LUNANET SOFTWARE DEFINED RECEIVER

NAVISP EL1-023 BIS

NAVISP Final Presentation

Contract Number:	4000133501/20/NL/GP
Code:	GMV-LUNANET SDR-NAVISP
Version:	V1.0
Date:	05/06/2026
Internal Code:	GMV

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Agenda

- Company Introduction
- Introduction to the LunaNet SW defined receiver project
- High Level Architecture of Receiver and Signal Simulator
- EGSE Tool and Experimental setup
- Test Campaign and Results
- Conclusions and Next Steps

Company Introduction

GMV, a European Global Technology Group

Multinational technology group

Headquarters in Spain (Madrid)

Private capital

c.a. 4000 employees

+530 M€ worldwide revenue

Companies in 12 countries, 8 EU MS (ops in 70+)

CMMI level 5

CMMIDEV/5

Space

#1 Worldwide in satellite control segments

Leader in ground segment for space missions
(+900 spacecrafts use GMV technology)

Prime contractor of GOVSATCOM Hub

Responsible of GNSS safety critical systems (Egnos and Galileo)

Prime contractor of the Galileo Ground Control Segment (& G2 IOV GCS)

Prime contractor of LEO PNT IOD

Defense and Security

Reference supplier of multidomain C4ISR

Leader in Resilient Position Navigation and Timming systems in all domains

Intelligent Transportation Systems

Leader of Intelligent Transportation Systems for the public transport sector
(+100 cities in 5 continents)

Leader on Highly Precise & Safe GNSS Positioning Engine for Autonomous Driving

Information Technologies

Pioneer in security for banking and telcos and Reference Supplier for European Space, Defense and Security Agencies

Worldwide leader cybersecurity protection for ATMs

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GMV in the UK

GMV UK is a Leading UK Supplier of Space and PNT Technology

UK based subsidiary of GMV

- ~100 people with offices in Nottingham and Harwell
- Currently based at two sites (Nottingham and Harwell)
- ISO 9001 certified Company
- Undergoing accreditations for UK MOD

Major Customers

- UK Space Agency
- European Space Agency
- UK Ministry of Defence (including DSTL)
- Square Kilometre Array

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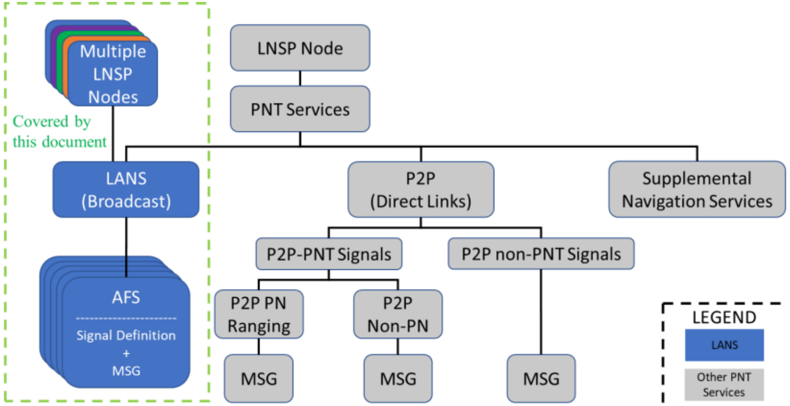
Introduction to the LunaNet SW defined receiver project

- ❑ LunaNet Interoperability Specification (LNIS) defines the framework for lunar communication and navigation services.
- ❑ A key component is the Lunar Augmented Navigation Service (LANS).
- ❑ LANS provides an S-Band Radionavigation Satellite Service (RNSS) through the Augmented Forward Signal (AFS).
- ❑ The service is based on principles similar to terrestrial GNSS.
- ❑ LANS enables simultaneous navigation support from multiple provider nodes to multiple lunar users.
- ❑ Designed to support future lunar PNT applications.
- ❑ Operates in the 2483.5–2500 MHz band using the AFS signal. (centered at 2492.028Mhz, derived from 2436 times 1.023MHz)



PNT Services Provided by Multiple LNSPs - (LSIS-AFS) VER 1

The first service providers:

- ❑ NASA's LCRNS
- ❑ European Space Agency's Moonlight LCNS
- ❑ Japan's LNSS

LCNS space segment:

For the Present Work:

- Latest available information from Moonlight
- At least four navigation satellites in LCNS at ELFO.

❑ The initial capabilities focus on lunar south pole region

Introduction to the LunaNet SW defined receiver project

Project Overview and Objectives

Background:

- Reliable Positioning, Navigation, and Timing (PNT) services are essential for future lunar exploration.
- LunaNet's LANS aims to provide navigation support through dedicated lunar communication and navigation signals.
- SDR technology enables rapid prototyping, validation, and performance assessment of emerging lunar navigation concepts.
- A real-time receiver implementation is required to evaluate the performance under representative lunar scenarios.

Key Objectives:

- Develop a real-time SDR-based LunaNet LANS AFS receiver on the Zynq-7030 platform.
- Design and implement acquisition, tracking, navigation message decoding, and PVT estimation algorithms.
- Develop an AFS signal simulator for representative lunar scenario signal generation.
- Establish an EGSE framework for IF streaming, tele-commanding, telemetry processing, and receiver evaluation.
- Validate end-to-end receiver functionality and assess navigation performance under realistic operational constraints.
- Provide a flexible testbed for algorithm development, system verification, and future lunar navigation receiver development.

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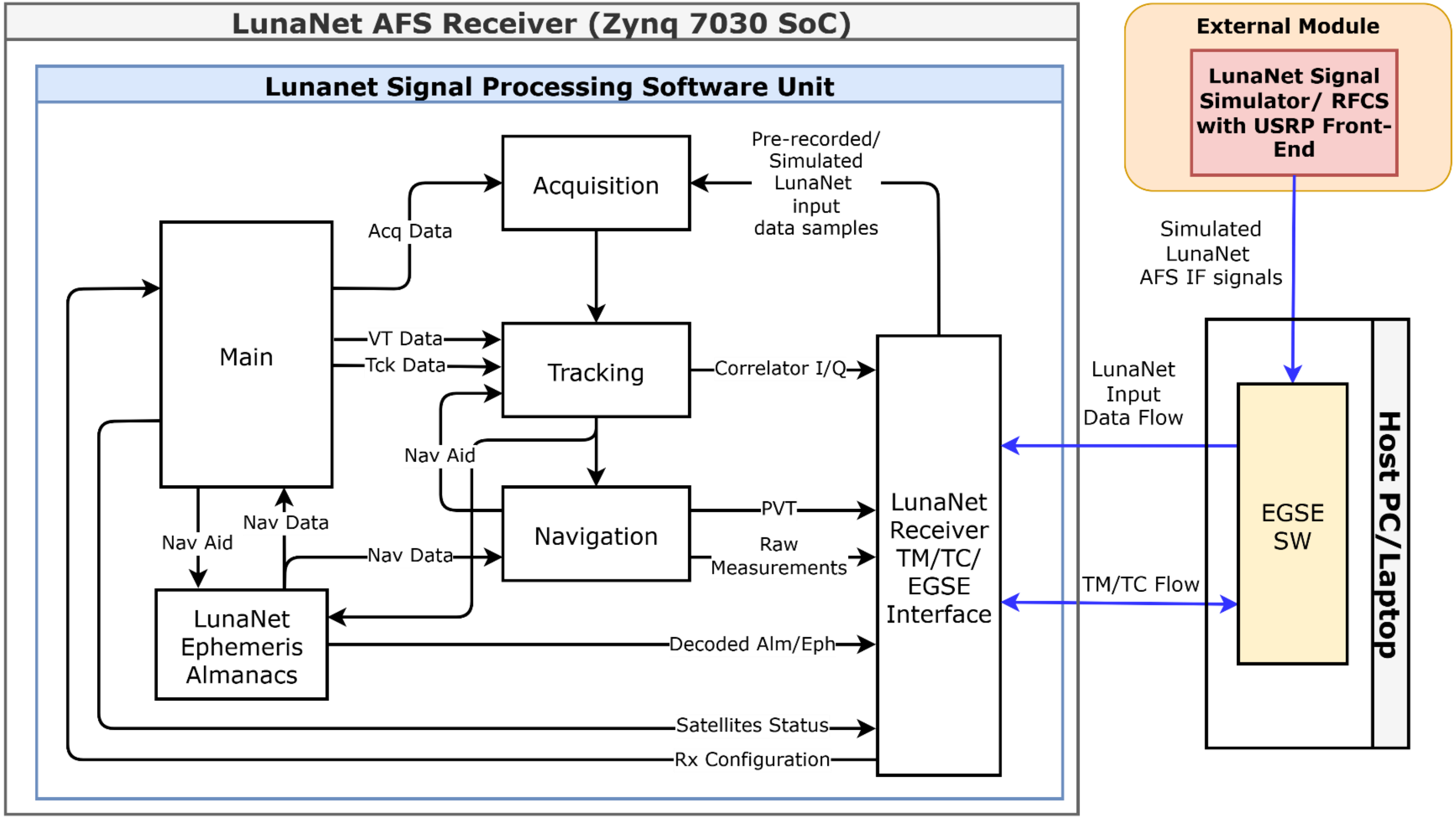
Receiver High Level Architecture

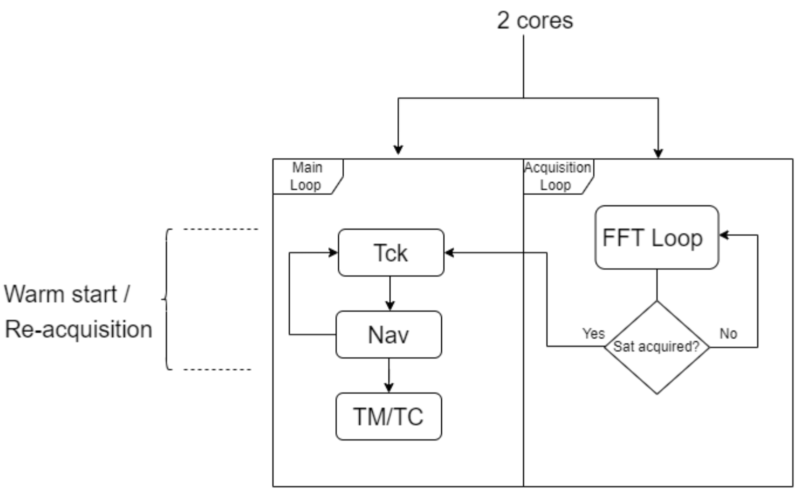


- ❑ IF Simulator (External)
- ❑ EGSE SW Tool (Host PC/Laptop)
- ❑ LunaNet AFS Receiver (Zynq-7030 SoC)

Baseline GNSS SDR receiver architecture:

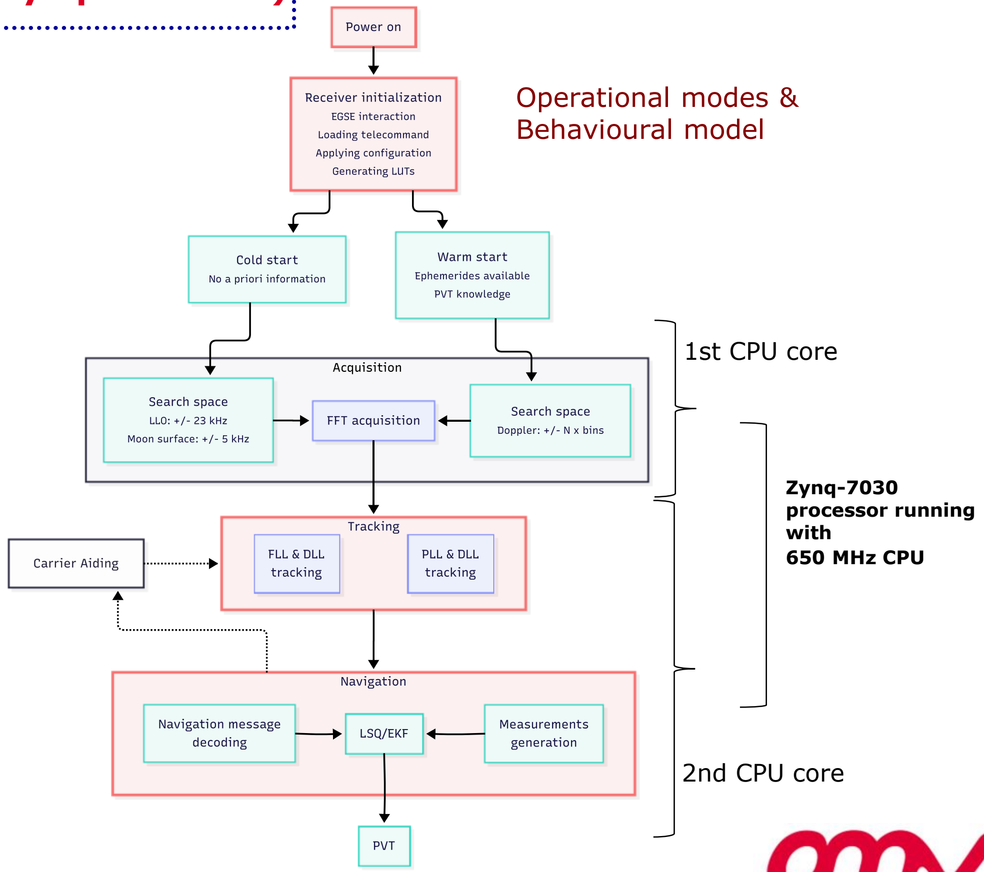
Sextans GMV®
Software defined GNSS receiver

LunaNet AFS Receiver (dual core Zynq-7030 SoC)

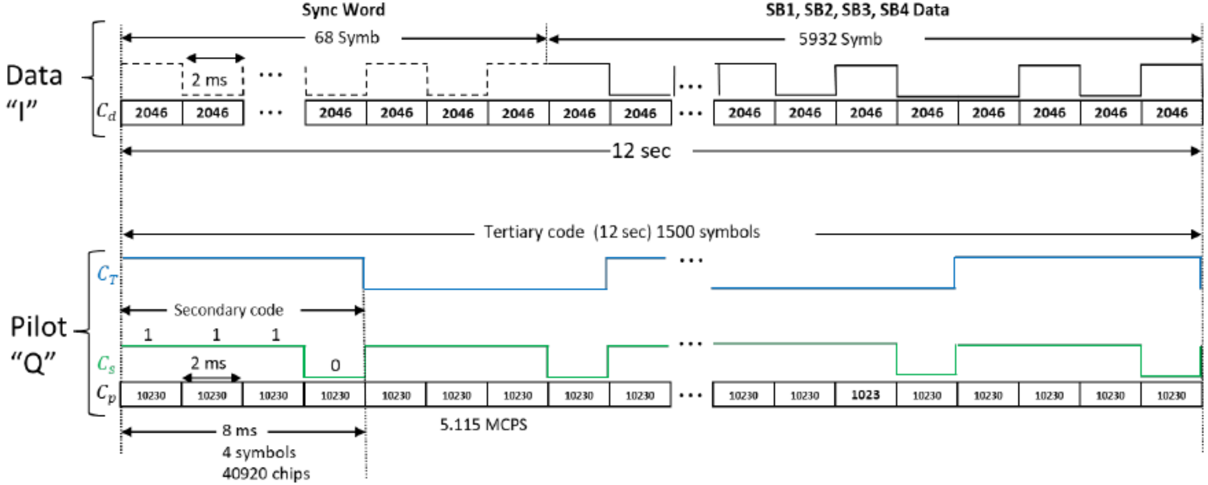


Processor core's task allocation

Operational modes & Behavioural model



AFS Data and Pilot Channels (Taken from LSIS-AFS VER 1, Jan 2025)

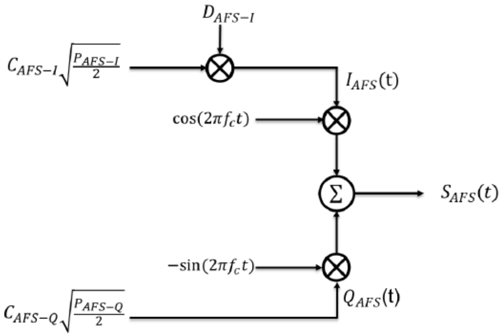


$C_{\substack{Intermediate\\Code}} = C_p \oplus C_S$

$C_{\substack{Tiered\\Code}} = C_p \oplus C_S \oplus C_T$

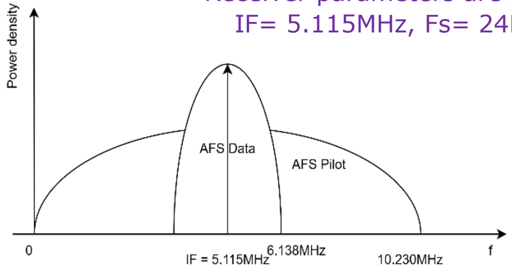
	AFS component	
Signal Design Parameter	Data (AFS-I)	Pilot (AFS-Q)
Spreading Modulation	BPSK	
Primary PRN Code Frequency	1.023 MHz	5.115 MHz
Primary Code Length (code period)	2046 chips (2ms)	10230 chips (2ms)
Secondary Code Length (code period)	N/A	4 chips (8ms)
Tertiary Code Length (code period)	N/A	1500 symbols (12 s)
Navigation data rate	500 sps	N/A
Navigation data structure	L1C-like	N/A

Multiplexing and modulation scheme



Receiver Frequency Plan:

Receiver parameters are set to:
IF= 5.115MHz, Fs= 24MHz



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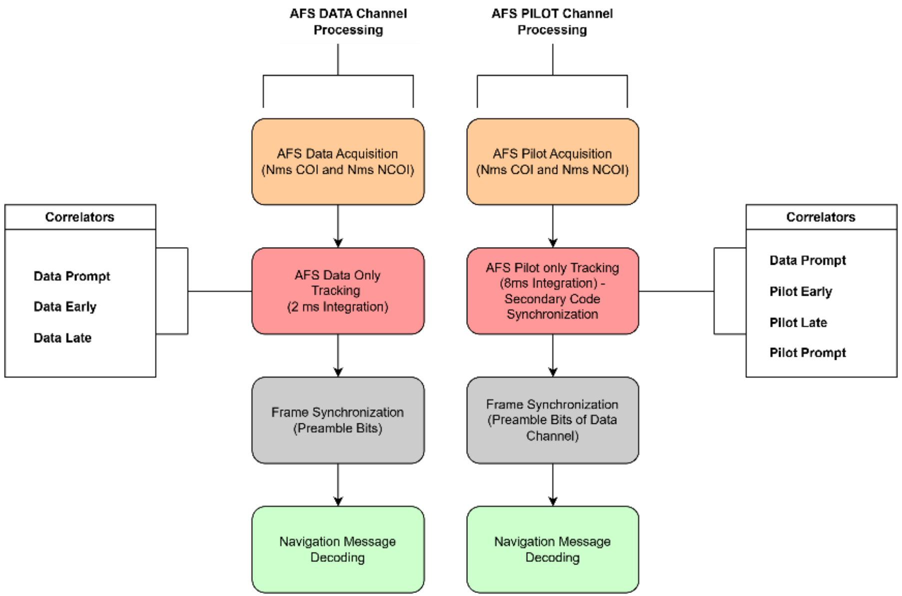
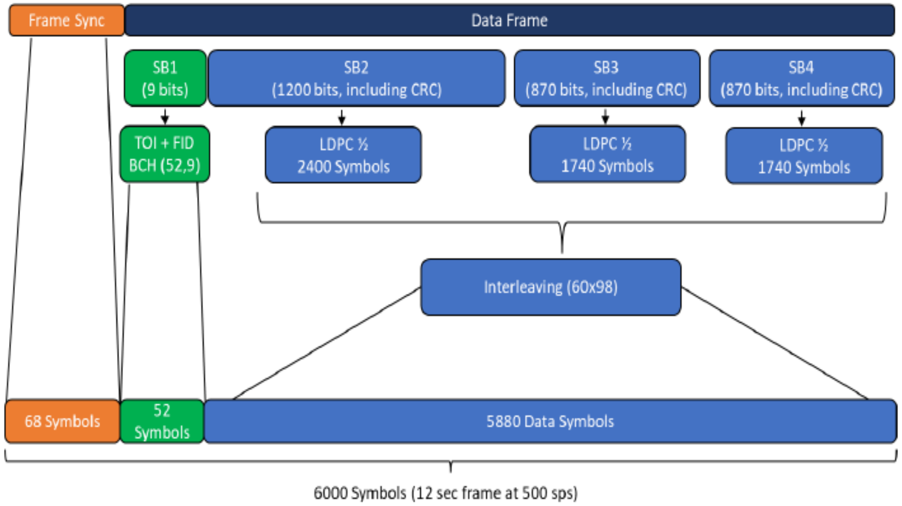
Acquisition & Tracking Strategy



AFS Message Structure (FID= 0)

(Taken from LSIS-AFS VER 1, Jan 2025)



- ❑ BCH decoding is implemented using a brute-force maximum-likelihood.
- ❑ LDPC decoding using the Sum-Product Algorithm (SPA) with normalized Min-Sum approx.

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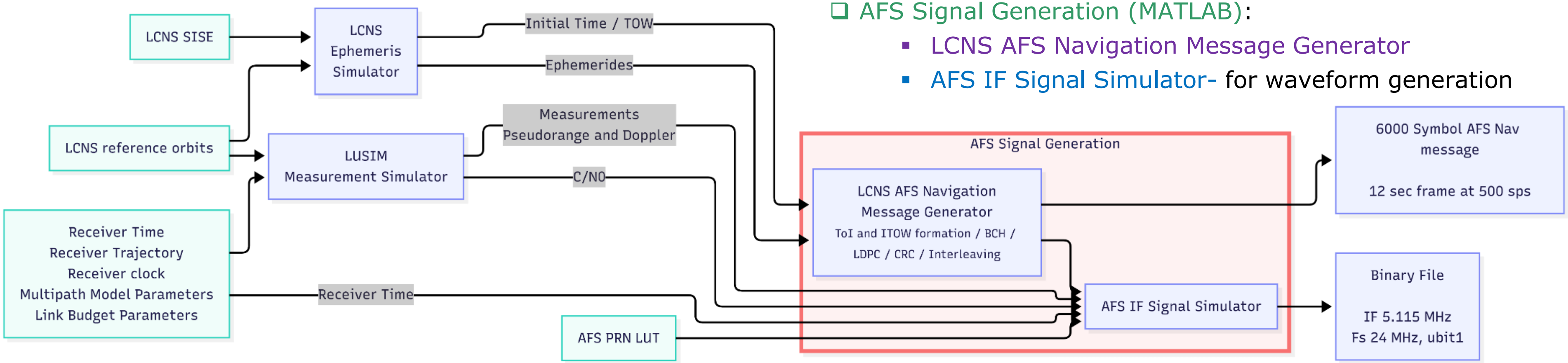
AFS IF Signal Simulator

- ❑ LUSIM Simulator (SIMULINK): Measurement generation
- ❑ Ephemeris simulator: Ephemeris parameter generation
- ❑ AFS Signal Generation (MATLAB):
  - LCNS AFS Navigation Message Generator
  - AFS IF Signal Simulator- for waveform generation



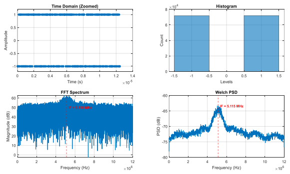
- ❑ Execution time
  - 4 LCNS satellites - approx. 10 sec. for 1 sec. of IF data.
- ❑ Memory- of approx. 3 MB for storing 1 sec. of IF data

For the current Work: Signals generated, considering:

- ➢ Sat. orbital position, velocity and clock errors (SISE)
- ➢ Satellite clock bias
- ➢ Receiver Clock modelling (OCXO type)
- ➢ Relativistic effect
- ➢ Multipath
- ➢ Gaussian/thermal noise

The receiver scenarios tested are:

- ➢ Static or Stationary
- ➢ Rover (15km/hr. or 4.1666m/s)
- ➢ Orbiter (100km altitude)



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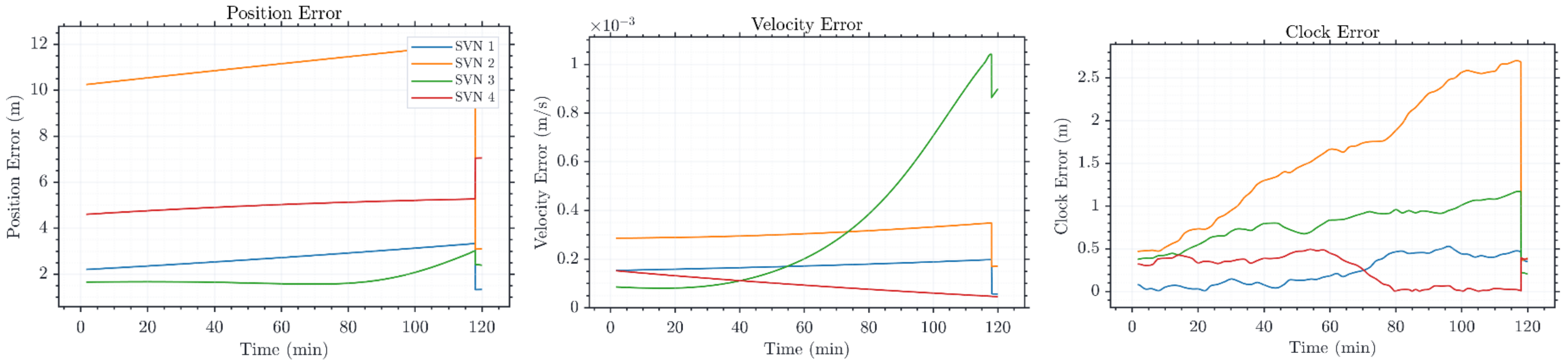
Signal and Measurement Error Models

- **LCNS SISE Components**: comprising position, velocity, and clock errors, provided by ESA, have been utilized in this work



- **Multipath** is simulated as a function of the elevation of the arriving signal.

- **Receiver clock** model using parameters suited for an OCXO receiver clock and are configurable

- **Carrier-to-Noise ratio model**

$$\left(\frac{C}{N_0}\right)_{L,k} = P_{L,k} - 10\log_{10}(T_{sys,L}) + 228.6 + AD_{c,L}$$

$T_{sys,L}$ is the receiver system temperature (which has been set to 190K

$AD_{c,L}$ is the loss caused by Analog-to-Digital Converter (which has been set to -0.16dB

$P_{L,k} = EIRP_{L,k} + G_{t,L,k}(\alpha_{L,k}) + G_{r,u}(\beta_{L,k}) + L_{FS,L,k} - L_{occ,L,k}$

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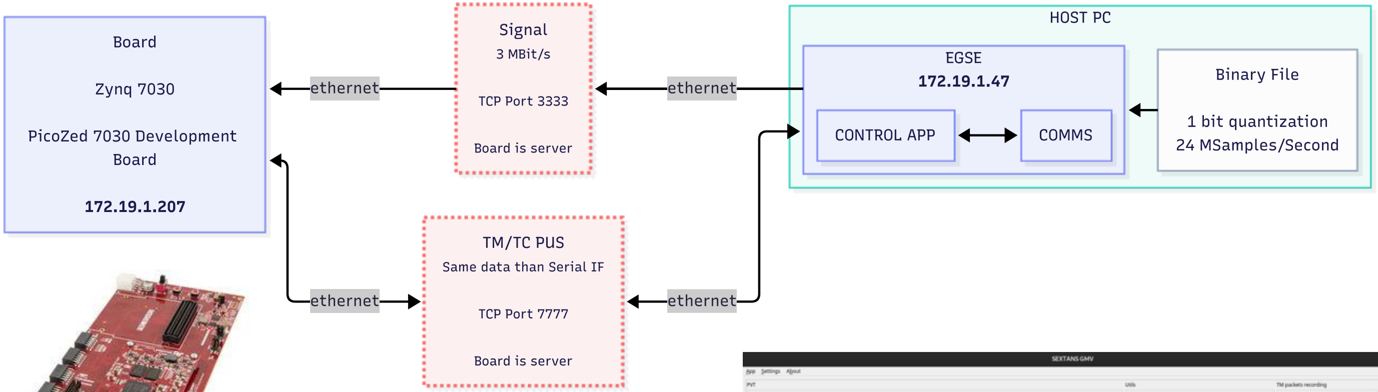
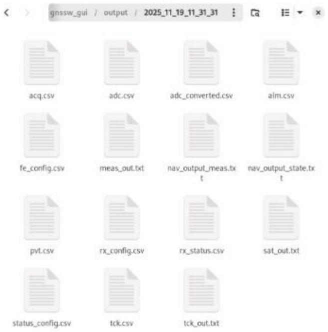
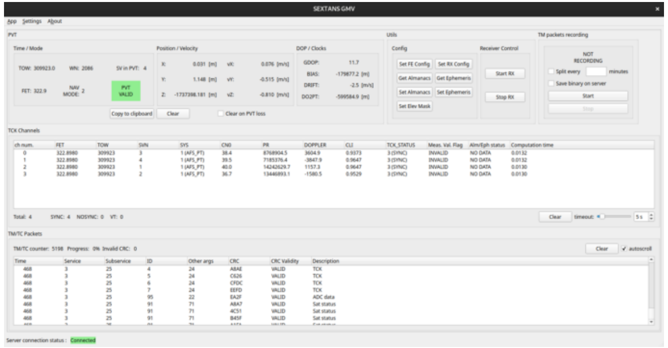
EGSE (Electrical Ground Support Equipment) Tool



Avnet's Picozed (Zynq7030) with FMC Carrier Card V2



Logged TM csv files

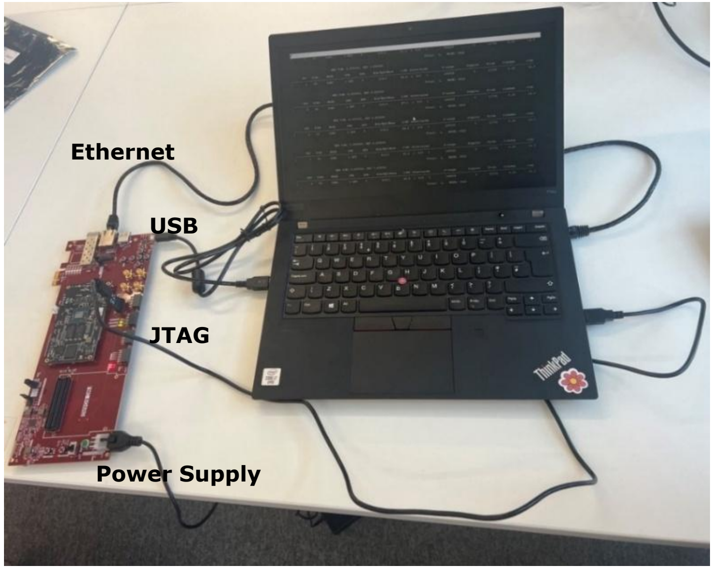


EGSE GUI

EGSE logs the following data:

- Code measurements
- Doppler measurements
- Signal C/N_0 ratio
- Measurement residuals
- Receiver channel status
- Raw measurement time
- Satellite PRN
- LSIS navigation messages
- Raw navigation bits
- Receiver position, velocity and time

Experimental Setup



Hardware Used

- Avnet's Picozed (Zynq7030, AES-Z7PZ-7Z030-SOM-I-G/REV-E)
- Avnet PicoZed FMC Carrier Card V2 (Picozed FMC Carrier Card Gen2 / AVNET AES-PZCC-FMC-V2-G)
- JTAG Programmer
- PC containing the LunaNet receiver development environment

Software Used

- Ubuntu 24.04.2 LTS
- Xilinx Vitis 2023.2
- EGSE GUI handles RX configuration, parses and displays incoming telemetry from the receiver.
- "commsd" handle communication between the GUI and the HW.
- “top_script.h” oversees all the operations inside receiver development and testing environment, minimizing user interaction
- (OPTIONAL) Putty - used for displaying the logged debug data from HW

Acquisition Tracking sensitivity and TTFF

Acquisition Sensitivity

COI-1, N-COHI- 8		
	Data (AFS-I)	**Pilot (AFS-Q)**
Surface User (Static and Rover)	35 dB-Hz	35 dB-Hz
LLO	37 dB-Hz	38 dB-Hz

Tracking Sensitivity

Data 2ms, Pilot 8ms integration	
Data (AFS-I)	32 dB-Hz
Pilot (AFS-Q)	30 dB-Hz

TTFF

TTFF (Cold start): COI=1, ±23 kHz Doppler search			
Data/Pilot	**Non Coh Integ.**	**Scenario**	**Mean**
Data Channel	1	Static	108.79
		Rover	96.89
		Orbiter	63.09
Data Channel	4	Static	132.79
		Rover	132.79
		Orbiter	132.79
Pilot Channel	1	Static	73.91
		Rover	96.89
		Orbiter	71.89
Pilot Channel	4	Static	151.29
		Rover	71.89
		Orbiter	84.89

TTFF (Warm start)): COI=1; ±23 kHz Doppler search			
Data/Pilot	**Non Coh Integ.**	**Scenario**	**Mean**
Data Channel	1	Static	73.49
		Rover	73.088
Data Channel	4	Static	81.986
		Rover	77.09
Pilot Channel	1	Static	60.39
		Rover	53.086
Pilot Channel	4	Static	68.288
		Rover	53.784

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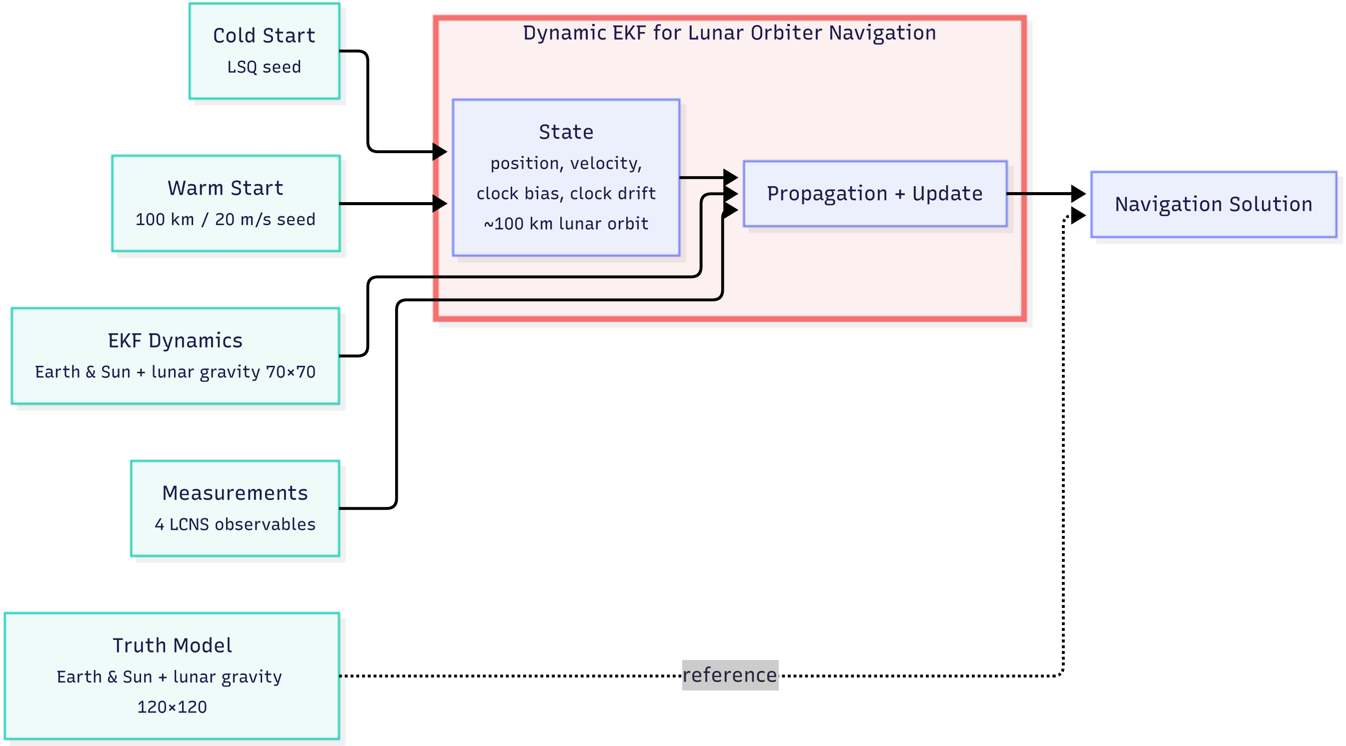
Receiver PVT- EKF



RECEIVER PVT PERFORMANCE- SUMMARY OF THE TEST CASES

Summary of the tests performed				
Case	Channel	Duration	Estimator	Focus
Static Data	Data	20 min	LSQ	Surface static baseline
Static Pilot	Pilot	20 min	LSQ	Surface static pilot comparison
Rover Data	Data	20 min	LSQ	Surface rover on circular path
Rover Pilot	Pilot	20 min	LSQ	Surface rover pilot comparison
Orbiter Data 20 min LSQ	Data	20 min	LSQ	Orbiter LSQ baseline
Orbiter Pilot 20 min LSQ	Pilot	20 min	LSQ	Orbiter LSQ pilot comparison
Orbiter Data 20 min EKF	Data	20 min	EKF	First nominal orbiter EKF case
Orbiter Pilot 20 min EKF	Pilot	20 min	EKF	Pilot counterpart to the nominal 20 min EKF case
RPY Data	Data	5 min	LSQ	Surface RPY power-swing assessment
RPY Pilot	Pilot	5 min	LSQ	Surface RPY pilot assessment
Orbiter Data 2 h EKF	Data	2 h	EKF	Long-run orbiter EKF assessment
Orbiter Pilot 2 h EKF	Pilot	2 h	EKF	Long-run pilot-versus-data EKF comparison
Orbiter 20min 3sat Data	Data	20 min	EKF	Reduced-visibility 3-satellite case
Orbiter 20min 2sat Data	Data	20 min	EKF	Reduced-visibility 2-satellite case

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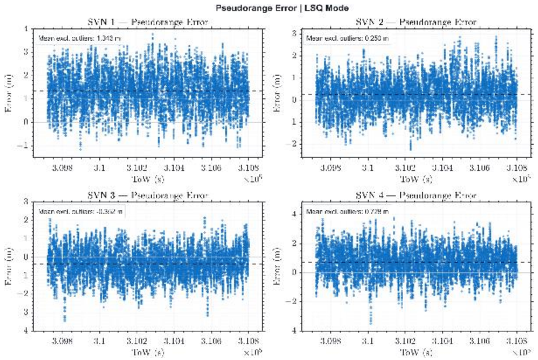
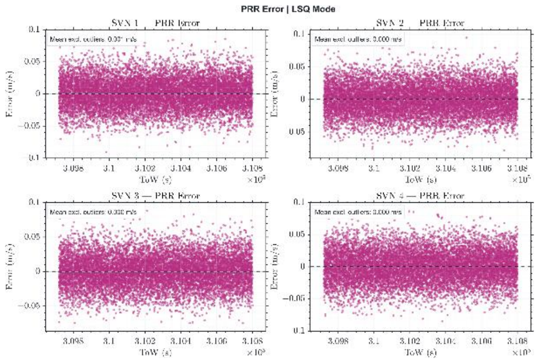
RECEIVER PERFORMANCE : Ground truth vs acquired measurement

Data

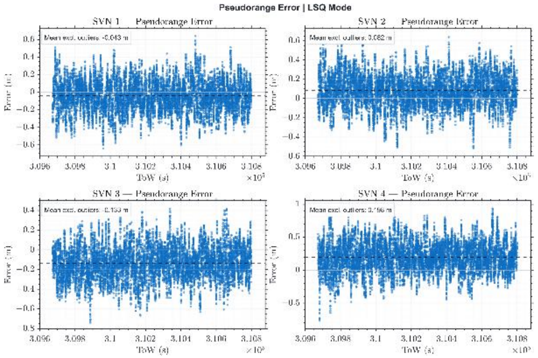


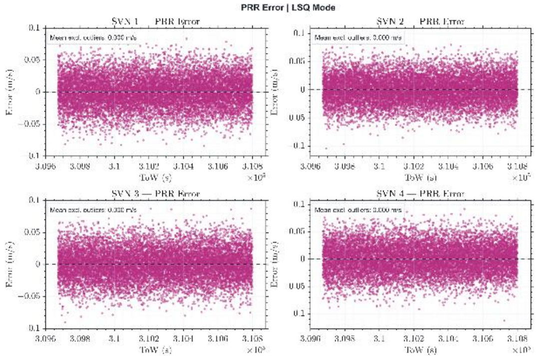


Pseudorange (PR) measurement KPMs (Static)	
Metric	All SVN (m)
P95	2.219
P99	2.785

Pseudorange rate (PRR) measurement KPMs (Static)	
Metric	All SVN (m/s)
P95	0.046
P99	0.060

Pilot





Pseudorange (PR) measurement KPMs (Static)	
Metric	All SVN (m)
P95	0.439
P99	0.603

Pseudorange rate (PRR) measurement KPMs (Static)	
Metric	All SVN (m/s)
P95	0.049
P99	0.064

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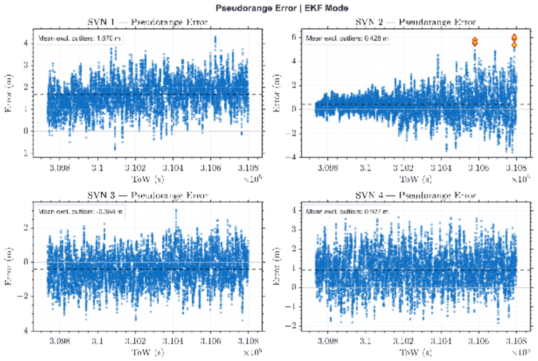
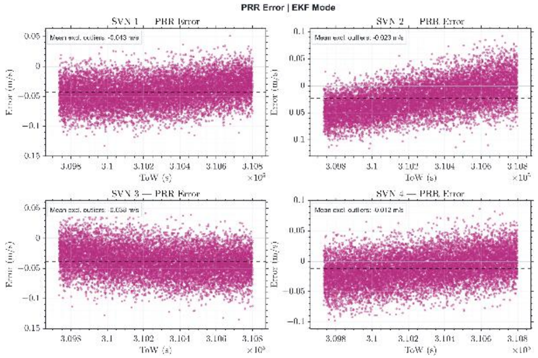
RECEIVER PERFORMANCE : Ground truth vs acquired measurement

Data

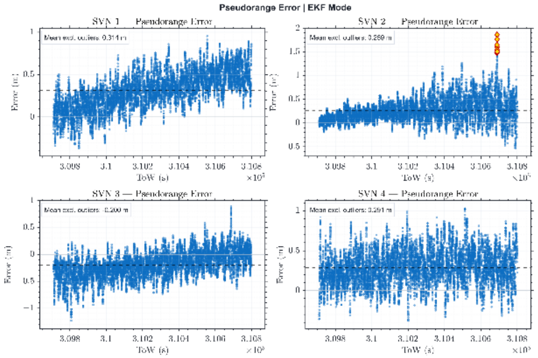


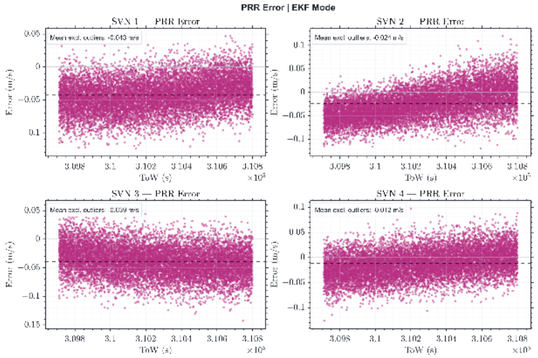


Pseudorange (PR) measurement KPMs (Orbiter)	
Metric	All SVN (m)
P95	2.487
P99	3.119

Pseudorange rate (PRR) measurement KPMs (Orbiter)	
Metric	All SVN (m/s)
P95	0.074
P99	0.091

Pilot





Pseudorange (PR) measurement KPMs (Orbiter)	
Metric	All SVN (m)
P95	0.655
P99	0.836

Pseudorange rate (PRR) measurement KPMs (Orbiter)	
Metric	All SVN (m/s)
P95	0.077
P99	0.095

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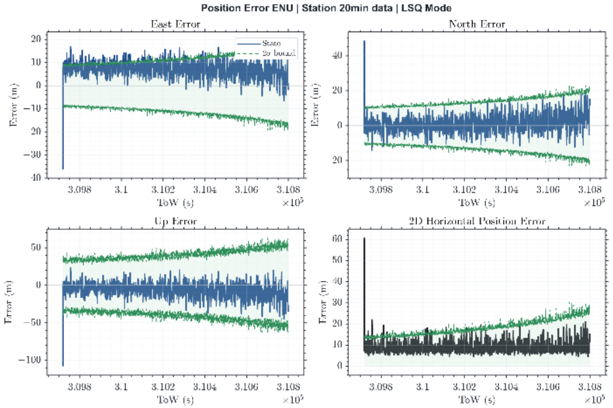
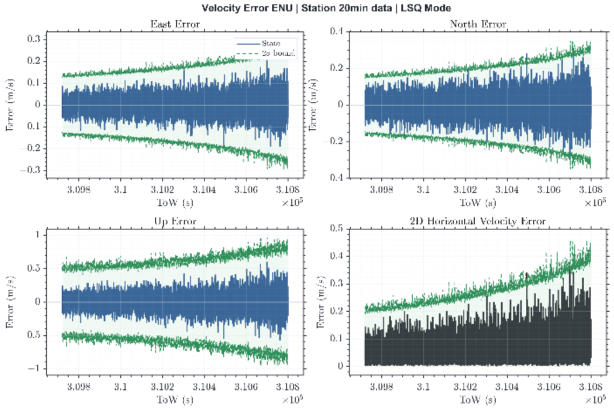
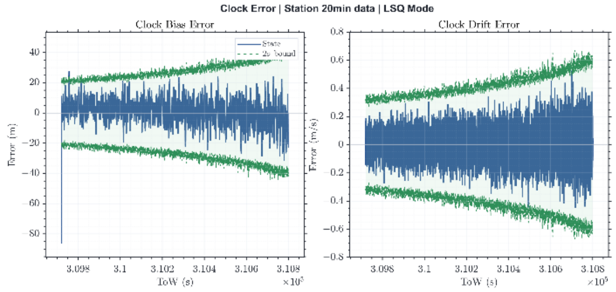
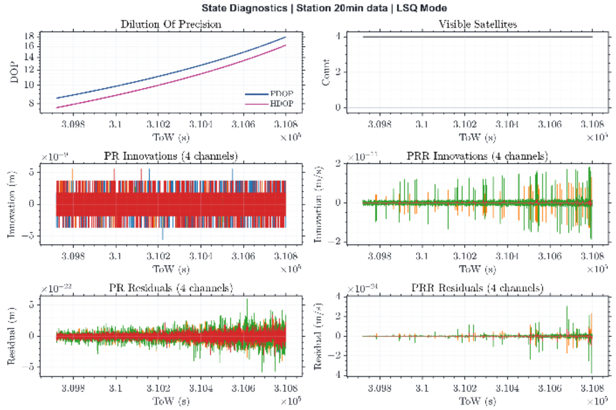
PVT PERFORMANCE : STATIC DATA CHANNEL LSQ









ENU position-error KPMs

Metric	E (m)	N (m)	U (m)	2D (m)
P95	12.102	9.573	22.192	13.876
P99	14.119	13.576	32.055	16.962

ENU position-error KPMs

Metric	Ve (m/s)	Vn (m/s)	Vu (m/s)	2D (m/s)
P95	0.083	0.123	0.248	0.147
P99	0.115	0.171	0.347	0.205

Clock Error KPMs

Metric	Bias (m)	Drift (m/s)
P95	15.69	0.211
P99	21.63	0.297

Geometry KPMs

Metric	PDOP	HDOP
P95	17.04	15.41
P99	17.79	16.09

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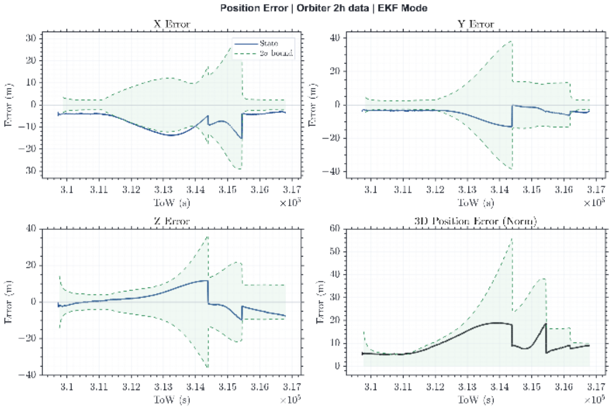
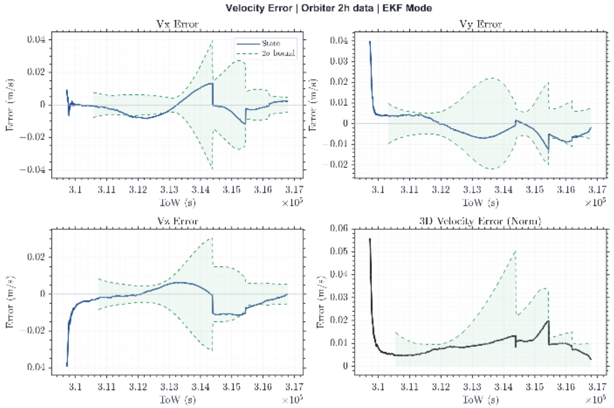
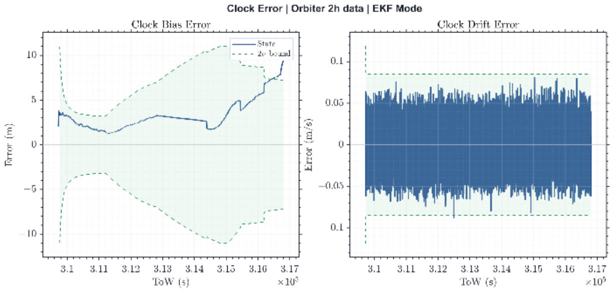
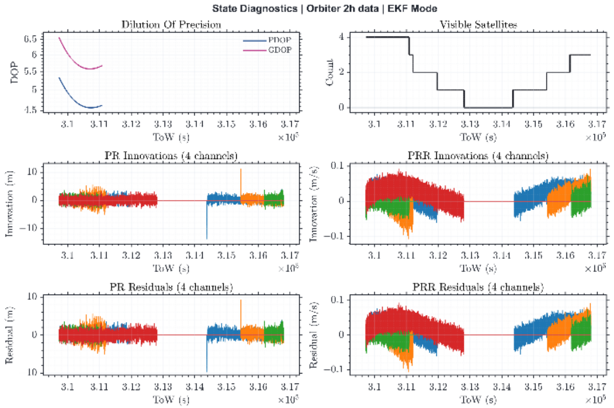
PVT PERFORMANCE : ORBITER DATA CHANNEL 2H EKF









ME position-error KPMs

Metric	X (m)	Y (m)	Z (m)	3D (m)
P95	13.660	12.217	11.081	18.788
P99	14.439	12.936	11.622	18.909

ME velocity-error KPMs

Metric	Vx (m/s)	Vy (m/s)	Vz (m/s)	3D (m/s)
P95	0.011	0.009	0.011	0.016
P99	0.013	0.015	0.016	0.023

Clock Error KPMs

Metric	Bias (m)	Drift (m/s)
P95	7.367	0.039
P99	8.436	0.051

Geometry KPMs

Metric	PDOP	GDOP
P95	5.24	6.43
P99	5.33	6.55

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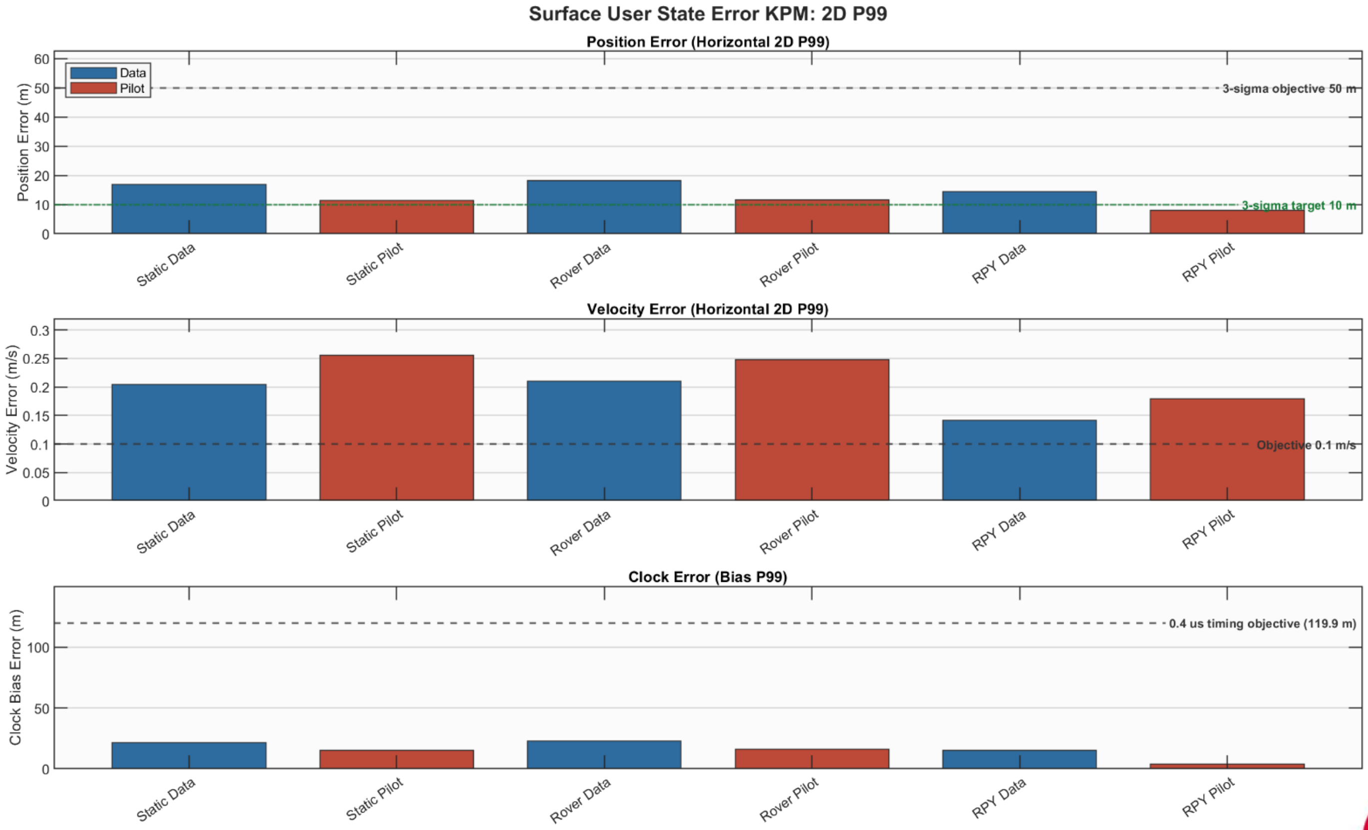
SUMMARY OF PVT PERFORMANCE



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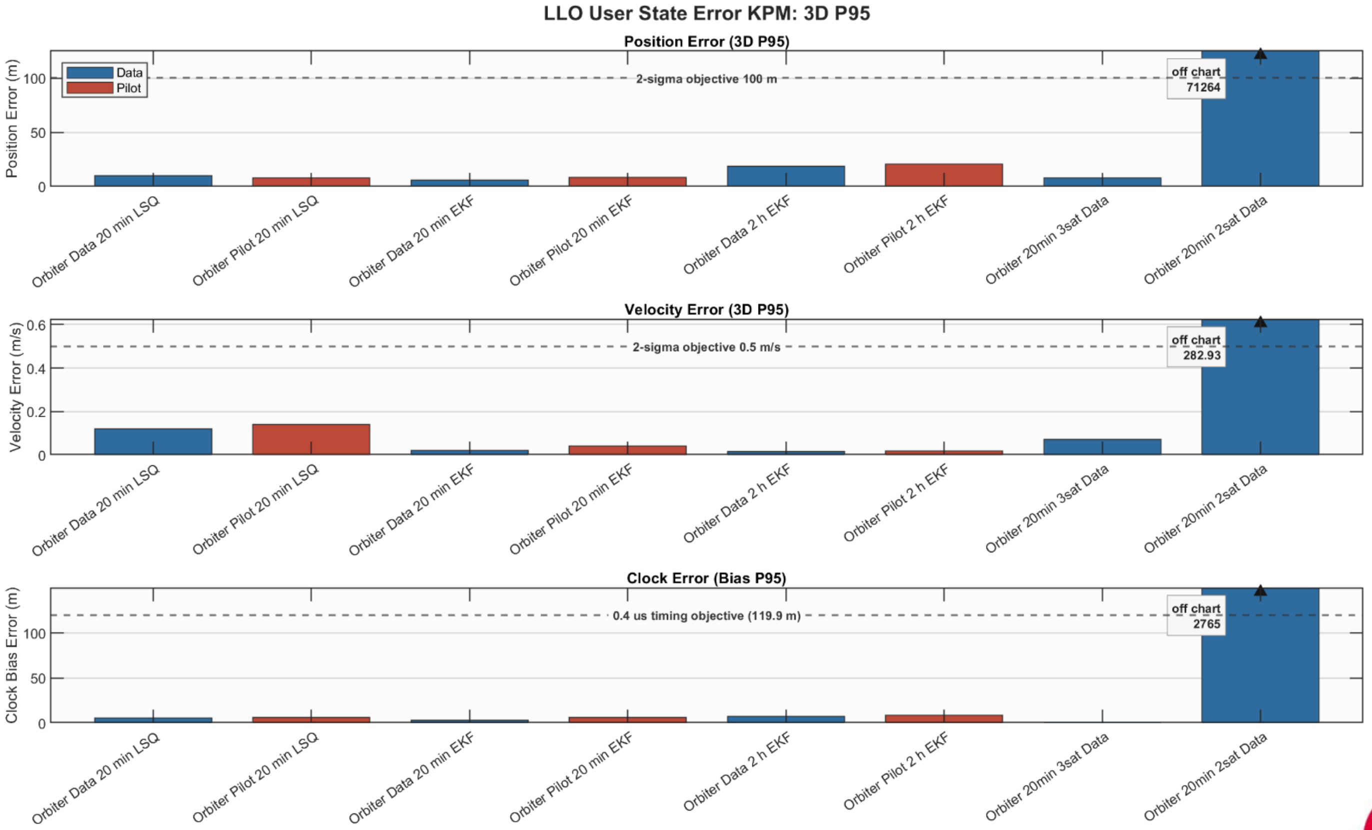
SUMMARY OF PVT PERFORMANCE



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KEY OUTCOMES

- A breadboard SDR-based LunaNet LANS AFS receiver on the Zynq-7030 platform and a MATLAB-based AFS signal simulator.
- an EGSE with a dedicated GUI.
- Demonstrated end-to-end receiver functionality.
- An effective testbed and framework for signal validation, algorithm development, and system-level verification of lunar navigation concepts with flexibility for future upgrades, message updates, and evolving lunar ICD.
- Satellite visibility, geometry, and broadcast-state quality as the primary factors influencing navigation performance and positioning accuracy.
- Demonstrated the feasibility of lunar navigation using a software-defined receiver architecture, establishing a foundation for further receiver and system-level development.

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FUTURE WORK

Future work targets improved robustness, testing with longer datasets and extended end-to-end validation, including

- Signal simulation: to an FPGA-based hardware implementation, to enable real-time signal processing, improved hardware-in-the loop validation.
- Acquisition and tracking: Improve robustness using larger FFT sizes and secondary/tertiary code utilization.
- Navigation message: Continue updating message handling and orbital interpretation as LunaNet service definitions stabilize.
- Receiver channel capacity enhancement

Transition toward a flight-ready PCB implementation.

- ESA GSTP Element 1 activity, NAV-LAVUT (Navigation Lunar Augmented Validation User Terminal) (led by GMV-Spain)
  - NAV-LAVUT: a LunaNet-compatible lunar PNT receiver engineering model for future cislunar and lunar surface missions.
  - The activity focuses on, Multi-LNSP interoperability, NovaMoon correction integration, SWaP optimization, adaptable navigation algorithms, Signal quality monitoring and validation of Moonlight PNT services etc.

NAV-LAVUT, builds upon the outcomes, lessons learned, and technical expertise gained from this work, leading to the development of a high-TRL, flight-ready product in the near future.

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Thank you

Juan Bevan (juan.bevan@gmvnsl.com)
Srinu Chittimalla (schittimalla@gmv.com)
Jorge E. Martínez Esmeral (jemartinez@gmv.com)

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