SDR subsystem of OPS-SAT & M17 protocol test

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M17 Conference

Nowy Dwór Mazowiecki, Poland

07/09/2025

What is the OPS-SAT Space Lab?

OPS-SAT Space Lab is an **ESA service** to help accelerate innovation in ops related areas.

- It uses **powerful, reconfigurable** space elements that can be used for in-flight experimentation **not possible or desirable** on other missions - “never flown, will never fly”
- The service provides access to these labs for **all** European industry and institutions, using a **fast, cost free, non-bureaucratic process**
- ESA assumes the **risk and cost** of executing these in-flight experiments
- Each space element has a “theme”

OPS-SAT-1 theme: Communication Protocols

OPS-SAT-2 theme: Optical and Quantum Communication

Images: ESA

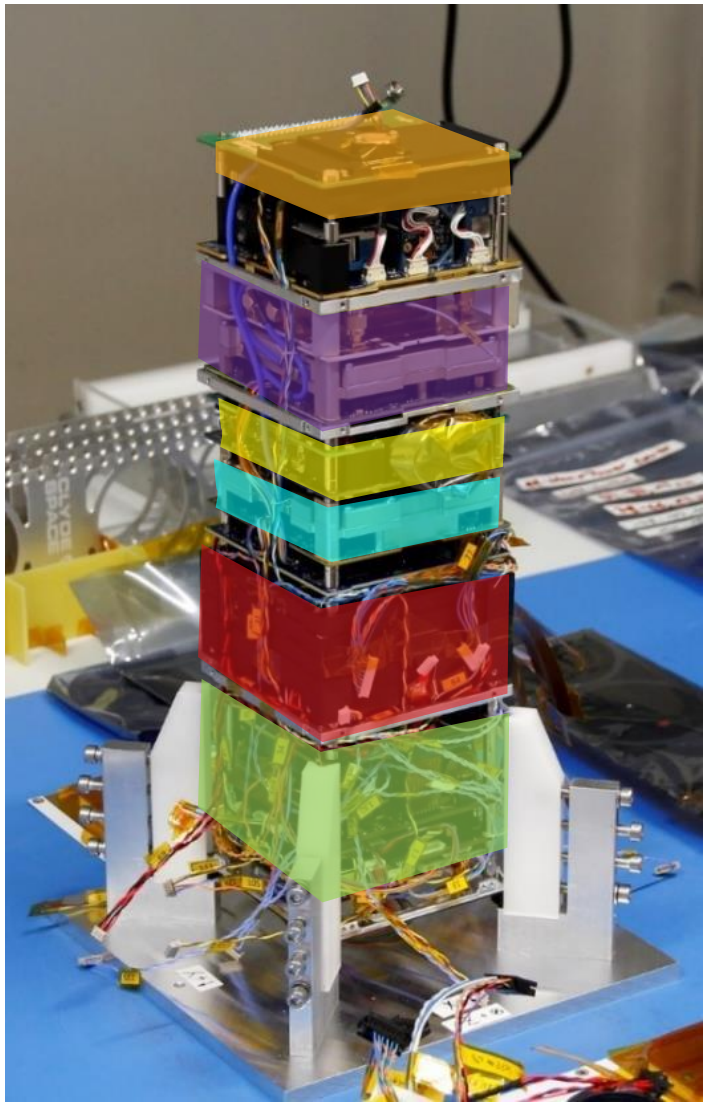
OPS-SAT-1 Hardware

Satellite bus / Platform part:

- Nanomind A3200 on-board computer
- UHF AX100 radio (9.6 kbps↑↓)
- S-band TRX TMTC encoder/decoder (256kbps↑ 1Mbps↓)
- Coarse ADCS system: magnetometer, magnetorquers, photodiodes, gyroscope

Payload / Experimental part:

- Satellite Experimental Processing Platform (SEPP)
  - ALTERA Cyclone V System-on-Chip
  - 800 MHz dual-core ARM CPU; 1GB DDR3 memory
  - FPGA module - reconfigurable for experiments
- Software Defined Radio (LMS6002D)
- GNSS receiver
- HD-camera (Nadir-facing)
- Optical receiver (data uplink via laser)
- Fine ADCS
  - Attitude Determination: magnetometer, star tracker and fine sun sensor
  - Attitude Control: reaction wheels, magnetorquers
- X-band transmitter (3-50 Mbps↓)



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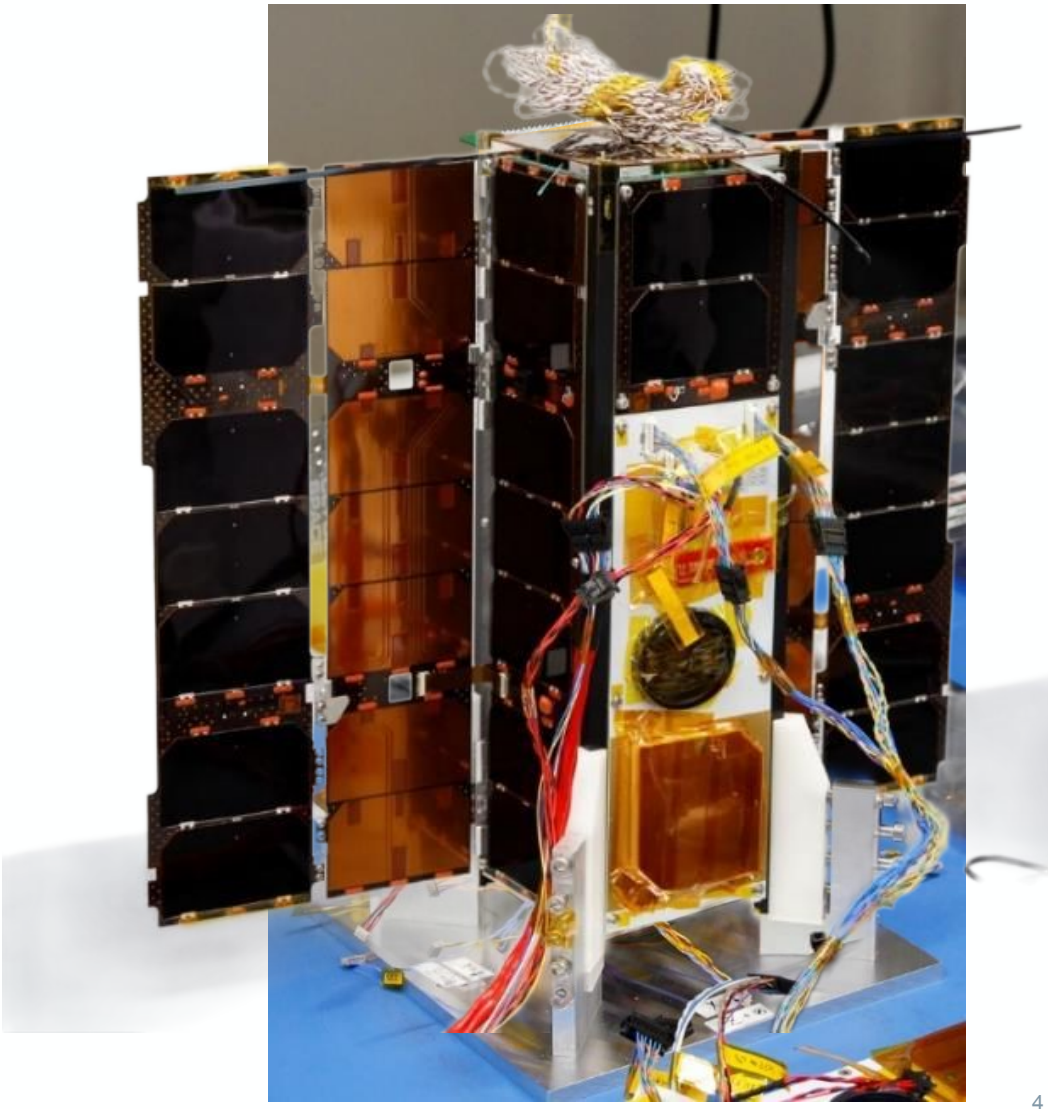
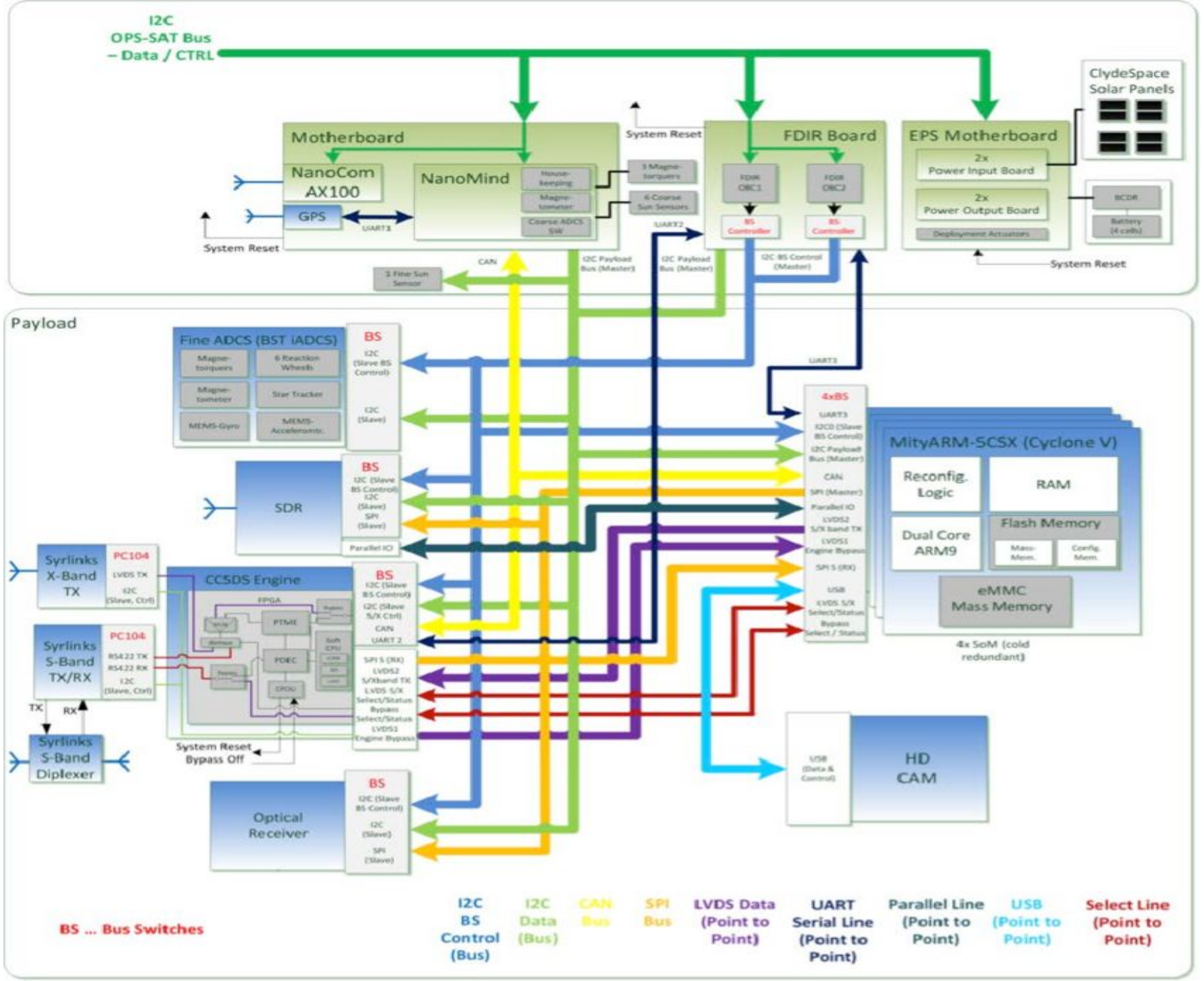


System layout



OPS-SAT-1 Orbit

Launched 2019-12-18 (VS23)

from Kourou with CHEOPS and COSMO-SkyMed SG

Orbit: LEO 515km, Dusk-Dawn Sun-Synchronous Orbit

De-orbited in April 2024

Image: ESA - AOES Medialab

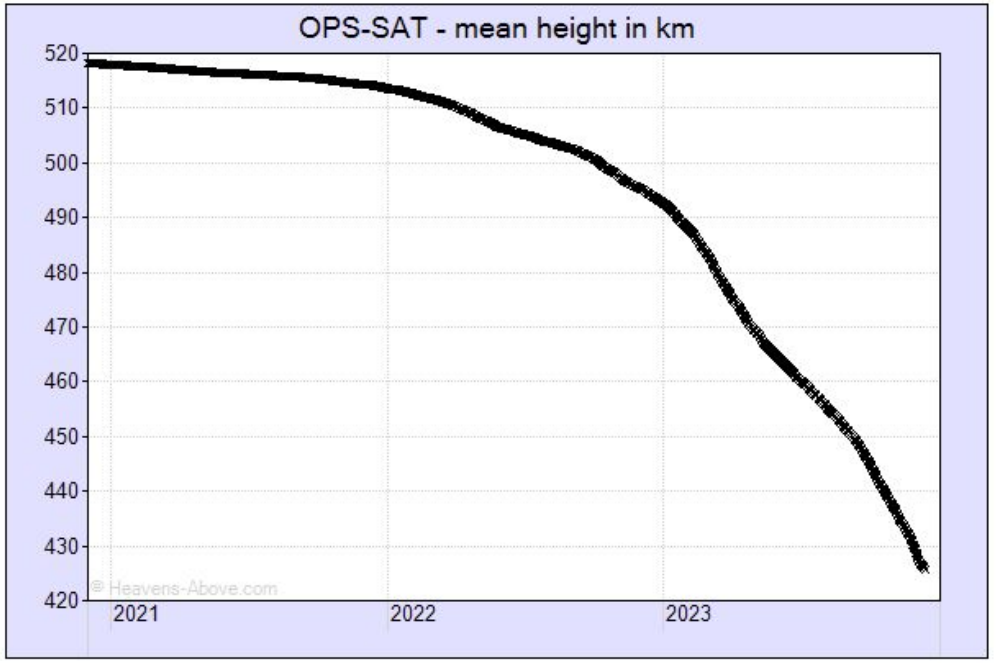


Image: ESA

Image: Arianespace

Ground Segment – SMILE lab & Ground Stations

- SMILE LAB at ESOC

- SMILE = Special Mission Infrastructure Laboratory Environment

- ESOC-1 (S/X)
- ESOC-2 (UHF)
- TUG-1 (UHF), Austria

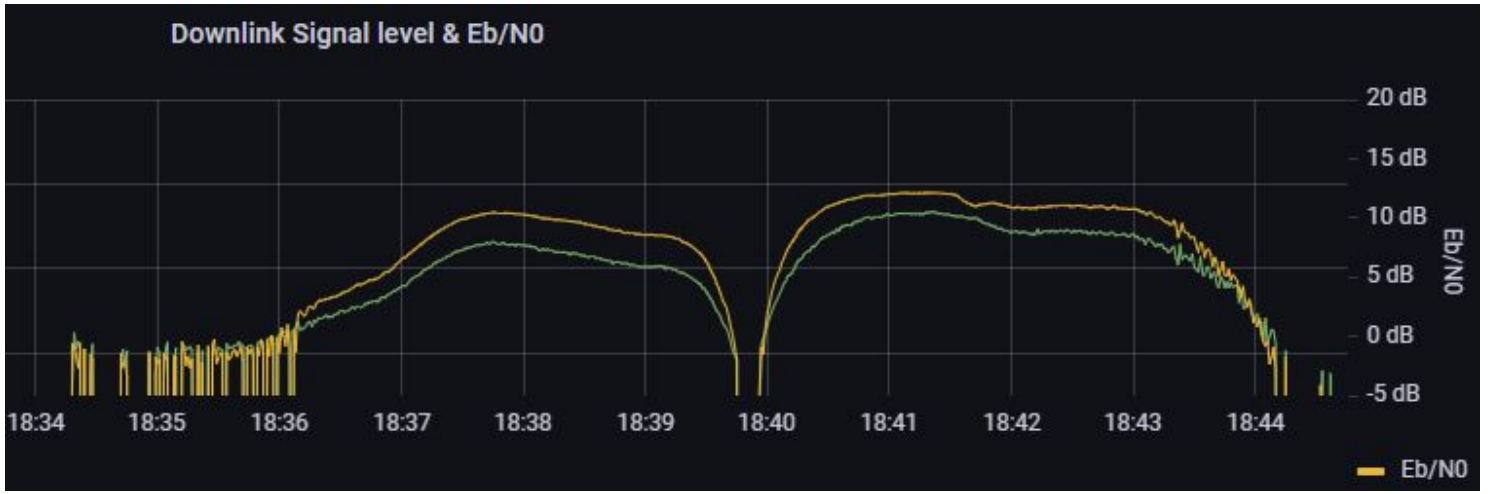
3 frequency bands:

- UHF (437 MHz)
- S-band (2.3 GHz)
- X-band (8.1 GHz)

Ground Segment – S-band / X-band

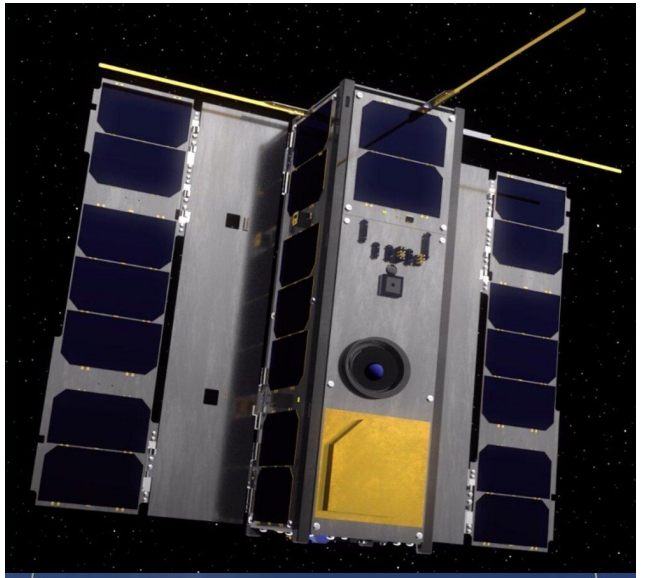
S-band:

- Primary operational communication channel
- 256kbps↑ 1Mbps↓



X-band:

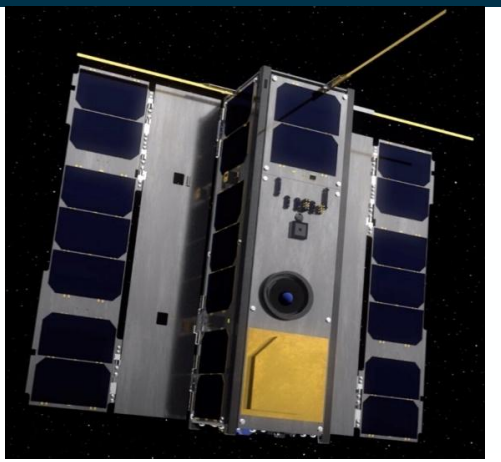
- Operational / experimental channel
- Downlink only
- 3-50Mbps↓

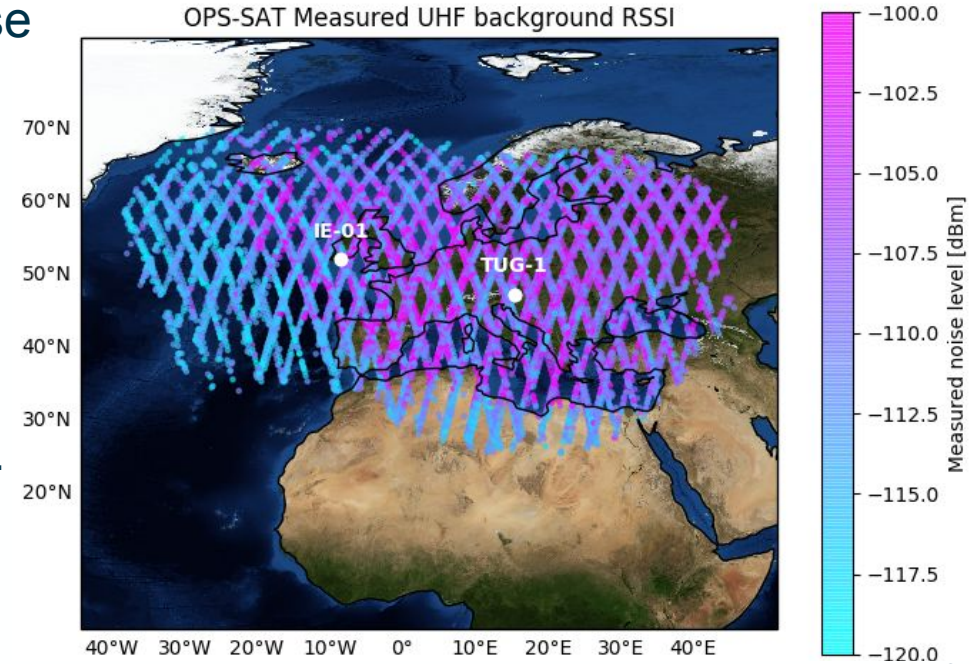


Ground Segment – UHF

UHF Properties:

- UHF Transceiver On-board: GOMspace Nanocom (AX100)
- Low gain UHF antennas in a dipole configuration, allowing nearly omnidirectional coverage
- Uses UHF amateur radio frequencies: 437.2 MHz GMSK
- Uplink / Downlink rates: 9.6 kbps
- Originally calculated uplink budget did not take background noise into account
- Link performed better over some areas / particular times

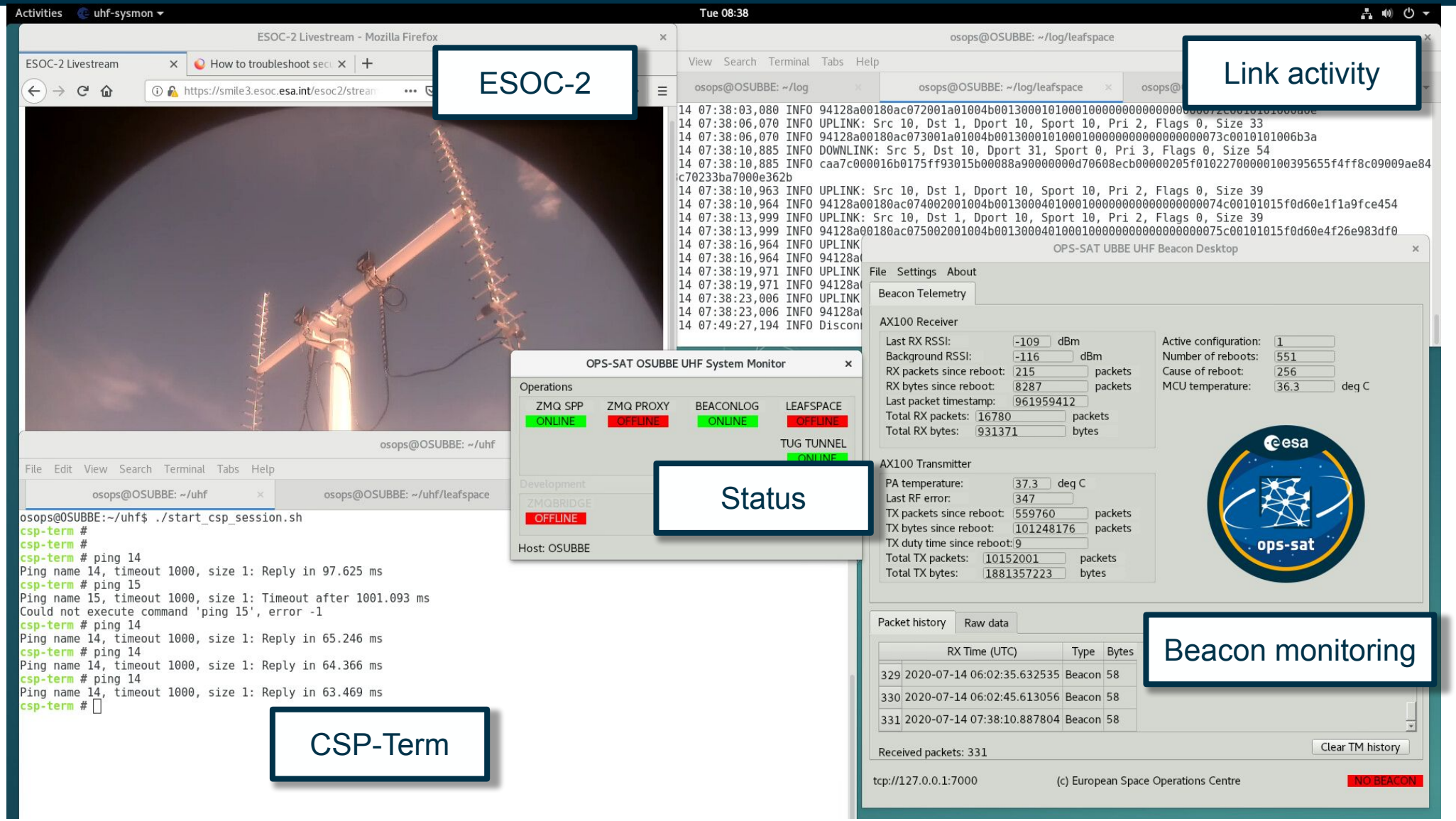




Communication in 2 ways:

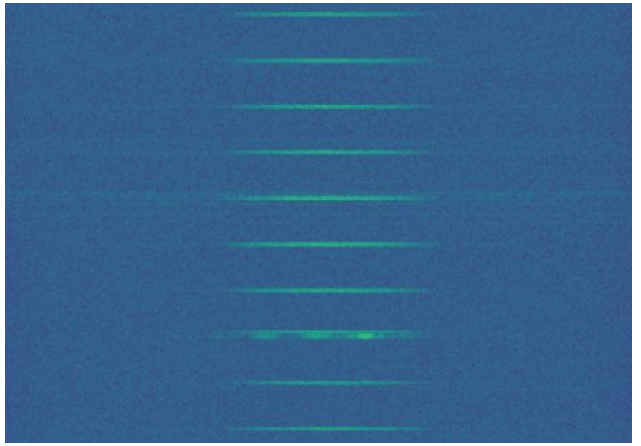
1. Can substitute S-band, Uplink/Downlink rates: 9.6 kbps
2. Uses Cubesat Space Protocol (CSP): Non-CCSDS compatible. Basic TMTC capabilities and beacons: basic telemetry in a single CSP packet, every 10s

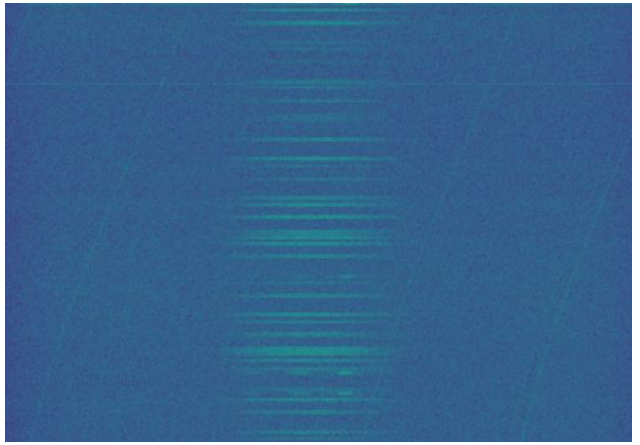
Ground Segment – UHF GUI



Ground Segment – UHF – Radio Amateur Collaboration

Published UHF link specifications and open-source telemetry decoder software (GNU Radio) https://github.com/esa/gr-opssat

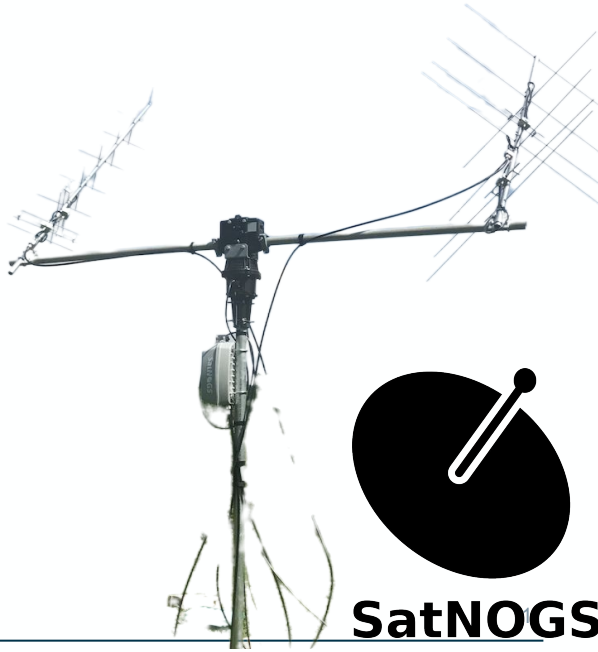




Supported integration into SatNOGS

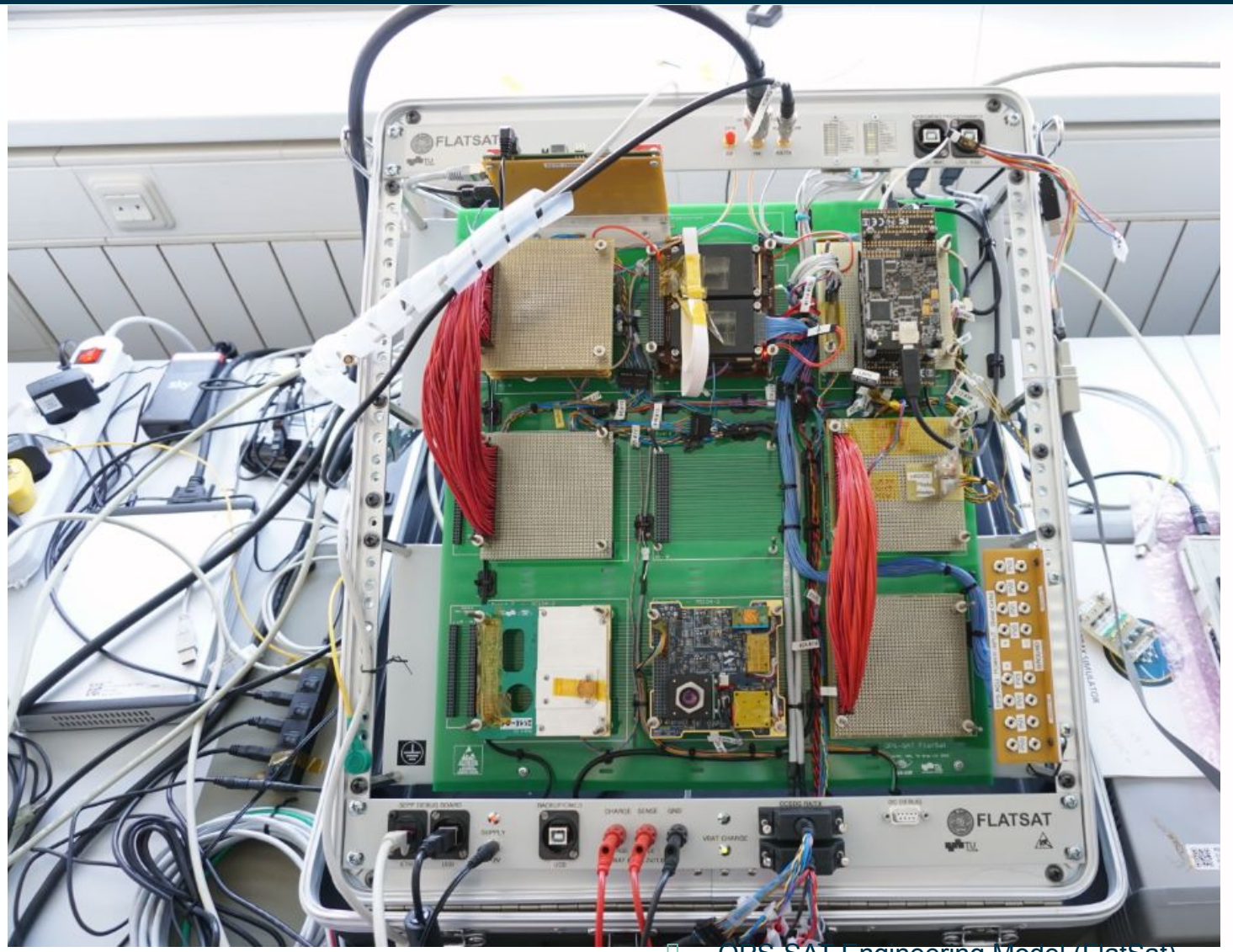
- External Stations receiving and producing artefacts
- Dedicated beacon monitoring webpage
- Received 1M+ UHF packets
- Took 16000+ passes with OPS-SAT
- Were critical to the LEOP phase due to early communications issues

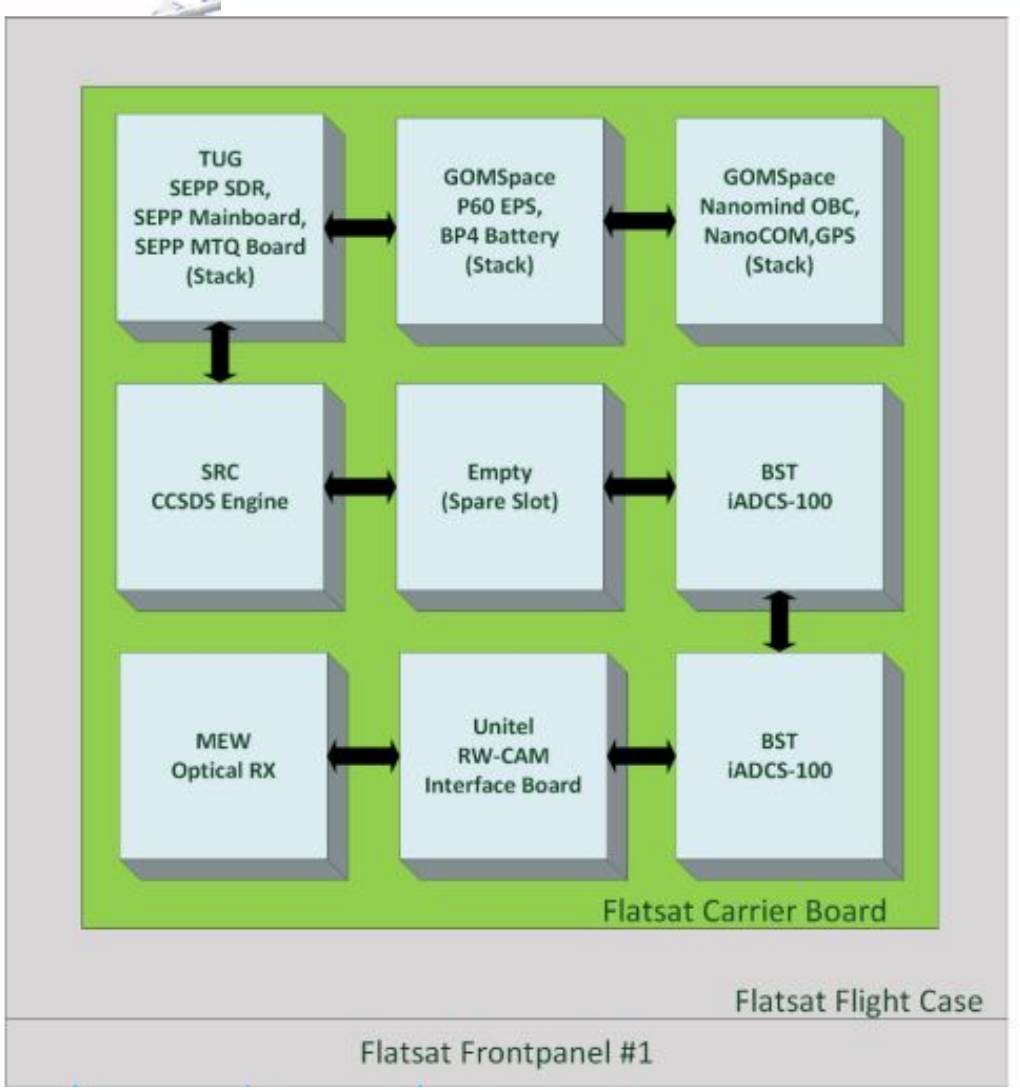
6776435	OPS-SAT	437.200 MHz	MSK AX.100 Mode 6 9600	2022-11-23 10:25:33 2022-11-23 10:28:47		KevinC	1290 - Shed yagi
6780223	OPS-SAT	437.200 MHz	MSK AX.100 Mode 6 9600	2022-11-23 05:40:59 2022-11-23 05:49:57		Brian Yeomans	2760 - M0GKK-BB
6772847	OPS-SAT	437.200 MHz	MSK AX.100 Mode 6 9600	2022-11-23 05:40:46 2022-11-23 05:47:38		erwinunger	2675 - OE6ISP_1
6779329	OPS-SAT	437.200 MHz	MSK AX.100 Mode 6 9600	2022-11-23 05:39:40 2022-11-23 05:51:16		Brian Yeomans	2433 - M0GKK
6772856	OPS-SAT	437.200 MHz	MSK AX.100 Mode 6 9600	2022-11-23 05:39:36 2022-11-23 05:48:49		erwinunger	2859 - OE6EUR15



SatNOGS

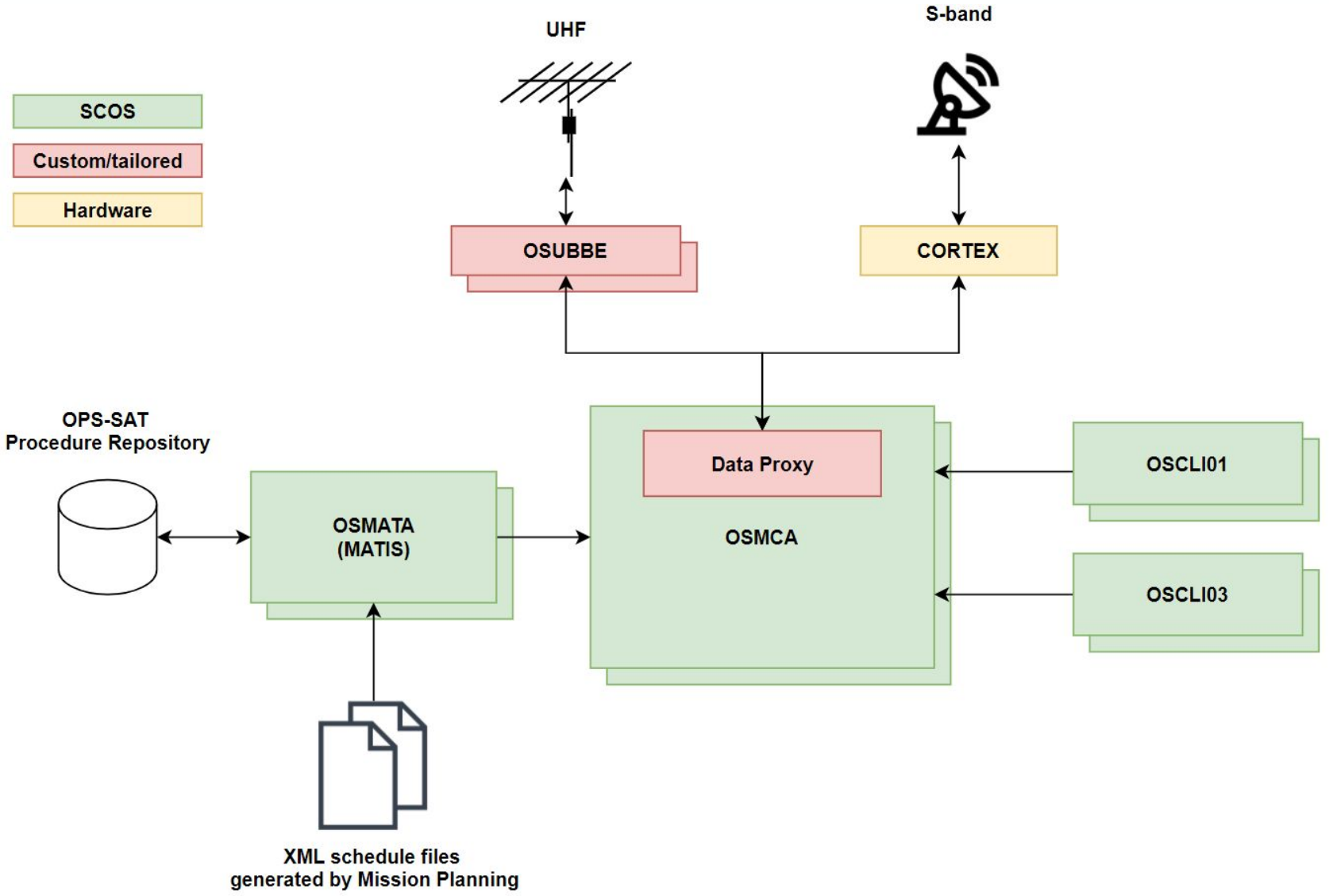
Ground Segment – FlatSat





- OPS-SAT Engineering Model (FlatSat)

Ground Segment – Software

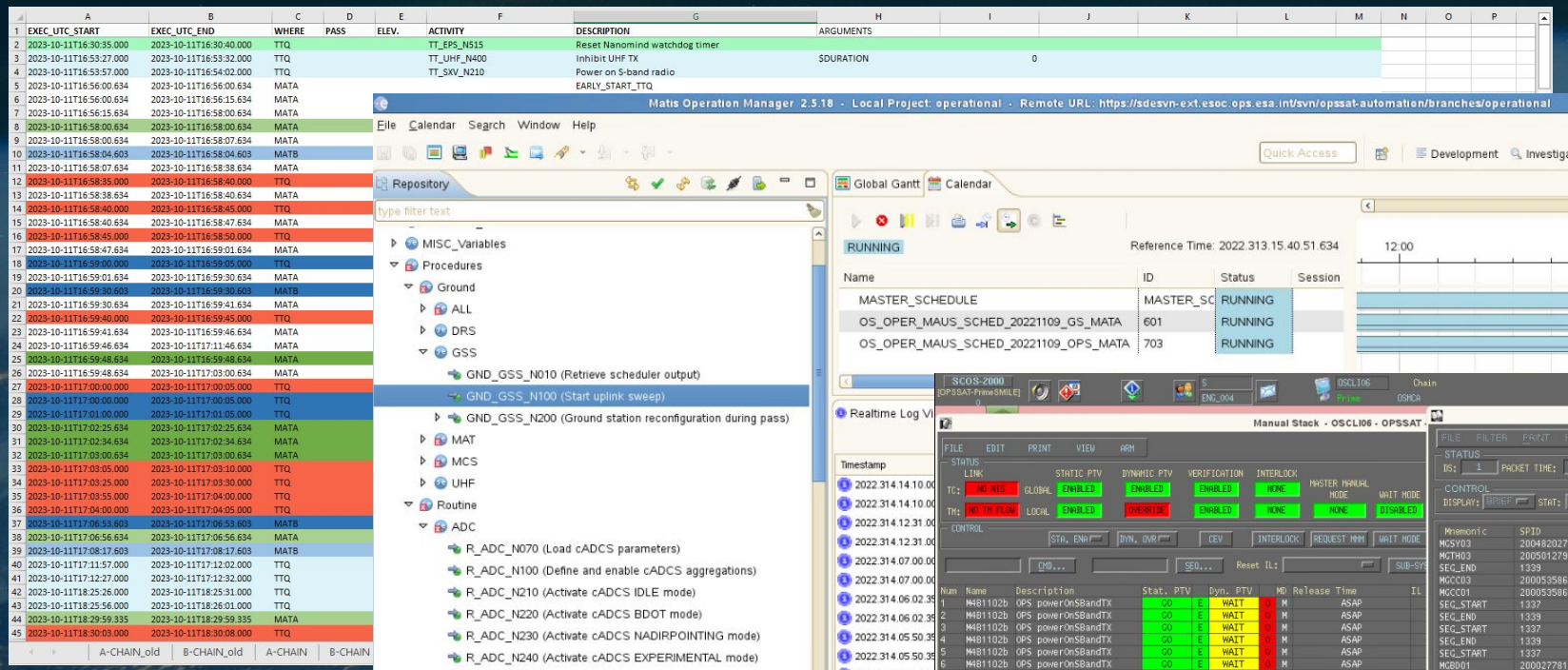


- A-Chain (prime): S-band
- B-Chain (backup): UHF

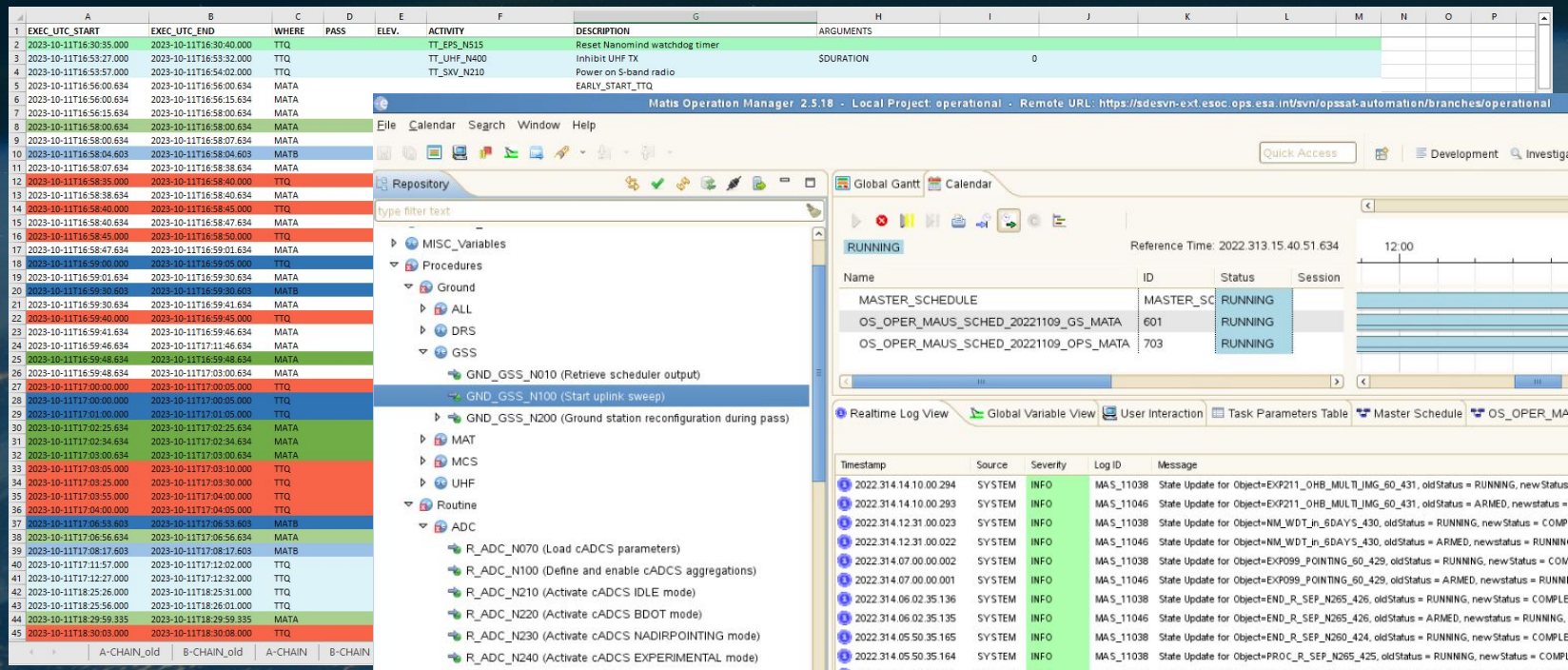
- VMs running on a server
- A/B chain Virtual Machines hosted on separate cluster within server

- ESA SCOS2000 as a frontend + more advanced backend for MATIS automation
- Custom SW: MPS, UHF, Data Proxy

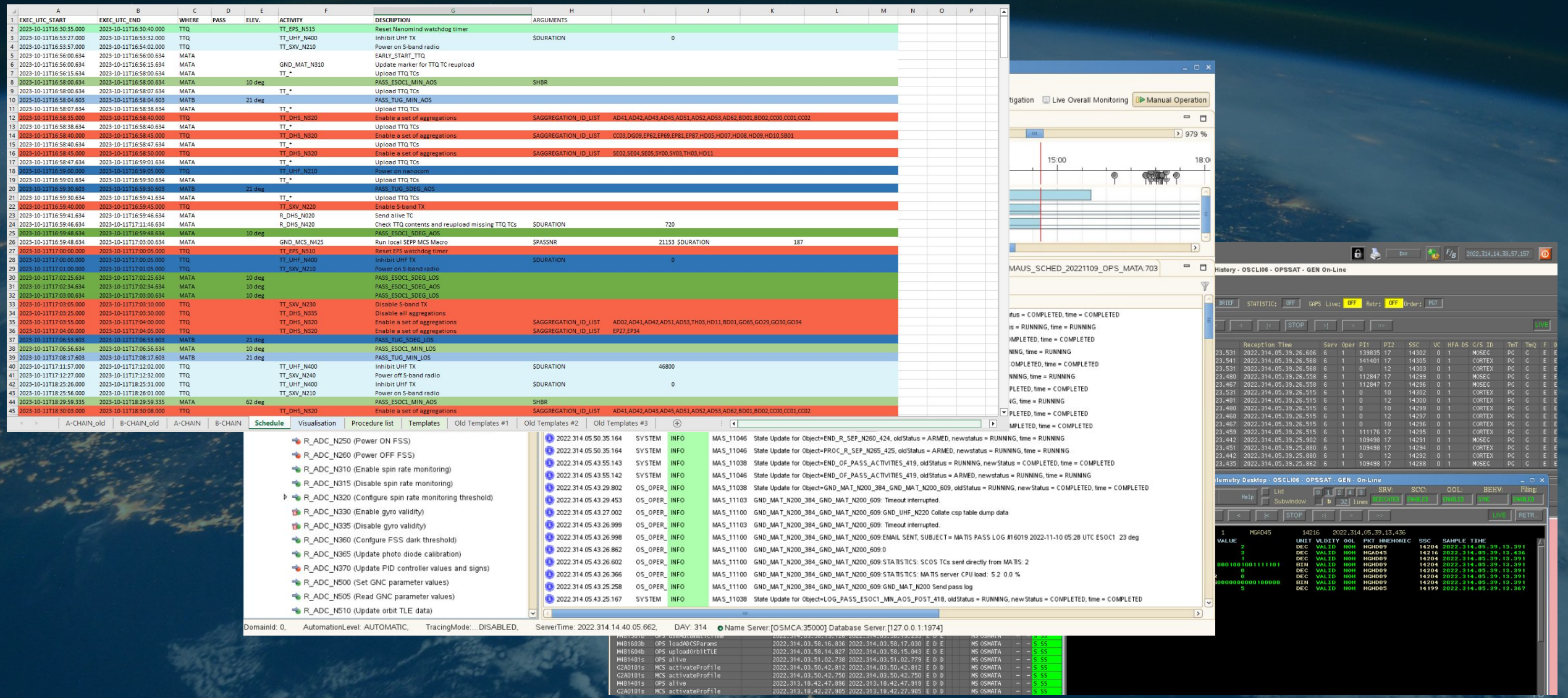
OPS-SAT Operations – MCS and Ground Tools



OPS-SAT Operations – MCS and Ground Tools



OPS-SAT Operations – MCS and Ground Tools



EXEC_UTC_START	EXEC_UTC_END	WHERE	PASS	ELEV.	ACTIVITY	DESCRIPTION	ARGUMENTS								
2023-10-11T16:30:35.000	2023-10-11T16:30:40.000	TTQ			TT_EPS_N515	Reset Nanomind watchdog timer									
2023-10-11T16:53:27.000	2023-10-11T16:53:32.000	TTQ			TT_UHF_N400	Inhibit UHF TX	$DURATION	0							
2023-10-11T16:53:57.000	2023-10-11T16:54:02.000	TTQ			TT_SXV_N210	Power on S-band radio									
2023-10-11T16:56:00.634	2023-10-11T16:56:00.634	MATA				EARLY_START_TTQ									
2023-10-11T16:56:00.634	2023-10-11T16:56:15.634	MATA			GND_MAT_N310	Update marker for TTQ TC reupload									
2023-10-11T16:56:15.634	2023-10-11T16:58:00.634	MATA			TT_*	Upload TTQ TCs									
2023-10-11T16:58:00.634	2023-10-11T16:58:00.634	MATA		10 deg		PASS_ESOC1_MIN_AOS	$HBR								
2023-10-11T16:58:00.634	2023-10-11T16:58:07.634	MATA			TT_*	Upload TTQ TCs									
2023-10-11T16:58:04.603	2023-10-11T16:58:04.603	MATB		21 deg		PASS_TUG_MIN_AOS									
2023-10-11T16:58:07.634	2023-10-11T16:58:38.634	MATA			TT_*	Upload TTQ TCs									
2023-10-11T16:58:35.000	2023-10-11T16:58:40.000	TTQ			TT_DHS_N320	Enable a set of aggregations	$AGGREGATION_ID_LIST	AD41,AD42,AD43,AD45,AD51,AD52,AD53,AD62,BD01,BD02,CC00,CC01,CC02							
2023-10-11T16:58:38.634	2023-10-11T16:58:40.634	MATA			TT_*	Upload TTQ TCs									
2023-10-11T16:58:40.000	2023-10-11T16:58:45.000	TTQ			TT_DHS_N320	Enable a set of aggregations	$AGGREGATION_ID_LIST	CC03,DG09,EP62,EP69,EP81,EP87,HD05,HD07,HD08,HD09,HD10,SB01							
2023-10-11T16:58:40.634	2023-10-11T16:58:47.634	MATA			TT_*	Upload TTQ TCs									
2023-10-11T16:58:45.000	2023-10-11T16:58:50.000	TTQ			TT_DHS_N320	Enable a set of aggregations	$AGGREGATION_ID_LIST	SE02,SE04,SE05,SY00,SY03,TH03,HD11							
2023-10-11T16:58:47.634	2023-10-11T16:59:01.634	MATA			TT_*	Upload TTQ TCs									
2023-10-11T16:59:00.000	2023-10-11T16:59:05.000	TTQ			TT_UHF_N210	Power on nanocom									
2023-10-11T16:59:01.634	2023-10-11T16:59:30.634	MATA			TT_*	Upload TTQ TCs									
2023-10-11T16:59:30.603	2023-10-11T16:59:30.603	MATB		21 deg		PASS_TUG_5DEG_AOS									
2023-10-11T16:59:30.634	2023-10-11T16:59:41.634	MATA			TT_*	Upload TTQ TCs									
2023-10-11T16:59:40.000	2023-10-11T16:59:45.000	TTQ			TT_SXV_N220	Enable S-band TX									
2023-10-11T16:59:41.634	2023-10-11T16:59:46.634	MATA			R_DHS_N020	Send alive TC									
2023-10-11T16:59:46.634	2023-10-11T17:11:46.634	MATA			R_DHS_N420	Check TTQ contents and reupload missing TTQ TCs	$DURATION	720							
2023-10-11T16:59:48.634	2023-10-11T16:59:48.634	MATA		10 deg		PASS_ESOC1_5DEG_AOS									
2023-10-11T16:59:48.634	2023-10-11T17:03:00.634	MATA			GND_MCS_N425	Run local SEPP MCS Macro	$PASSNR	21153	$DURATION	187					
2023-10-11T17:00:00.000	2023-10-11T17:00:05.000	TTQ			TT_EPS_N510	Reset EPS watchdog timer									
2023-10-11T17:00:00.000	2023-10-11T17:00:05.000	TTQ			TT_UHF_N400	Inhibit UHF TX	$DURATION	0							
2023-10-11T17:01:00.000	2023-10-11T17:01:05.000	TTQ			TT_SXV_N210	Power on S-band radio									
2023-10-11T17:02:25.634	2023-10-11T17:02:25.634	MATA		10 deg		PASS_ESOC1_5DEG_LOS									
2023-10-11T17:02:34.634	2023-10-11T17:02:34.634	MATA		10 deg		PASS_ESOC1_5DEG_AOS									
2023-10-11T17:03:00.634	2023-10-11T17:03:00.634	MATA		10 deg		PASS_ESOC1_5DEG_LOS									
2023-10-11T17:03:05.000	2023-10-11T17:03:10.000	TTQ			TT_SXV_N230	Disable S-band TX									
2023-10-11T17:03:25.000	2023-10-11T17:03:30.000	TTQ			TT_DHS_N335	Disable all aggregations									
2023-10-11T17:03:55.000	2023-10-11T17:04:00.000	TTQ			TT_DHS_N320	Enable a set of aggregations	$AGGREGATION_ID_LIST	AD02,AD41,AD42,AD51,AD53,TH03,HD11,BD01,GO65,GO29,GO30,GO34							
2023-10-11T17:04:00.000	2023-10-11T17:04:05.000	TTQ			TT_DHS_N320	Enable a set of aggregations	$AGGREGATION_ID_LIST	EP27,EP34							
2023-10-11T17:06:53.603	2023-10-11T17:06:53.603	MATB		21 deg		PASS_TUG_5DEG_LOS									
2023-10-11T17:06:56.634	2023-10-11T17:06:56.634	MATA		10 deg		PASS_ESOC1_MIN_LOS									
2023-10-11T17:08:17.603	2023-10-11T17:08:17.603	MATB		21 deg		PASS_TUG_MIN_LOS									
2023-10-11T17:11:57.000	2023-10-11T17:12:02.000	TTQ			TT_UHF_N400	Inhibit UHF TX	$DURATION	46800							
2023-10-11T17:12:27.000	2023-10-11T17:12:32.000	TTQ			TT_SXV_N240	Power off S-band radio									
2023-10-11T18:25:26.000	2023-10-11T18:25:31.000	TTQ			TT_UHF_N400	Inhibit UHF TX	$DURATION	0							
2023-10-11T18:25:56.000	2023-10-11T18:26:01.000	TTQ			TT_SXV_N210	Power on S-band radio									
2023-10-11T18:29:59.335	2023-10-11T18:29:59.335	MATA		62 deg		PASS_ESOC1_MIN_AOS	$HBR								
2023-10-11T18:30:03.000	2023-10-11T18:30:08.000	TTQ			TT_DHS_N320	Enable a set of aggregations	$AGGREGATION_ID_LIST	AD41,AD42,AD43,AD45,AD51,AD52,AD53,AD62,BD01,BD02,CC00,CC01,CC02							

A-CHAIN_old | B-CHAIN_old | A-CHAIN | B-CHAIN | Schedule | Visualisation | Procedure list | Templates | Old Templates #1 | Old Templates #2 | Old Templates #3

- R_ADC_N250 (Power ON FSS)
- R_ADC_N260 (Power OFF FSS)
- R_ADC_N310 (Enable spin rate monitoring)
- R_ADC_N315 (Disable spin rate monitoring)
- R_ADC_N320 (Configure spin rate monitoring threshold)
- R_ADC_N330 (Enable gyro validity)
- R_ADC_N335 (Disable gyro validity)
- R_ADC_N360 (Confgure FSS dark threshold)
- R_ADC_N365 (Update photo diode calibration)
- R_ADC_N370 (Update PID controller values and signs)
- R_ADC_N500 (Set GNC parameter values)
- R_ADC_N505 (Read GNC parameter values)
- R_ADC_N510 (Update orbit TLE data)

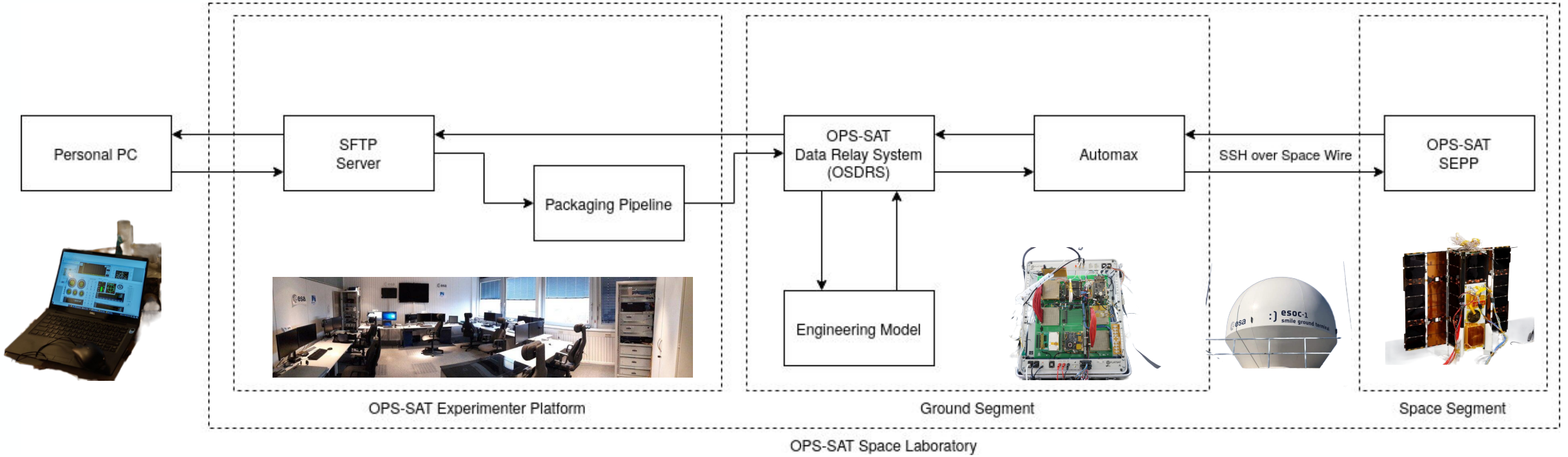
2022.314.05.50.35.164	SYSTEM	INFO	MAS_11046	State Update for Object=END_R_SEP_N260_424, oldStatus = ARMED, newstatus = RUNNING, time = RUNNING
2022.314.05.50.35.164	SYSTEM	INFO	MAS_11046	State Update for Object=PROC_R_SEP_N265_425, oldStatus = ARMED, newstatus = RUNNING, time = RUNNING
2022.314.05.43.55.143	SYSTEM	INFO	MAS_11038	State Update for Object=END_OF_PASS_ACTIVITIES_419, oldStatus = RUNNING, newStatus = COMPLETED, time = COMPLETED
2022.314.05.43.55.142	SYSTEM	INFO	MAS_11046	State Update for Object=END_OF_PASS_ACTIVITIES_419, oldStatus = ARMED, newstatus = RUNNING, time = RUNNING
2022.314.05.43.29.802	OS_OPER_	INFO	MAS_11038	State Update for Object=GND_MAT_N200_384_GND_MAT_N200_609, oldStatus = RUNNING, newStatus = COMPLETED, time = COMPLETED
2022.314.05.43.29.453	OS_OPER_	INFO	MAS_11103	GND_MAT_N200_384_GND_MAT_N200_609: Timeout interrupted.
2022.314.05.43.27.002	OS_OPER_	INFO	MAS_11100	GND_MAT_N200_384_GND_MAT_N200_609:GND_UHF_N220 Collate csp table dump data
2022.314.05.43.26.999	OS_OPER_	INFO	MAS_11103	GND_MAT_N200_384_GND_MAT_N200_609: Timeout interrupted.
2022.314.05.43.26.998	OS_OPER_	INFO	MAS_11100	GND_MAT_N200_384_GND_MAT_N200_609:EMAIL SENT, SUBJECT = MATIS PASS LOG #16019 2022-11-10 05:28 UTC ESOC1 23 deg
2022.314.05.43.26.862	OS_OPER_	INFO	MAS_11100	GND_MAT_N200_384_GND_MAT_N200_609:0
2022.314.05.43.26.602	OS_OPER_	INFO	MAS_11100	GND_MAT_N200_384_GND_MAT_N200_609:STATISTICS: SCOS TCs sent directly from MATIS: 2
2022.314.05.43.26.366	OS_OPER_	INFO	MAS_11100	GND_MAT_N200_384_GND_MAT_N200_609:STATISTICS: MATIS server CPU load: 5.2 0.0 %
2022.314.05.43.25.258	OS_OPER_	INFO	MAS_11100	GND_MAT_N200_384_GND_MAT_N200_609:GND_MAT_N200 Send pass log
2022.314.05.43.25.167	SYSTEM	INFO	MAS_11038	State Update for Object=LOG_PASS_ESOC1_MIN_AOS_POST_418, oldStatus = RUNNING, newStatus = COMPLETED, time = COMPLETED

DomainId: 0, AutomationLevel: AUTOMATIC, TracingMode:...DISABLED, ServerTime: 2022.314.14.40.05.662, DAY: 314 Name Server:[OSMCA:35000] Database Server:[127.0.0.1:1974]

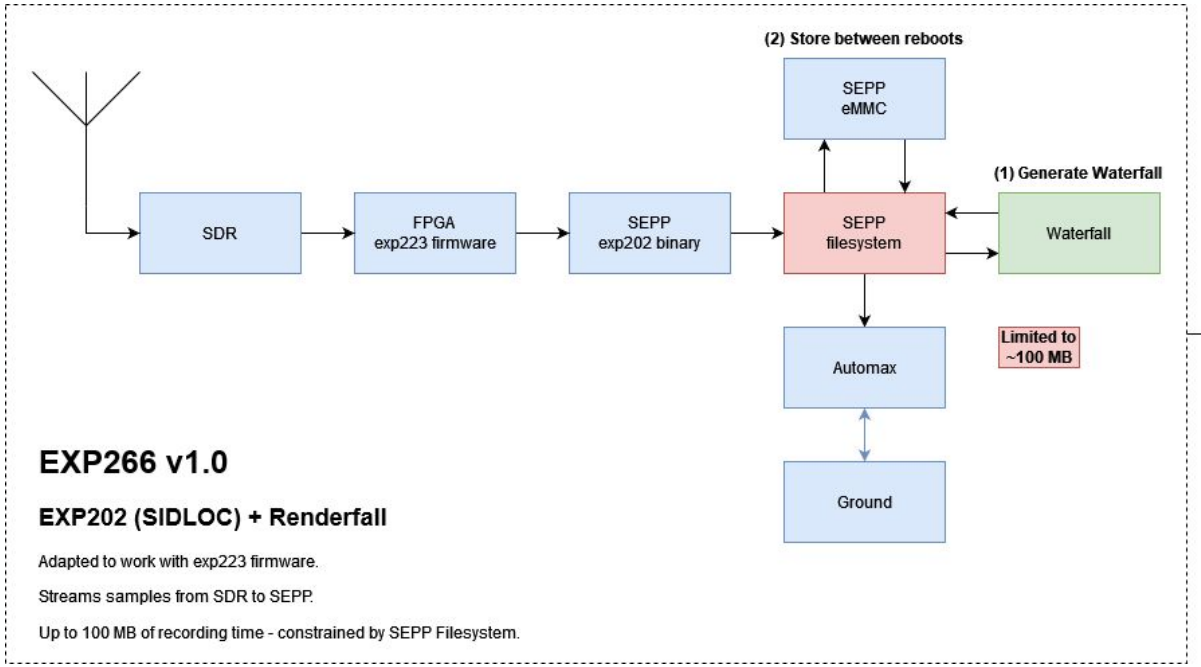
MIB1603b	OPS	loadADCSParams	2022.314.03.58.16.806	2022.314.03.58.17.000	E	D	E	MS OSMATA	S
MIB1604b	OPS	uploadOrbitTLE	2022.314.03.58.14.827	2022.314.03.58.15.043	E	D	E	MS OSMATA	S
MIB1401s	OPS	alive	2022.314.03.51.02.738	2022.314.03.51.02.779	E	D	D	MS OSMATA	S
G2A0101s	MCS	activateProfile	2022.314.03.50.42.812	2022.314.03.50.42.812	E	D	D	MS OSMATA	S
G2A0101s	MCS	activateProfile	2022.314.03.50.42.750	2022.314.03.50.42.750	E	D	D	MS OSMATA	S
MIB1401s	OPS	alive	2022.313.18.42.47.896	2022.313.18.42.47.919	E	D	D	MS OSMATA	S
G2A0101s	MCS	activateProfile	2022.313.18.42.27.905	2022.313.18.42.27.905	E	D	D	MS OSMATA	S

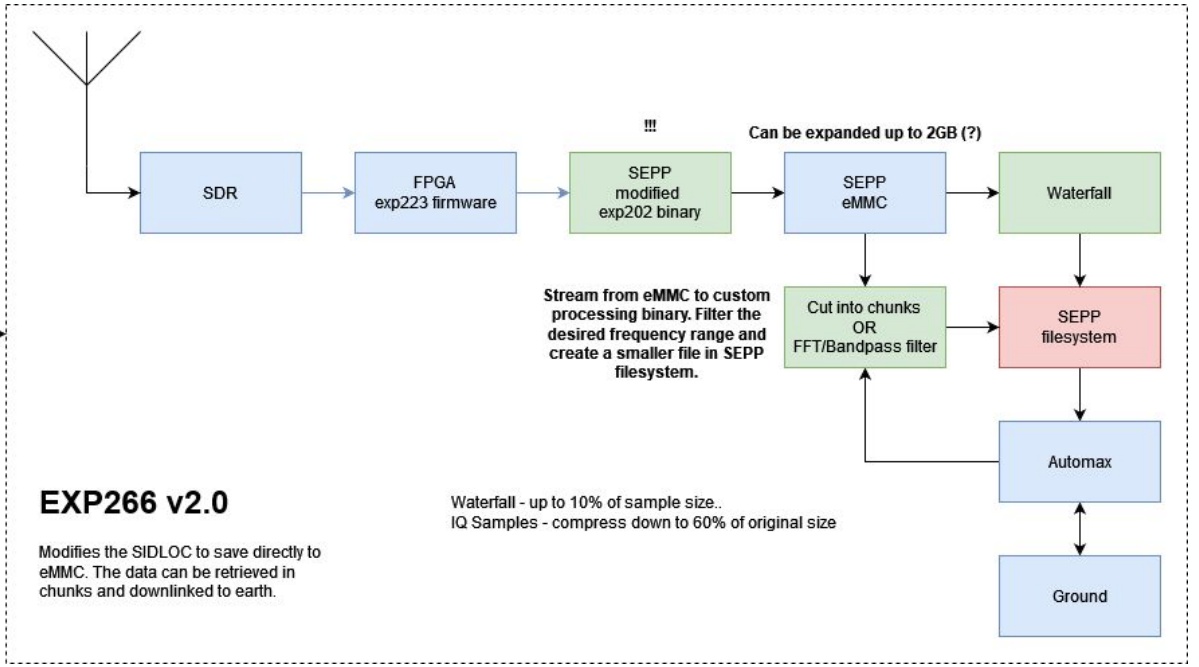
Experimenter pipeline

OPKG (OpenWrt) package format



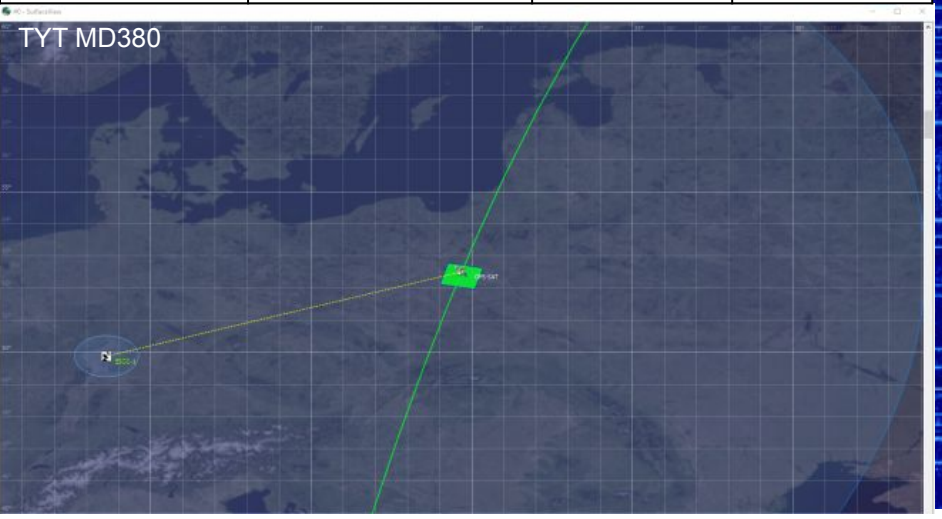
Master Thesis – SDR Subsystem Data Handling

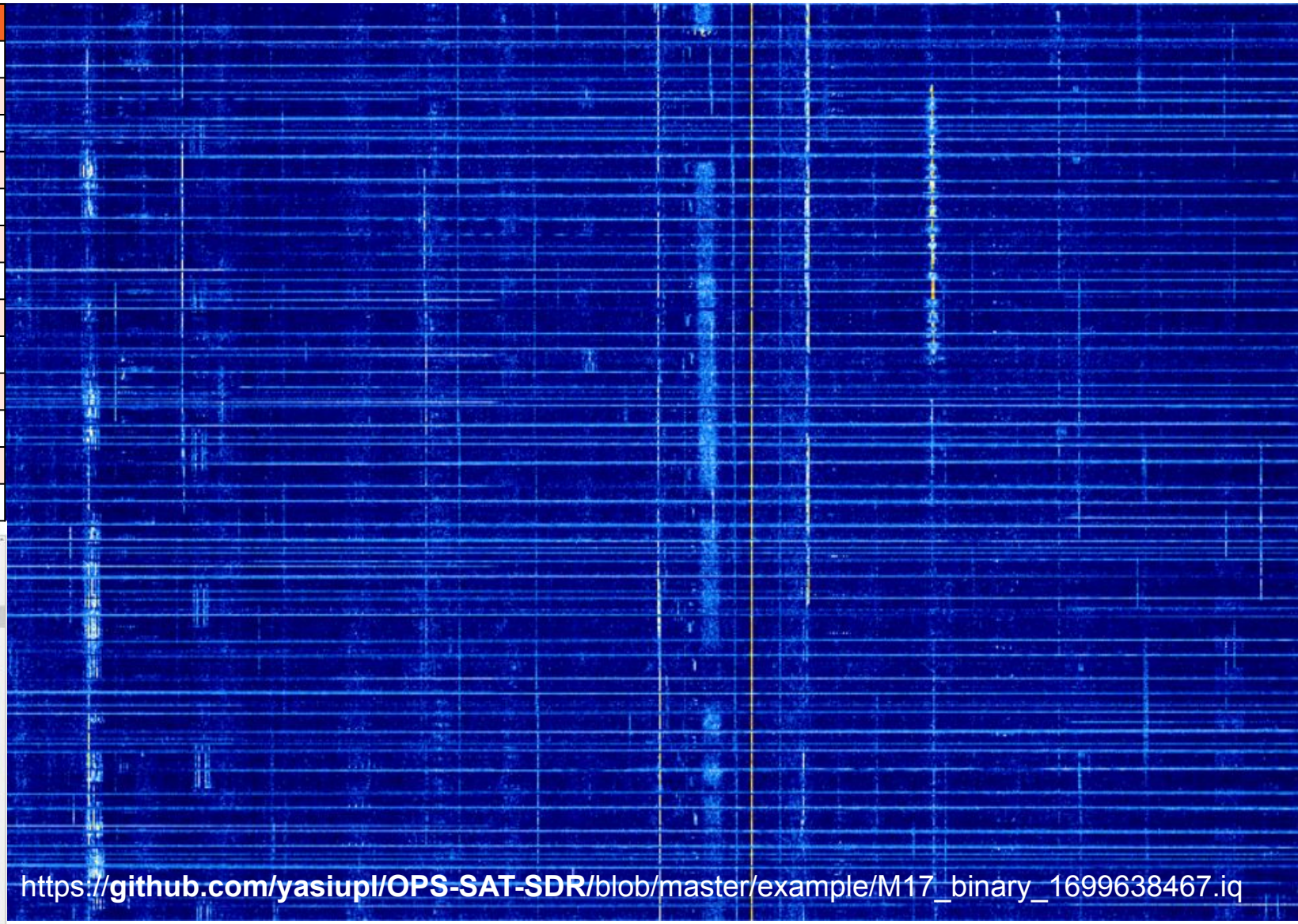




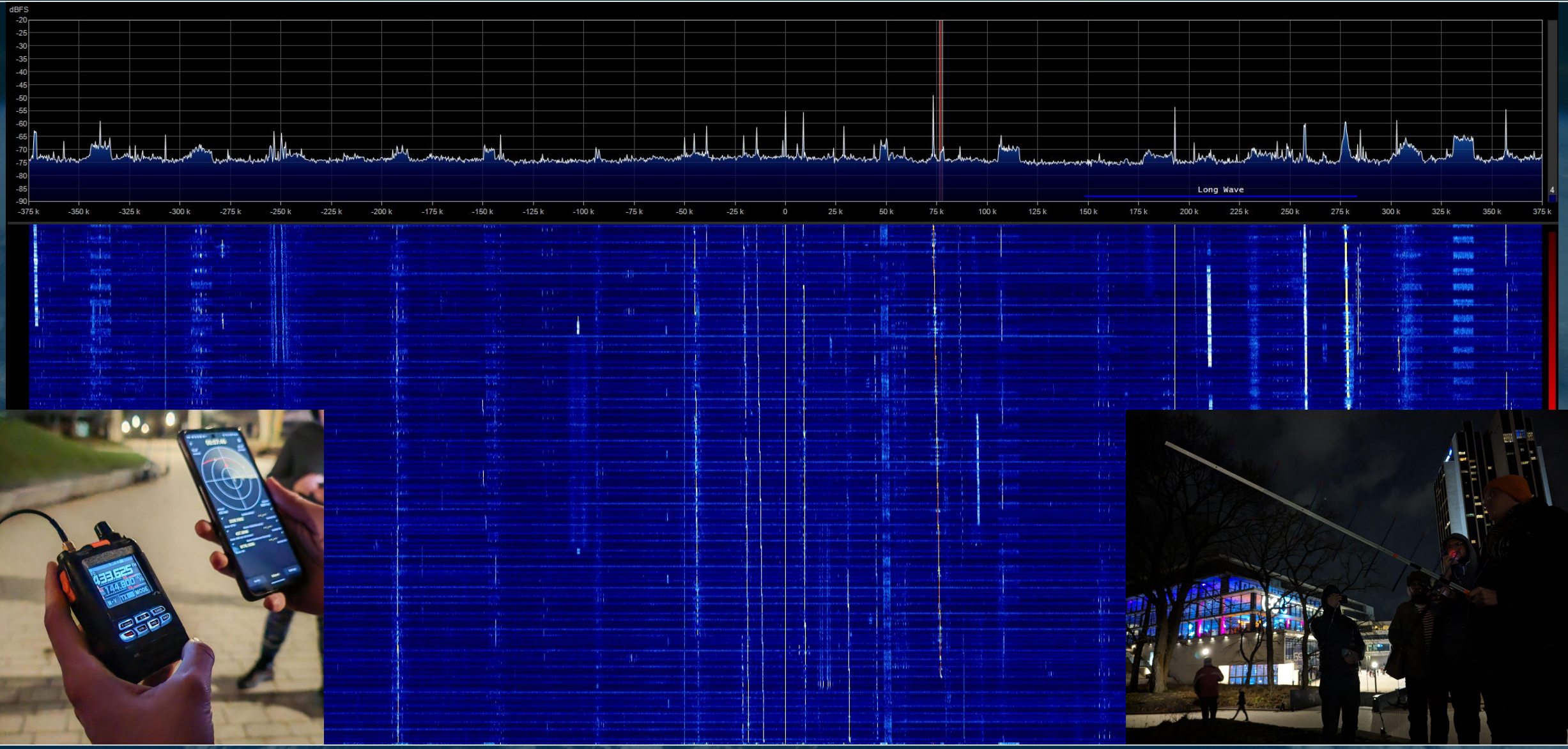
First test trial with M17 and SP5WWP

Component	Description	Value	Unit
Transmitter	Transmit Power	34.77	dBm
	Yagi elements	7	
	Antenna Gain	9.88	dBi
	Cable Loss	0.25	dB
Path	Distance	500000	m
	Frequency	433.475	MHz
	Wavelength	692.08	mm
	Free Space Loss	139.169	dB
Satellite	Antenna Gain	19.5	dBi
	Cable Loss	0.25	dB
	Receiver sensitivity	-98	dBm
System	Expected Signal Level	-75.519	dBm
	Link Margin	22.481	dBm

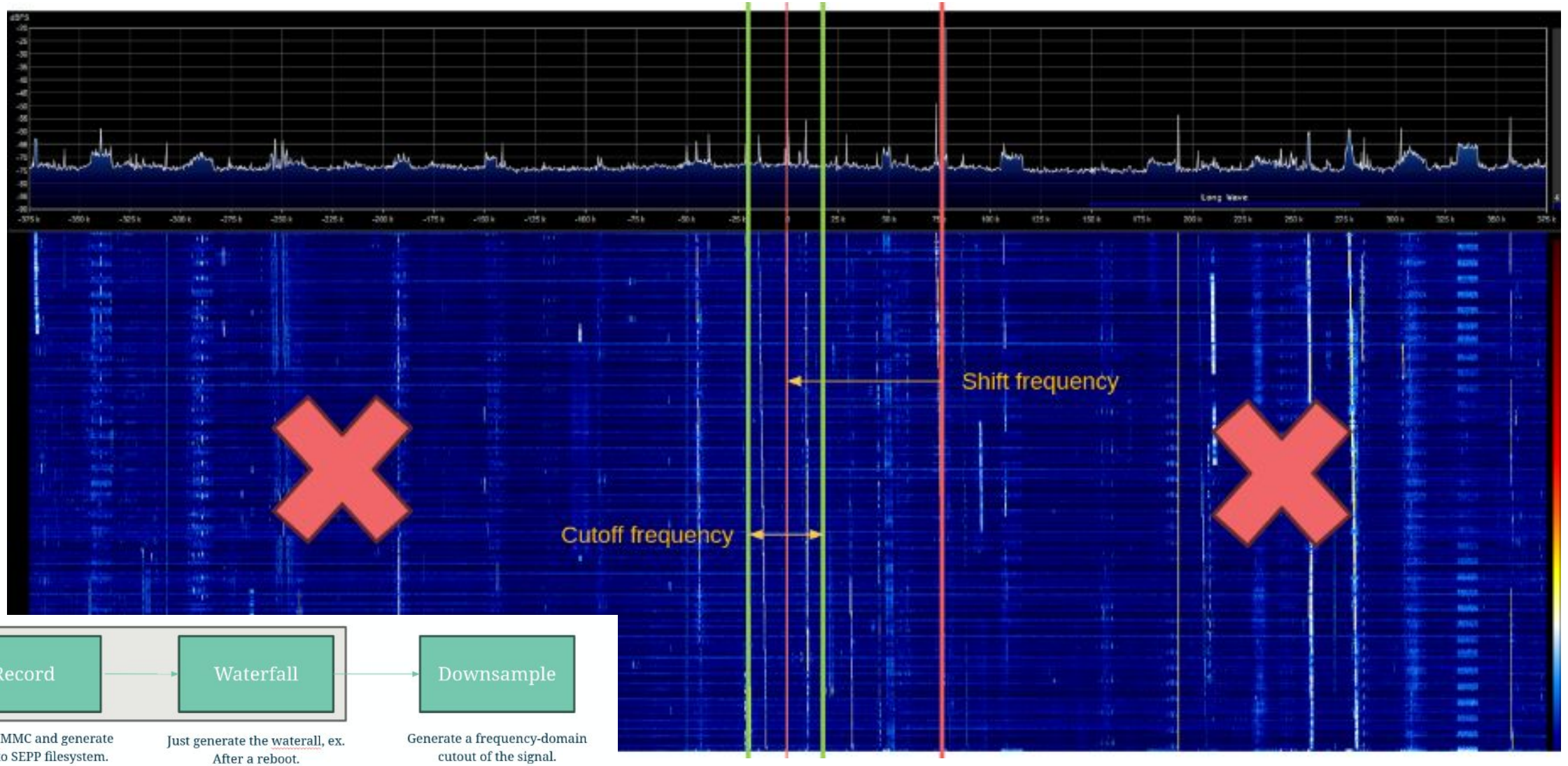




Final test - 37C3 in Hamburg



SDR Operations experiment



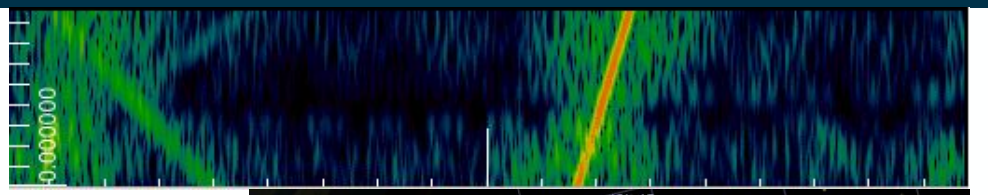
Record to eMMC and generate waterfall to SEPP filesystem.

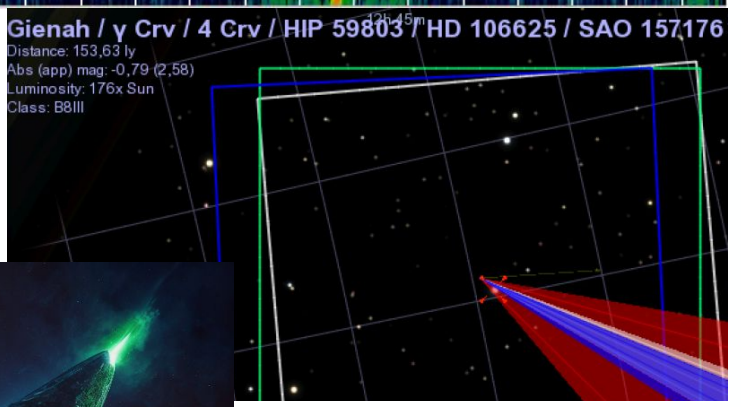
Just generate the waterall, ex. After a reboot.

Generate a frequency-domain cutout of the signal.

OPS-SAT Experiment Highlights

- Autonomous ADCS control
- Astrometry via CubeSat
- Compression algorithms -> part of the operational routine
- FPGA experiments running routinely
- Rover operations via OPS-SAT
- SDR experiments acquiring and processing radio signals on-board
- Telecommanding by experimenters over the internet
- Different experiments building on top of each other





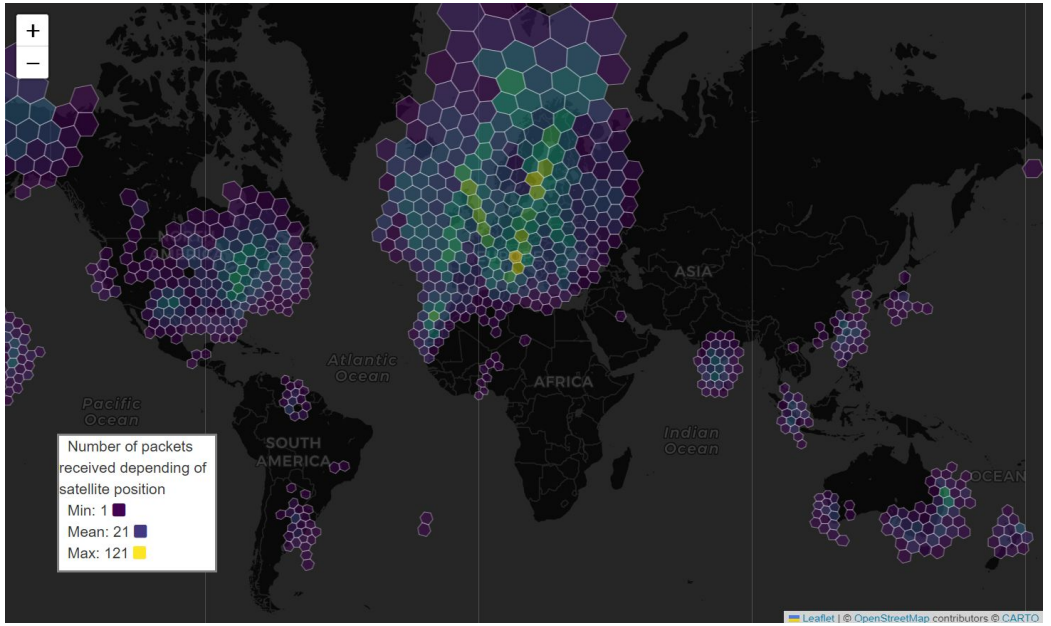
Firsts by OPS-SAT:

- First in-orbit use of CFDP by ESA (CCSDS file delivery protocol)
- First ML model training done on-board an ESA mission
- First stock trade in space
- First S/C controlled via the new ESA MCS
- First cybersecurity test on a flying spacecraft!
- First chess match in space (https://chess-ops.space)

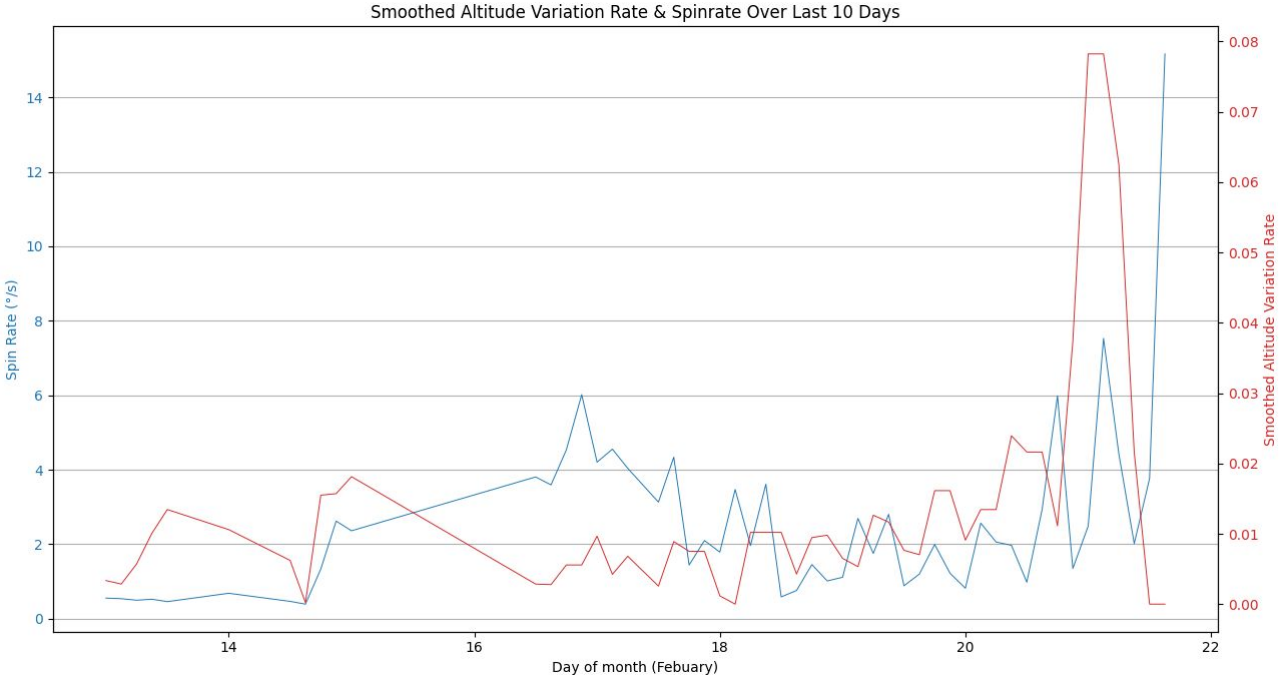

Ladies and Gentelman. We have officialy run Doom on OPS-SAT!
[2023-12-28 18:16:40] 2023-12-28 18:16:36 OK - /home/exp272/demos/e
[2023-12-28 18:16:40] 2023-12-28 18:16:36 OK - /home/exp272/demos/u
[2023-12-28 18:16:40] 2023-12-28 18:16:37 OK - /home/exp272/demos/m
[2023-12-28 18:16:40] 2023-12-28 18:16:38 OK - /home/exp272/demos/m
[2023-12-28 18:16:40] 2023-12-28 18:16:39 OK - /home/exp272/demos/m
[2023-12-28 18:16:40] + cd toGround/
8
AMMO
96%
HEALTH
2 3 4
5 6 7
ARMS
98%
ARMOR
BULL 105 / 200
SHEL 0 / 50
RCKT 0 / 50
CELL 0 / 300

Radio Amateurs Campaign and End of Life

- SatNOGS: Worldwide coverage
- Telemetry Analysis
- Telemetry dataset is publicly available on https://opssat.esa.int/



UHF ground coverage



Thank you for your attention!

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