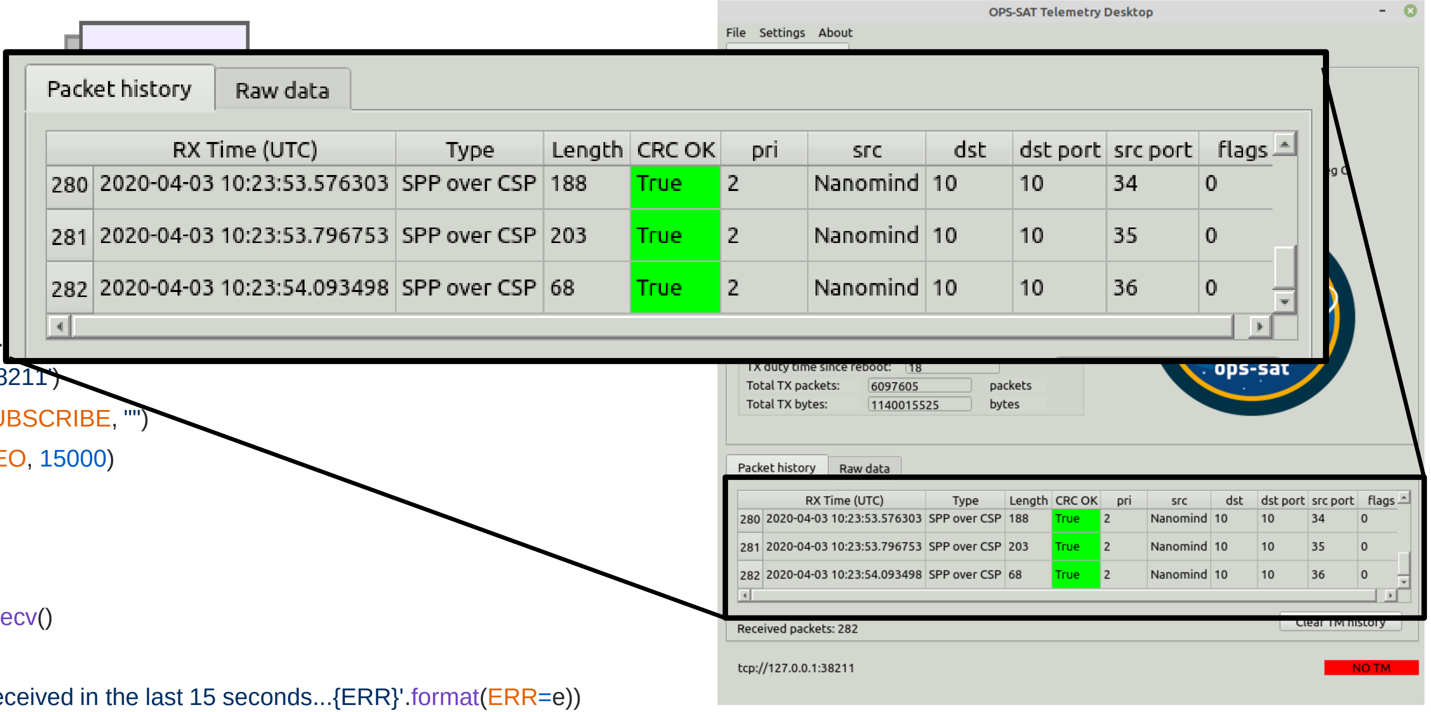
GUI Application

- Viewing the packets from GR in an interactive way



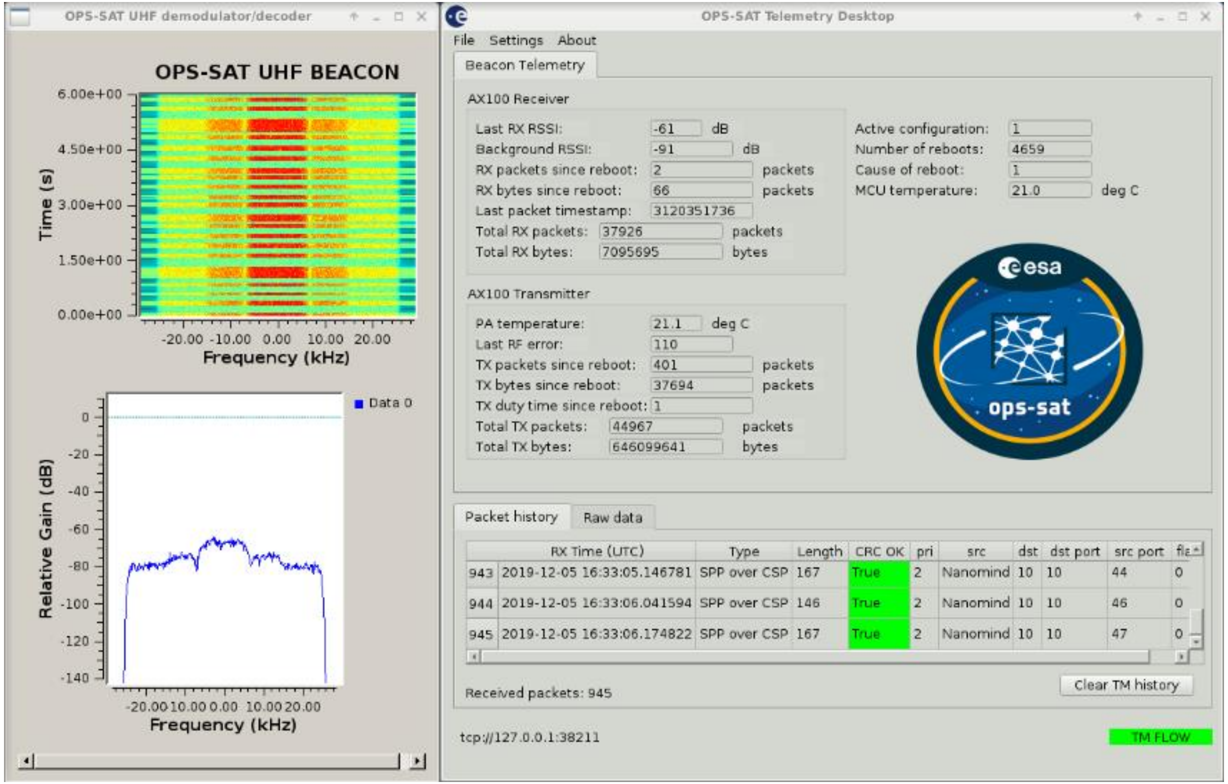

```
self.context = zmq.Context()
self.socket = self.context.socket(zmq.
self.socket.connect('tcp://127.0.0.1:38211')
self.socket.setsockopt_string(zmq.SUBSCRIBE, "")
self.socket.setsockopt(zmq.RCVTIMEO, 15000)

while self.active:
try:
        data = self.socket.recv()
except Exception as e:
        print('No packets received in the last 15 seconds...{ERR}'.format(ERR=e))
```

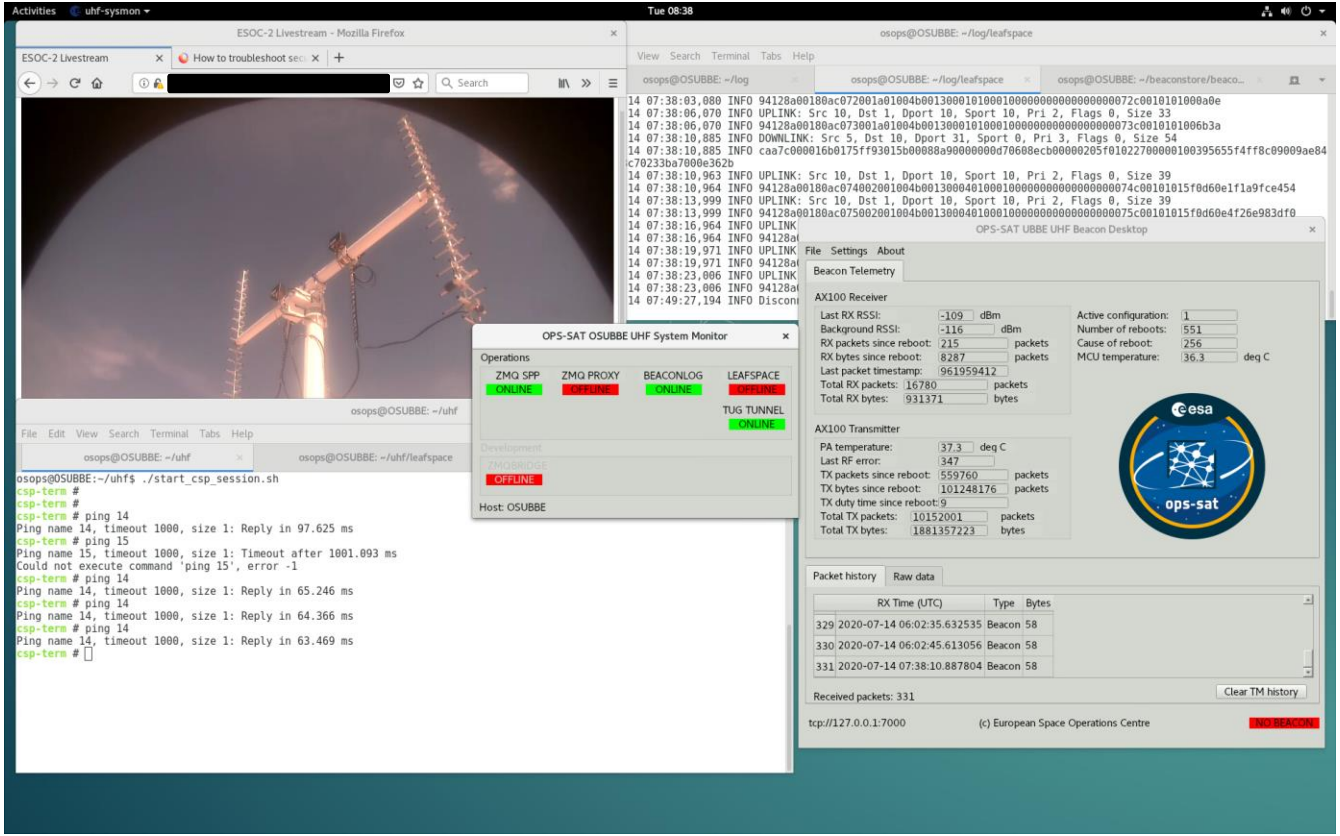


GUI Application

- GR integration with Python3 and PyQt5
- Use of ZMQ network sockets



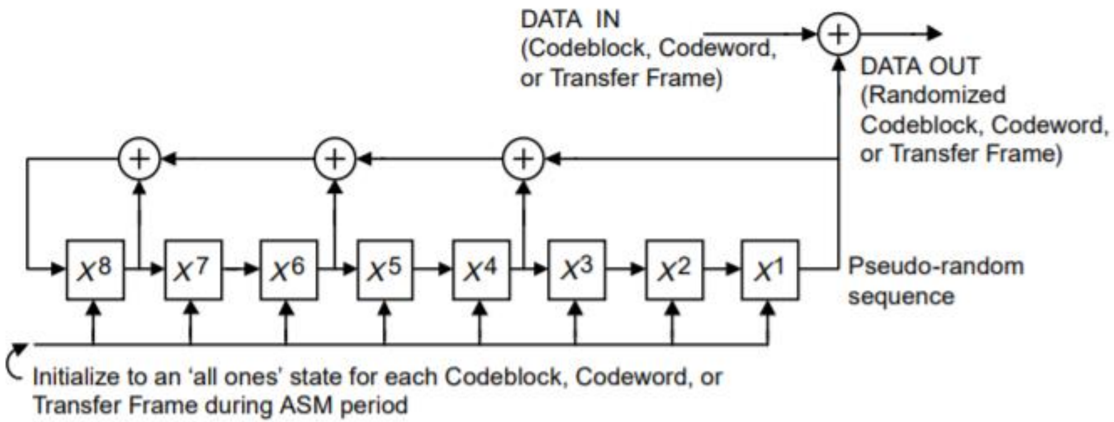
UHF link



Activities
uhf-sysmon
Tue 08:38
ESOC-2 Livestream - Mozilla Firefox
ESOC-2 Livestream
How to troubleshoot sec
[redacted]
Search
osops@OSUBBE: ~/log/leafspace
View Search Terminal Tabs Help
osops@OSUBBE: ~/log
osops@OSUBBE: ~/log/leafspace
osops@OSUBBE: ~/beaconstore/beaco...
14 07:38:06,070 INFO UPLINK: Src 10, Dst 1, Dport 10, Sport 10, Pri 2, Flags 0, Size 33
14 07:38:10,885 INFO DOWNLINK: Src 5, Dst 10, Dport 0, Sport 31, Pri 3, Flags 0, Size 54
14 07:38:10,963 INFO UPLINK: Src 10, Dst 1, Dport 10, Sport 10, Pri 2, Flags 0, Size 39
14 07:38:13,999 INFO UPLINK: Src 10, Dst 1, Dport 10, Sport 10, Pri 2, Flags 0, Size 39
OPS-SAT UBBE UHF Beacon Desktop
File Settings About
Beacon Telemetry
AX100 Receiver
Last RX RSSI: -109 dBm
Background RSSI: -116 dBm
RX packets since reboot: 215 packets
RX bytes since reboot: 8287 packets
Last packet timestamp: 961959412
Total RX packets: 16780 packets
Total RX bytes: 931371 bytes
Active configuration: 1
Number of reboots: 551
Cause of reboot: 256
MCU temperature: 36.3 deg C
AX100 Transmitter
PA temperature: 37.3 deg C
Last RF error: 347
TX packets since reboot: 559760 packets
TX bytes since reboot: 101248176 packets
TX duty time since reboot: 9
Total TX packets: 10152001 packets
Total TX bytes: 1881357223 bytes
esa
ops-sat
Packet history
Raw data
RX Time (UTC) Type Bytes
329 2020-07-14 06:02:35.632535 Beacon 58
330 2020-07-14 06:02:45.613056 Beacon 58
331 2020-07-14 07:38:10.887804 Beacon 58
Received packets: 331
Clear TM history
tcp://127.0.0.1:7000
(c) European Space Operations Centre
NO BEACON
OPS-SAT OSUBBE UHF System Monitor
Operations
ZMQ SPP ONLINE
ZMQ PROXY OFFLINE
BEACONLOG ONLINE
LEAFSPACE OFFLINE
TUG TUNNEL ONLINE
Development
OFFLINE
Host: OSUBBE
osops@OSUBBE: ~/uhf
File Edit View Search Terminal Tabs Help
osops@OSUBBE: ~/uhf
osops@OSUBBE: ~/uhf/leafspace
osops@OSUBBE:~/uhf$ ./start_csp_session.sh
csp-term #
csp-term #
csp-term # ping 14
Ping name 14, timeout 1000, size 1: Reply in 97.625 ms
csp-term # ping 15
Ping name 15, timeout 1000, size 1: Timeout after 1001.093 ms
Could not execute command 'ping 15', error -1
csp-term # ping 14
Ping name 14, timeout 1000, size 1: Reply in 65.246 ms
csp-term # ping 14
Ping name 14, timeout 1000, size 1: Reply in 64.366 ms
csp-term # ping 14
Ping name 14, timeout 1000, size 1: Reply in 63.469 ms
csp-term #

S-band and X-band

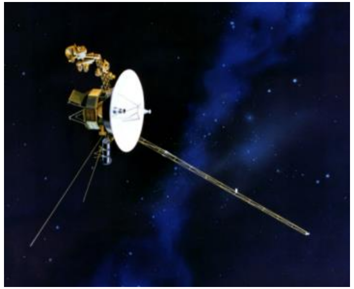
- Use of COTS equipment for decoding on-ground
- COTS limit for X-band = 10MBits/s -> working on SDR solution
- OPS-SAT (and many other satellites) uses the standard CCSDS Space Link
  - ✓ Scrambling of data bits using PRN sequence

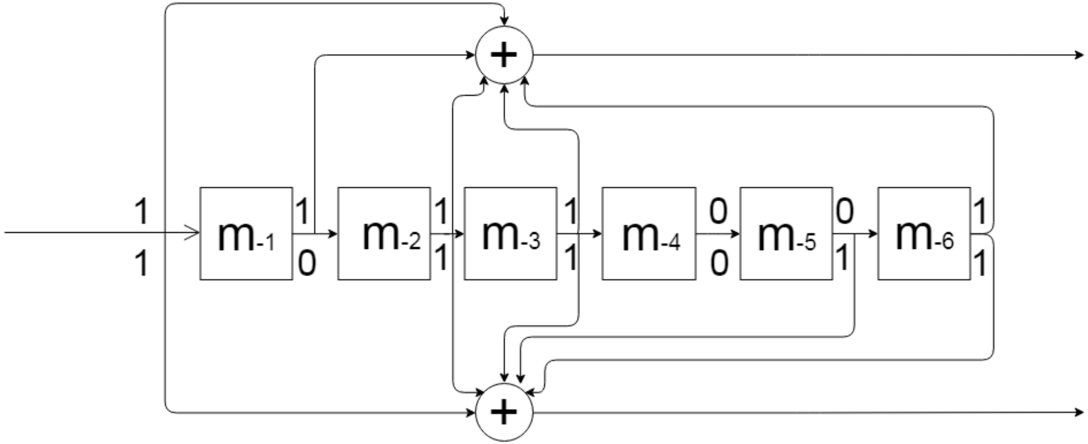


- Scrambling ensures transitions in long sets of 0's and 1's
- Easier for ground to perform symbol clock recovery
- Improves spectral efficiency
- Scrambler begin state (seed) is reset at the start of a packet

S-band and X-band

- Use of COTS equipment for decoding on-ground
- COTS limit for X-band = 10MBits/s -> working on SDR solution
- OPS-SAT (and many other satellites) uses the standard CCSDS Space Link
  - ✓ Scrambling of data bits using PRN sequence
  - ✓ Convolutional encoding at R=1/2, K=7 (Voyager code)

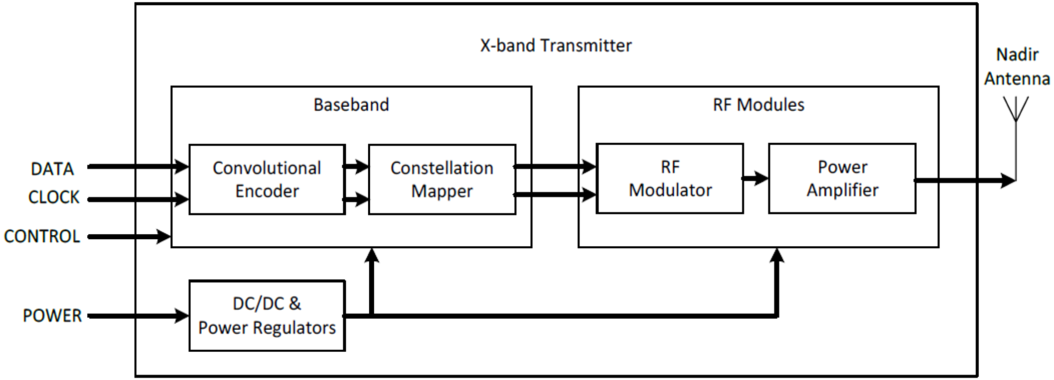


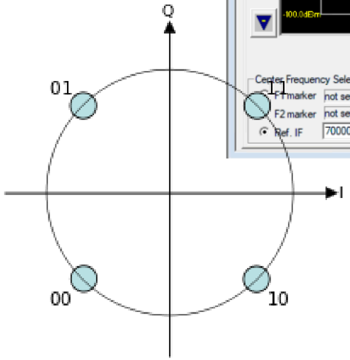


- Apply a sliding polynomial function to bitstream
- 1 error control bit is added to each data bit
- With the same throughput, the overall data rate is halved (R=1/2)
- Significantly improves chances of recovery and error correction

S-band and X-band

- Use of COTS equipment for decoding on-ground
- COTS limit for X-band = 10MBits/s -> working on SDR solution
- OPS-SAT (and many other satellites) uses the standard CCSDS Space Link
  - ✓ Scrambling of data bits using PRN sequence
  - ✓ Convolutional encoding at R=1/2, K=7 (Voyager code)
  - ✓ Constellation mapping and RF modulation





Launch day and Mission status

Launch and mission status

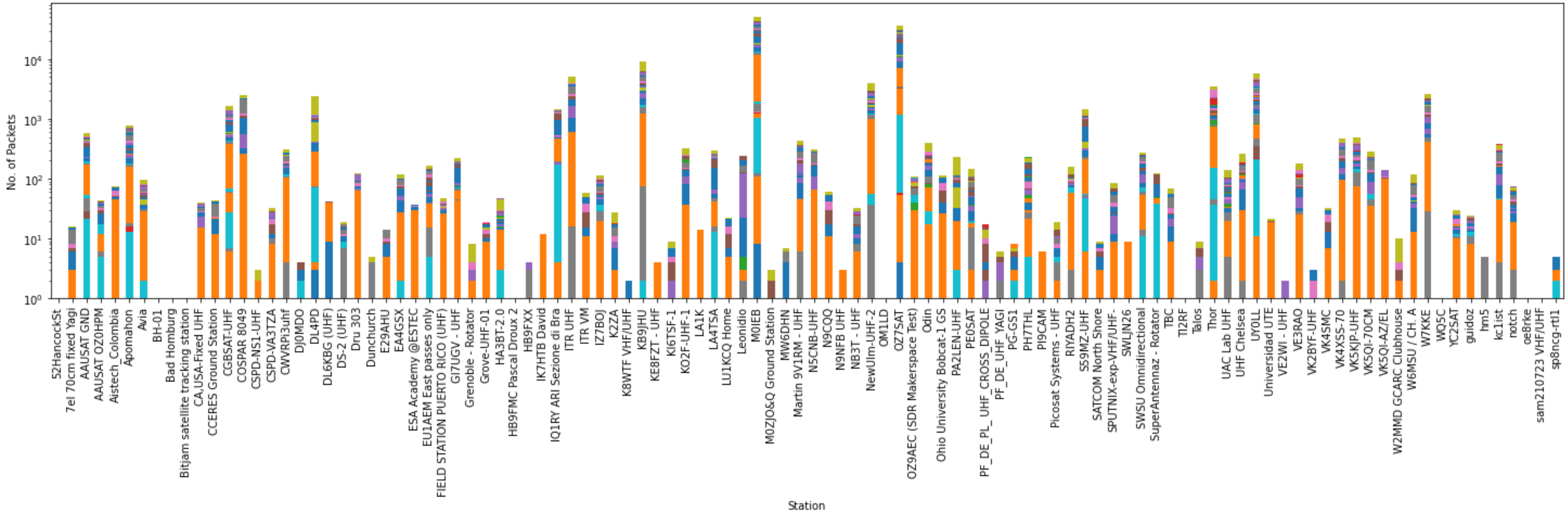
- Launch 18th Dec 2019 at 05:54:20 Kourou Local time
- Separation at 14:05 UTC with ANGELS and EyeSAT
- First beacon acquisition by radio amateurs and via SatNOGS
- S/C slow tumble seen in SatNOGS RF-waterfalls
- S/C healthy and plenty of power reserve
- SatNOGS* = Satellite Network Operated Groundstations

*https://db.satnogs.org/

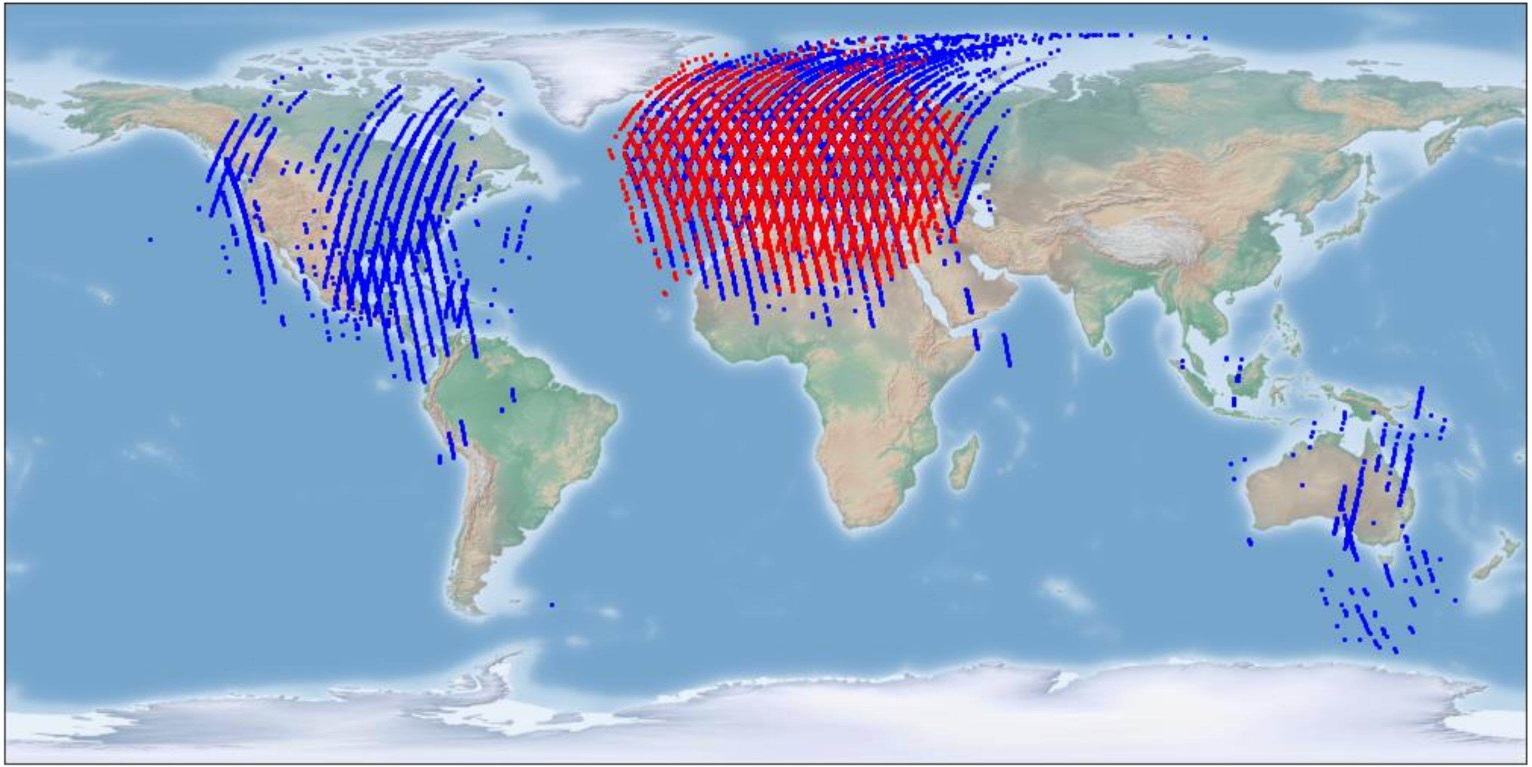
Amateur radio outreach

- Worldwide call for Radio Amateurs to listen for OPS-SAT
- Beacons received and decoded confirming S/C is healthy and functioning before ESA even made contact with the satellite

Launch and mission status

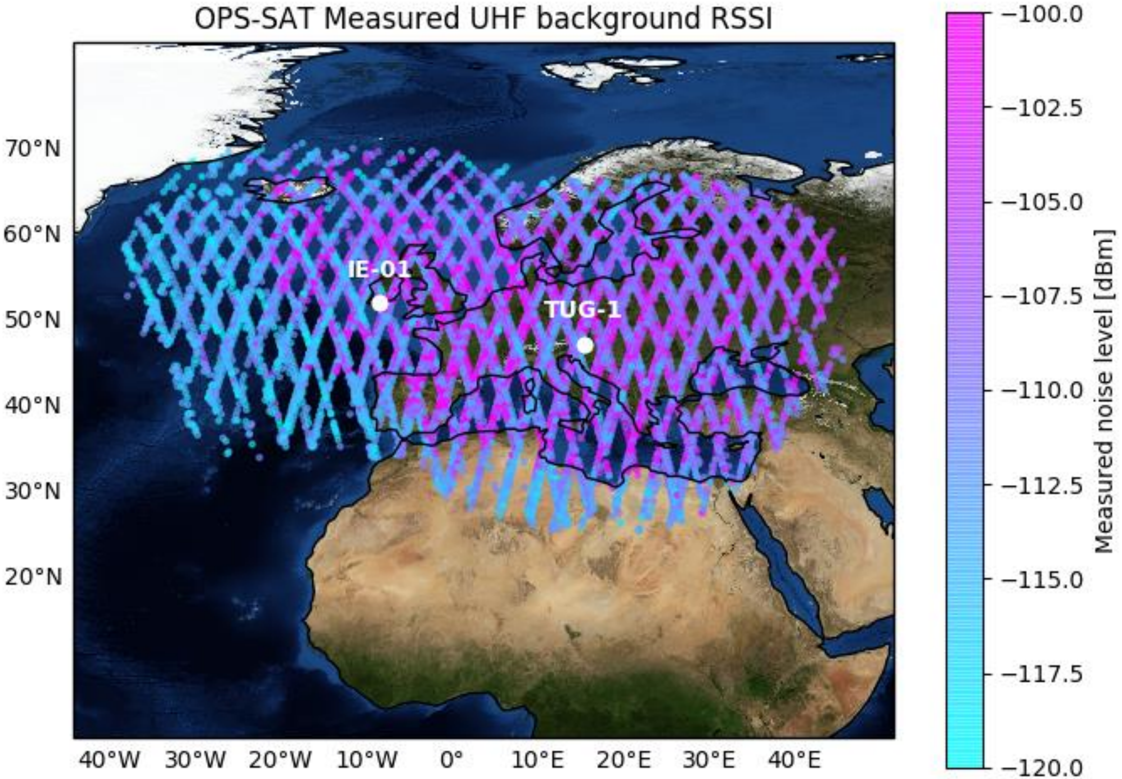


Launch and mission status



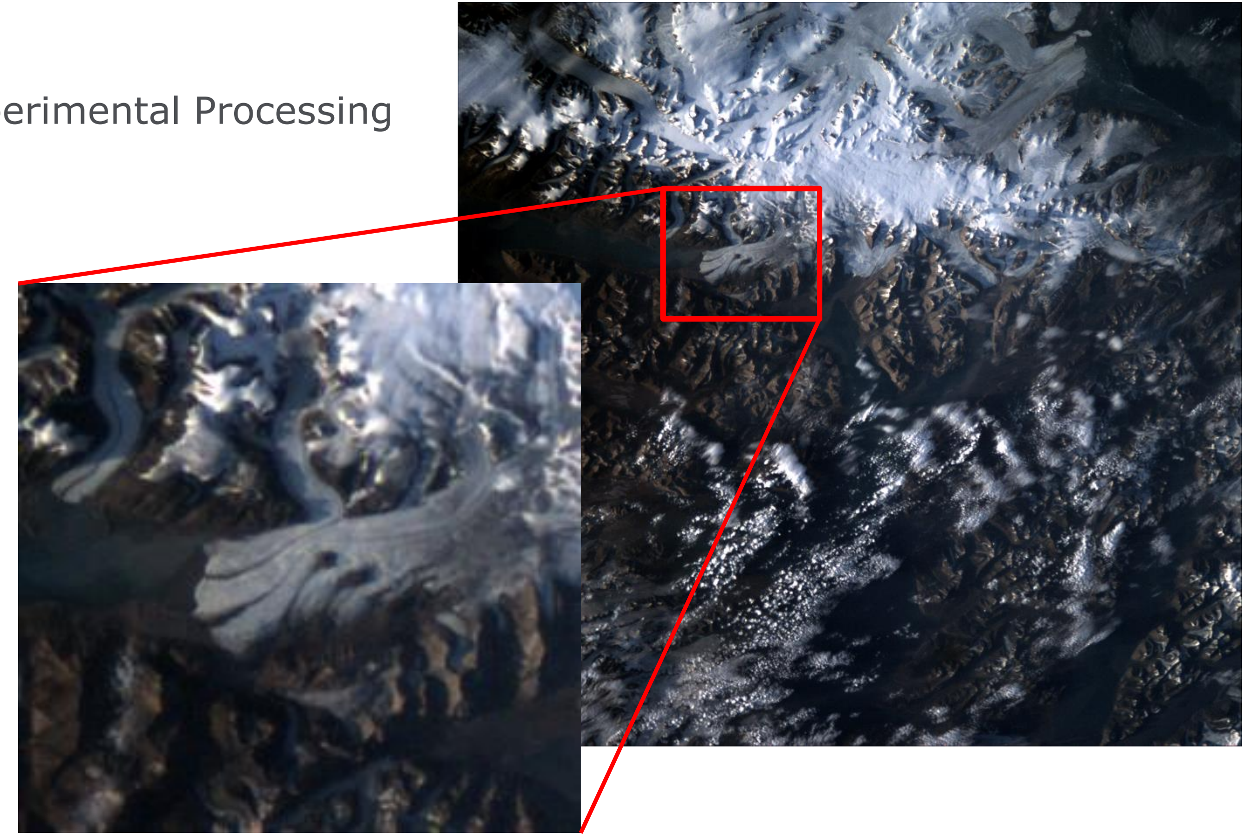
Launch and mission status

- Initial UHF communications were difficult
- Link quite marginal on UHF
- Noise levels 20dB higher over Europe
- Lower Noise levels over the Atlantic and North Africa

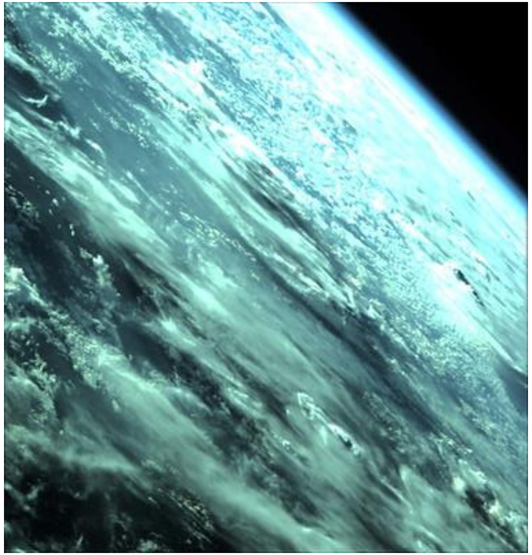


Launch and mission status

- Commissioned:
  - SEPP (Satellite Experimental Processing Platform)
  - SDR
  - HD-Camera



Launch and mission status



https://www.flickr.com/photos/esa_events/albums/72157716491073681

Launch and mission status

Outlook

- Beginning of experimental phase
  - ✓ Validation of 'experiments' (validated software packages) on satellite Engineering Model
  - ✓ Uplink to spacecraft
  - ✓ Execution
  - ✓ Dissemination of results to experimenter
- External experiments: Start-ups to large space and defence corporations
- Internal experiments by ESA
- Amateur radio experiments over the UHF link
  - ✓ Image dissemination
  - ✓ RF Uplink experiments

Thank you for your attention!

Contact:
Tom.Mladenov@esa.int

Links:
https://github.com/esa/gr-opssat
https://www.esa.int/Enabling_Support/Operations/OPS-SAT
https://public.ccsds.org/default.aspx

Personal blog:
https://tommladenov.github.io/