RIGOUR (Real-time Big Data Processing For GNSS Integrity)

NAVISP Element 1 - 053

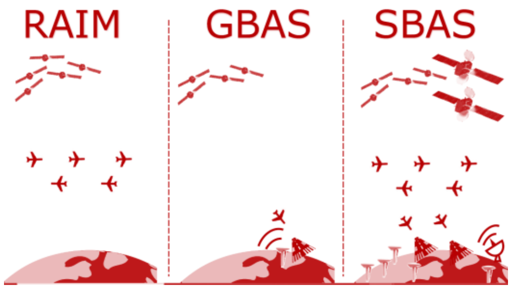
Final Presentation

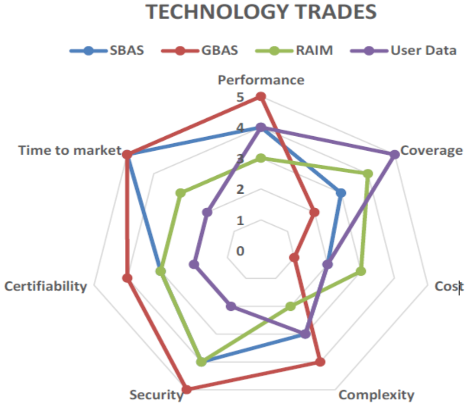
15/12/2023

INNOVATING SOLUTIONS

Context & Rationale for the Development

GNSS integrity past and future





Would it be possible to develop new integrity concepts?

- <u>Central Limit Theorem</u>:
  The worse input data can be largely compensated by the sheer number of samples.

Based on this idea RIGOUR project aimed to:

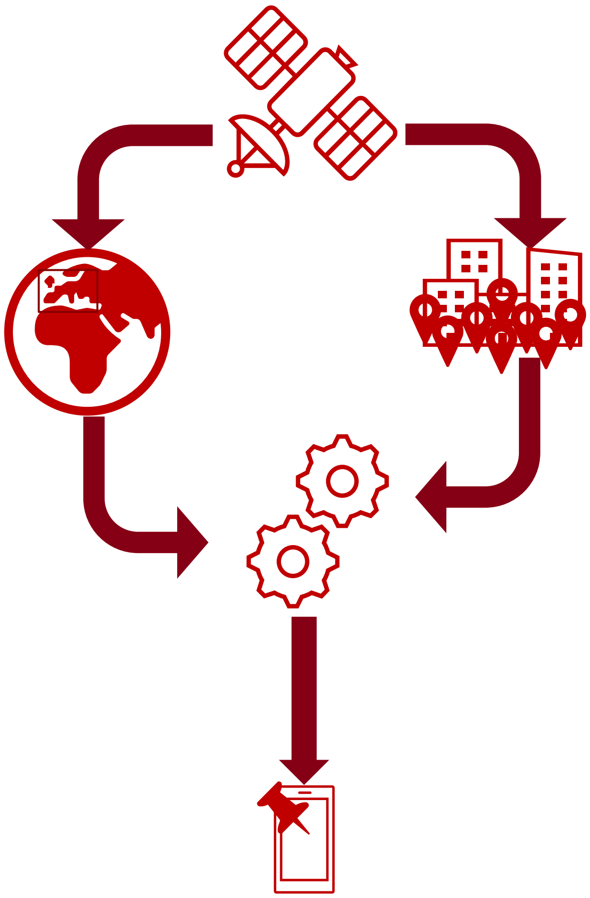
- <u>Design</u> new concepts and algorithms
- <u>Develop</u> a simulation platform
- <u>Determine</u> the performance requirements and their feasibility.

RIGOUR Project Objectives

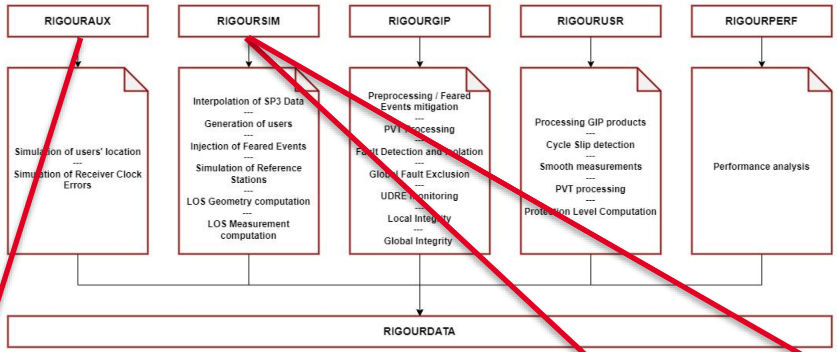
New GNSS Integrity Concepts

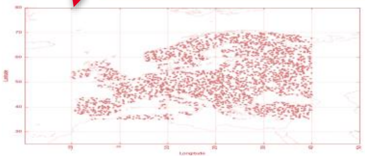
- **Satellite / Global Integrity:**
  Taking advantage of a large amount of general GNSS user terminals to generate satellite integrity information from a GNSS Integrity Processor (GIP), with no or a reduced number of reference stations.

- **Local Integrity:**
  Exploiting a given small area with a high concentration of GNSS users to increase, if needed, the protection levels and cover for the impact of multipath and occultation events without jeopardising the availability in other regions.

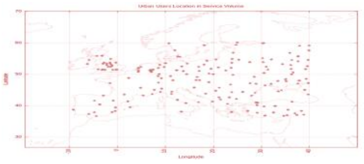


RIGOUR Demonstrator

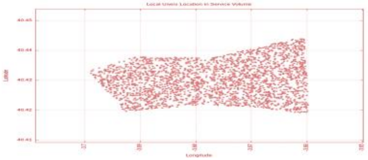




RURAL Users (25%)



URBAN Users (50%)



LOCAL Users (25%)

Total of 10 000 users

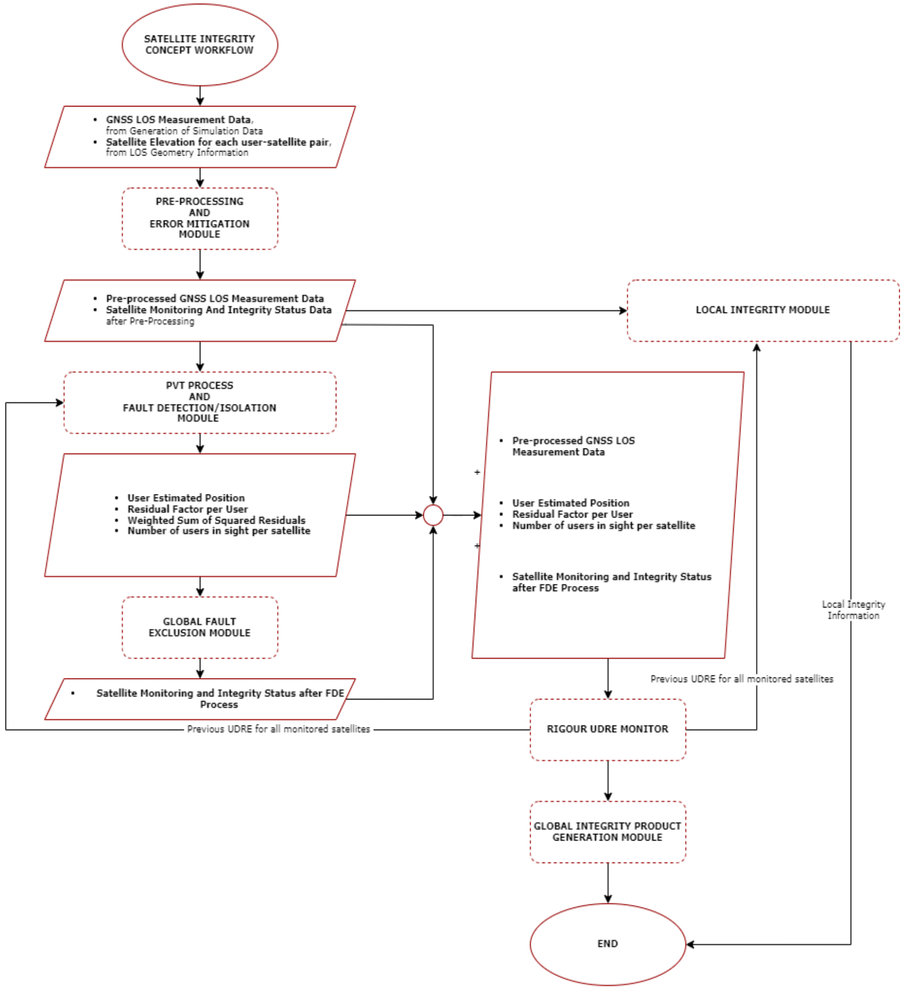
USERS	Mass-Market (95%)	High-End (5%)
Urban /Local	High Noise Model High Multipath Model High Prob. of NLOS […]	Medium Noise Model High Multipath Model High Prob. of NLOS […]
Rural	Medium Noise Model Low Multipath Model Low Prob. of NLOS […]	Low Noise Model Low Multipath Model Low Prob. of NLOS […]
1s	50%	100%
30s	50%	0%
Single Freq.	50%	0%
Dual Freq.	50%	100%

NOMINAL ERRORS	
Receiver Code & Phase Noise	White Gaussian Noise.
Intersystem Code & Phase Bias	Constants, Gaussian distribution.
Ionospheric Error & GPS to Galileo Time Offset Error (GGTOE)	Second Order Gauss Markov
Tropospheric Error, Satellite Ephemeris & Clock Error	First Order Gauss-Markov
Receiver Clock Error	Modelled as sum of stochastic (coloured noise) and deterministic (drift) components
DEGRADED CONDITIONS	
Multipath, Occultation & NLOS	GEMMA module (from MLUTB project)
Phase Error due to Ambiguity & Cycle Slips	Modelled as discrete jumps in the integer number of ambiguities with assigned probability.
FEARED EVENTS	
Erroneous Broadcast Ephemeris (EPH)	A single satellite provides a valid ephemeris before time T0 and broadcast an erroneous ephemeris after T0 resulting in a 3D ephemeris error.
Erroneous Broadcast Clock (CLK)	A single satellite provides valid clock corrections before time T0 and broadcast erroneous clocks after T0 resulting in an error.
Pseudorange Step (PRS)	Defined as any satellite failure that causes a sudden change in the satellite's code. This error can occur on L1(E1) and/or L5 (E5a).
Pseudorange Drift (PRD)	Defined as any satellite failure that causes a sudden drift in the satellite's code. This error can occur on L1(E1) and/or L5 (E5a).
Code-Carrier Divergence (CCD)	A single satellite provides a good quality ranging signal before time T0 and provides a degraded ranging signal after time T0 due to a change of the code minus carrier phase at the output of SV antenna on L1(E1) and/or L5 (E5a).
Degraded Carrier Phase (DPH)	The phase noise spectral density of the un-modulated carrier is out of specifications such that the receiver tracking error exceeds a defined threshold. It is simulated as an additional White Gaussian Noise.

RIGOURGIP

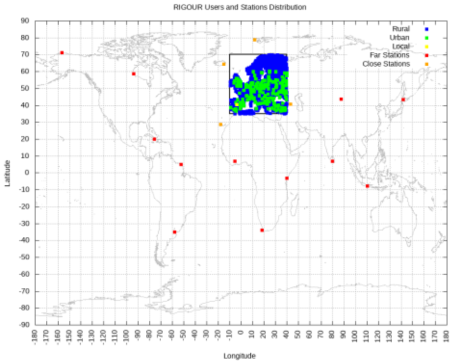
Main purposes

- **FE Detection and Mitigation**
  - User pre-processed algorithms for error mitigation
  - PVT processing
  - Fault Isolation/Global Exclusion
  - Over-bounding through satellite-level Sigma UDREs and threshold exclusion
- **User protection**
  - Satellite-level Sigma UDREs that better correlate weight assignments and enable Protection Level computation
- **Local Integrity products**
  - Take advantage of population density to provide increased protection through aggregated residual statistics.

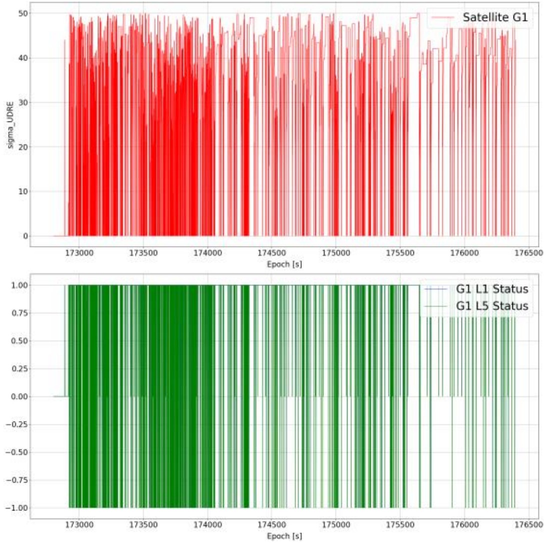


RIGOUR TEST CAMPAIGN

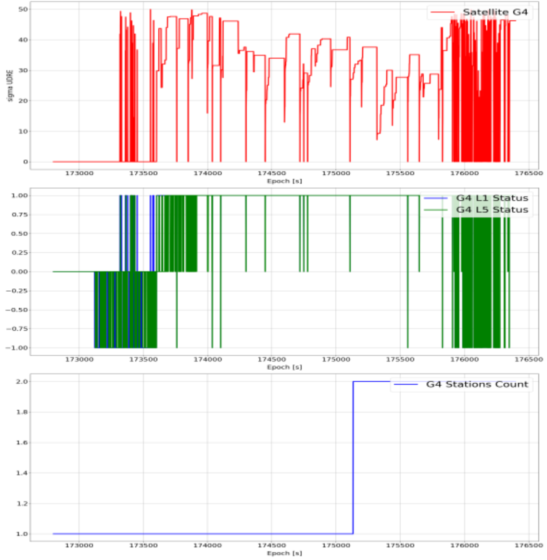
Considerations about Reference Stations



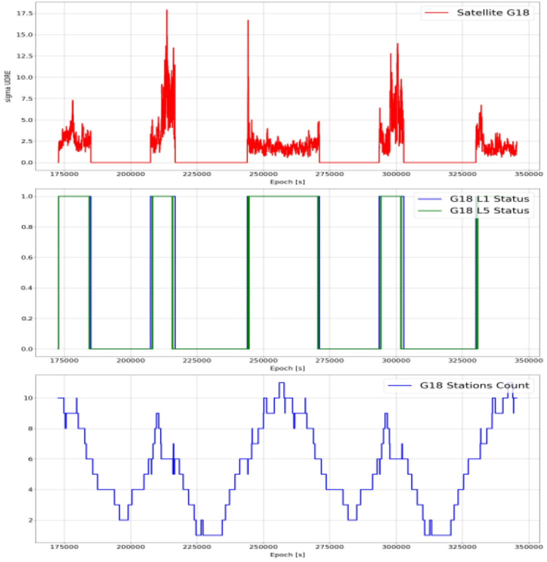
Distribution of Reference Stations for RIGOUR baseline scenario



Without Stations



4 stations, some unavailable



16 stations

RIGOUR TEST CAMPAIGN

Nominal vs. Degraded

Nominal

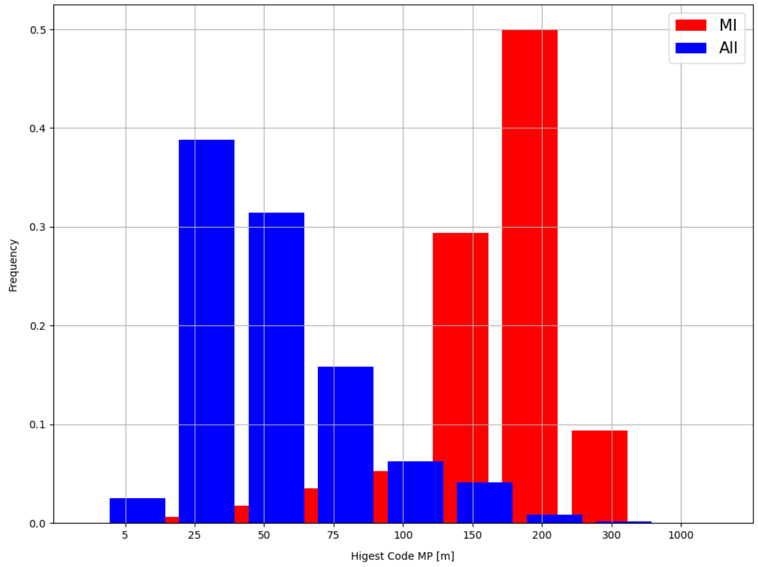
- No integrity failures.
- GIP products only marginally reduce the position errors.

Degraded

- **Multipath**, and **NLOS** severely affect the user's solution in urban environments
- **Occultation** reduces satellite availability, increasing position errors and protection levels

		NOMINAL		DEGRADED	
		Default over bounding	GIP	Default over bounding	GIP
HPE	Average [m]	0.687	0.684	8.529	8.284
	Worst [%]	4.55	3.98	144.72	145.08
HPL	Average [m]	29.47	26.76	49.54	45.64
	Worst [%]	39.02	36.19	382.696	372.22
HSI	Average [m]	0.02	0.03	0.16	0.17
	Worst [%]	0.16	0.17	1.75	1.84
Availability	APV-I [%]	47.9	70.5	9.0	15.4
	RIGOUR [%] *	N.A.	N.A.	97.7	98.1

* Custom Alert Limits with HAL = 120m & VAL = 225m



RIGOUR TEST CAMPAIGN

User Statistics, GIP on, degraded conditions

		ENVIRONMENT			SAMPLING RATE		RECEIVER TYPE		FREQUENCIES	
		Rural	Urban	Local	1 Hz	1/30 Hz	Mass-market	High-end	Single frequency	Double frequency
HPE	Average [m]	0.79	11.27	9.87	8.16	13.97	8.53	5.45	7.51	8.85
	Worst [m]	4.16	133.71	101.99	136.39	393.72	144.83	54.12	132.65	111.02
HPL	Average [m]	28.45	51.70	51.17	45.14	79.49	46.71	35.13	49.41	42.53
	Worst [m]	38.00	344.14	292.91	366.67	533.38	372.09	112.33	363.72	257.18
HSI	Average	0.03	0.23	0.20	0.17	0.16	0.17	0.14	0.14	0.19
	Worst	0.14	1.78	1.48	1.84	1.92	1.83	1.19	1.64	1.70
Aval.	RIGOUR [%]	100.0	97.6	97.4	98.6	71.2	98.0	99.8	97.1	99.0
MI (RIGOUR AL)	MI/user in 12 hours	0.00	140.27	113.72	182.62	169.48	97.36	121.38	80.66	114.76
MI – GIP without Local Users	MI/user in 12 hours			126	Local users reported a MI increase of 11.2%, from 113 up to 126 MI/localuser/12 hours of nominal conditions, as a result of the lack of a local integrity product					

RIGOUR
TEST CAMPAIGN

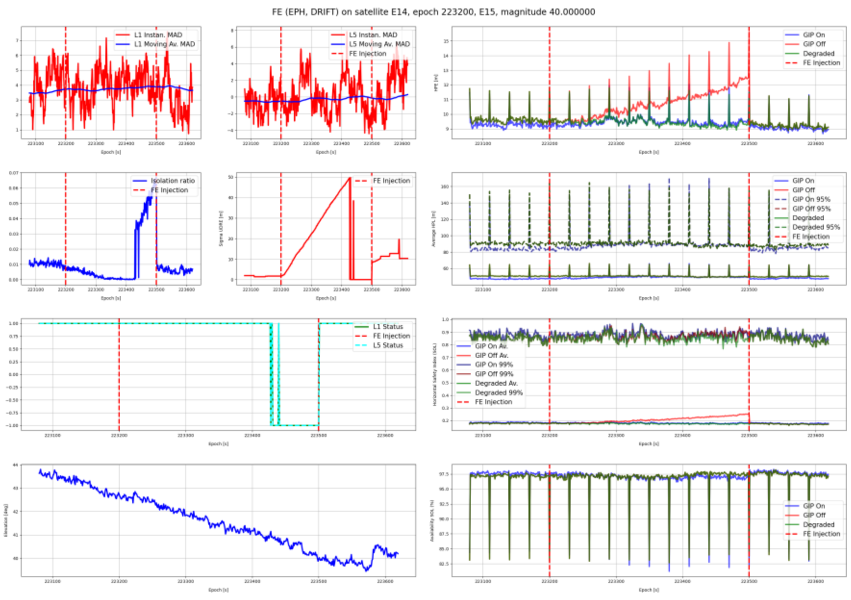
FE Mitigation:
EPHEMERIS & CLOCK

	Ephemeris				Clock			
AMPLITUDE / SUBTYPE	Fault exclusion	Increased Bounds	% Increased Bounds	Av. Sigma UDRE ↑	Fault exclusion	Increased Bounds	% Increased Bounds	Av. Sigma UDRE ↑
All	2	29	96.6	15.6	6	28	93.3	20.8
STEP	1	9	90	25.9	2	8	100	32.9
DRIFT	1	10	100	14	3	10	100	18.2
PARABOLA	0	10	100	7	1	10	100	11.3

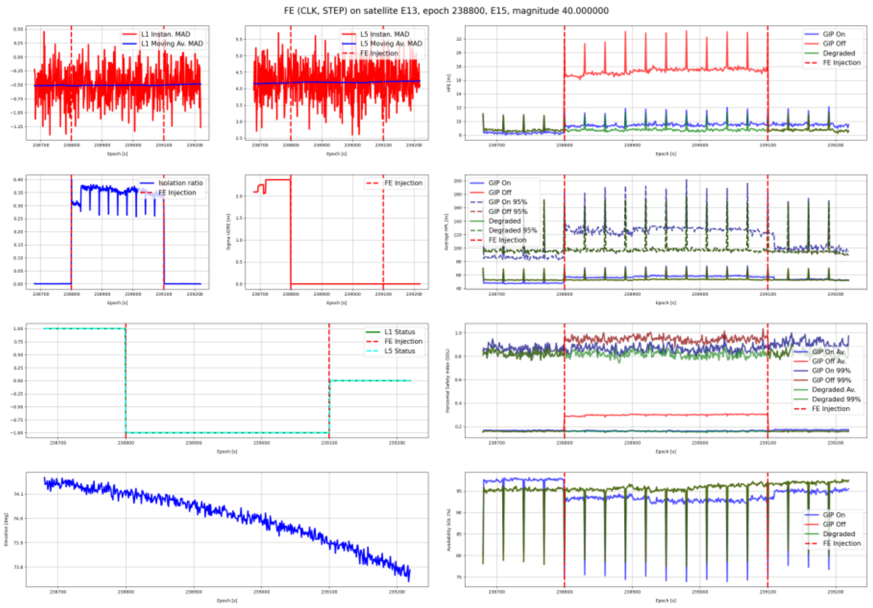
	USER TYPE		HPE ↑ [%]		HPL ↑ [%]		Average HSI ↑ [%]		99th HSI ↑ [%]		MI ↑ [%]		HMI ↑ [%]		AV ↑ [%]	
			No GIP	GIP	No GIP	GIP	No GIP	GIP	No GIP	GIP	No GIP	GIP	No GIP	GIP	No GIP	GIP
Ephemeris	RURAL	10m Amp.	20.6	11	0.6	0.4	21	10	8.9	4.9	-	-	-	-	0.3	0.3
		40m Amp.	277.8	1.73	~0	~0	278.3	1.8	116.4	0.81	-	-	-	-	0.3	0.3
	URBAN	10m Amp.	0.5	0.4	0.4	-0.1	0.3	0.29	0.4	0.3	4.4	1.8	-1.3	-5.3	0.4	0.6
		40m Amp.	20.2	3.2	0	2.9	18.9	0.7	4	1	23.3	5.3	25.2	24.6	0	-0.3
	LOCAL	10m Amp.	1.3	1.7	-0.2	0	0.3	1.2	0.6	0.8	3.5	3.9	-8.1	-0.1	0.7	0.8
		40m Amp.	26	1.4	0.8	9.8	20.5	-5.8	4.5	-3.7	26.7	-14	-6.1	-12.5	0	-2.1
Clock	RURAL	10m Amp.	76.8	12.5	-0.1	0.6	77.8	11.3	29.8	3.4	-	-	-	-	0.3	0.3
		40m Amp.	291.8	1.96	-0.2	0.4	293.5	1.48	163.2	0.3	-	-	-	-	0.3	0.3
	URBAN	10m Amp.	2.3	3	0	3	2.3	0.6	0.5	0.6	2.1	3.2	23.5	18.6	0.2	-0.4
		40m Amp.	17.7	3	0.2	3	14.9	0.3	3.2	0.8	18	5.4	15.2	24.9	0.5	-0.5
	LOCAL	10m Amp.	3.8	2.1	0.5	3	1.8	-0.8	-1.7	-2.2	-8.1	-9.4	-4.3	-8.5	0.2	-0.3
		40m Amp.	39.4	6	0.4	11.4	35.4	-2.6	6.4	-2.9	35.6	-14.3	68.9	25.6	0.5	-1.6

RIGOUR TEST CAMPAIGN

EPH DRIFT RESPONSE



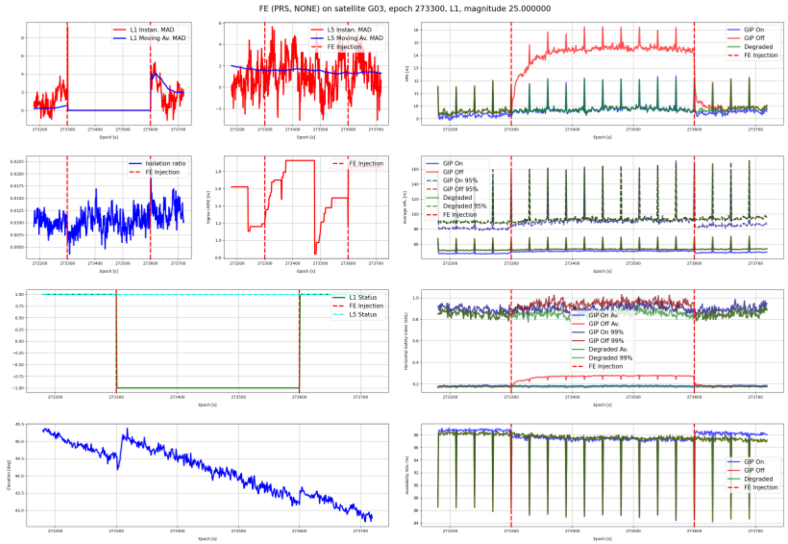
CLK STEP RESPONSE



RIGOUR TEST CAMPAIGN

FE Mitigation: PSEUDORANGE STEP

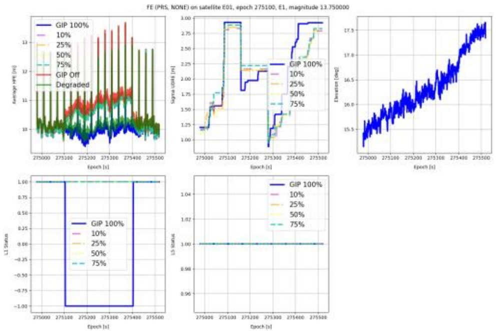
AMPLITUDE	L1/E1 Exclusion	L5/E5 Exclusion	Increased Bounds	% Exclusion
All	13	12	12	61.7
2.5	0	0	3	0
8.1	1	1	1	25
13.75	4	3	3	83.3
19.375	4	4	2	100
25	4	4	3	100

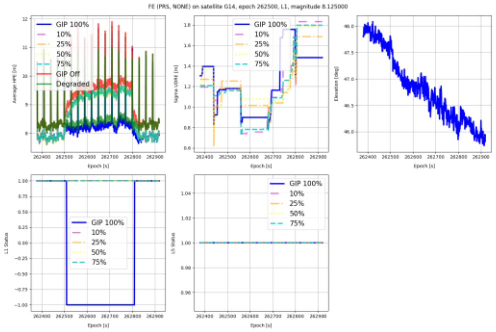


	USER TYPE		HPE ↑ [%]		HPL ↑ [%]		Average HSI ↑ [%]		99th HSI ↑ [%]		MI ↑ [%]		HMI ↑ [%]		AV ↑ [%]	
			No GIP	GIP	No GIP	GIP	No GIP	GIP	No GIP	GIP	No GIP	GIP	No GIP	GIP	No GIP	GIP
Ephemeris	RURAL	2.5m Amp.	14.2	13.8	0.3	0	7.1	14.5	0.2	7.5	-	-	-	-	0.3	0.3
		25m Amp.	381.5	0	0	1.4	352.5	-1.48	236	-1.3	-	-	-	-	0.3	0.3
	URBAN	2.5m Amp.	0	0.5	0.9	0.3	0	0.2	0.5	0.4	3	3	31.3	12.5	0.1	0.2
		25m Amp.	16.7	1.6	0.2	2.9	15	-0.8	4.8	0	26.3	0.9	52.9	35.1	0.3	-0.2
	LOCAL	2.5m Amp.	0.8	6.4	2.3	2.3	4.3	4.2	2.6	1.8	11.6	7.7	7.3	-5.9	-0.1	0
		25m Amp.	21.7	3.2	1.2	3.9	21.3	-0.2	6.4	0.6	36.4	8.9	14.2	6.5	0.7	0.3

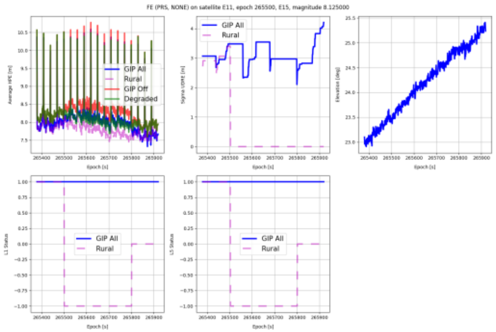
RIGOUR TEST CAMPAIGN

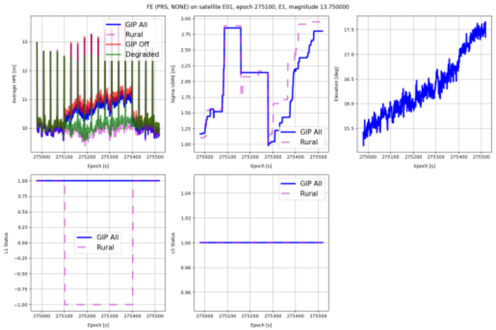
- Reducing the number of users impacts detectability of select feared events (PRS)





- Using only rural users, even being only 25% of total count, provides significantly more detections (37 out of 40 frequencies), 12 more detections.





RIGOUR TEST CAMPAIGN

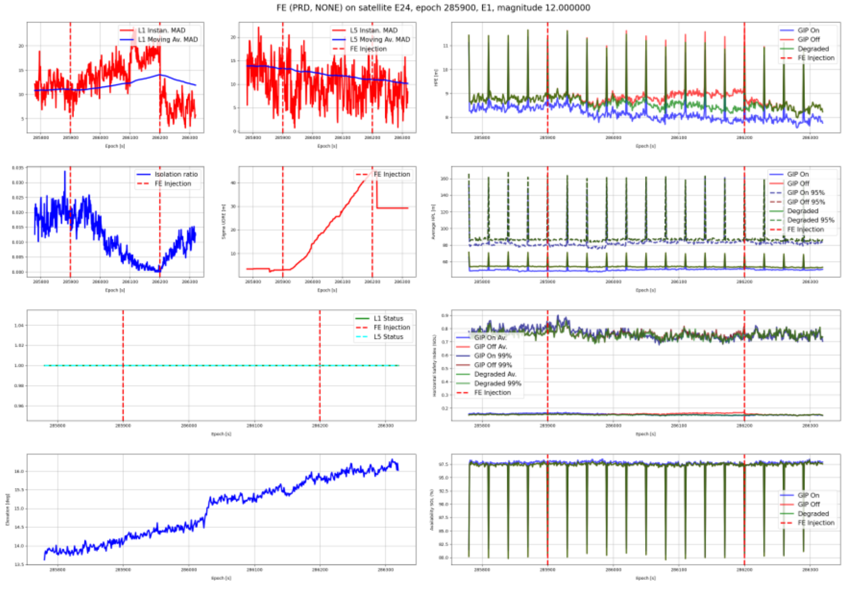
FE Mitigation: Pseudorange Drift & Code-Carrier Divergence

	Pseudorange Drift					Code-Carrier Divergence				
Amplitude	1.5	4.125	6.75	9.375	12	1.5	4.125	6.75	9.375	12
Av. Sigma UDRE ↑ [m]	-1.1	2.1	4.5	8.6	7.9	0	0.8	1.3	2.2	2.7

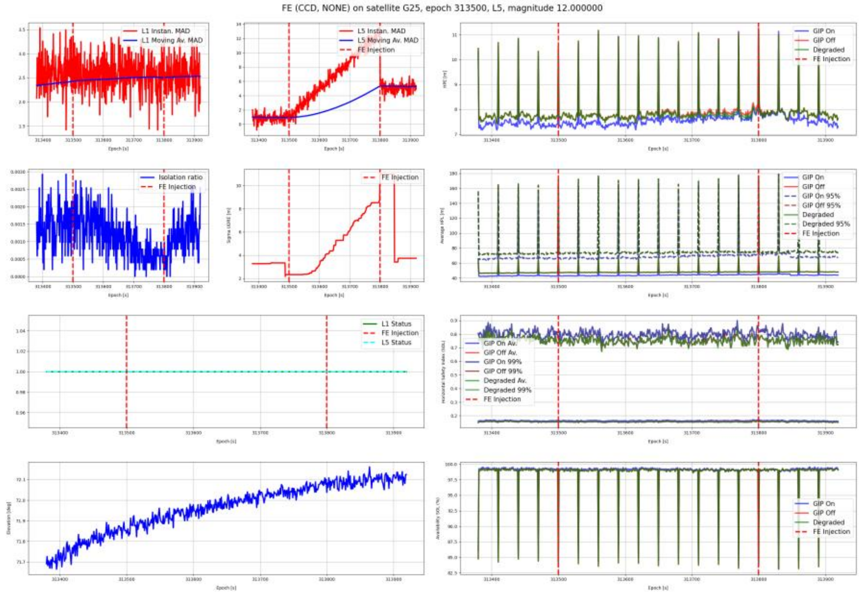
	USER TYPE		HPE ↑ [%]		HPL ↑ [%]		Average HSI ↑ [%]		99th HSI ↑ [%]		MI ↑ [%]		HMI ↑ [%]		AV ↑ [%]	
			No GIP	GIP	No GIP	GIP	No GIP	GIP	No GIP	GIP	No GIP	GIP	No GIP	GIP	No GIP	GIP
PRD 12m	RURAL	1.5m	2.9	3.1	0.1	0	0	3.2	-1.8	1.9	-	-	-	-	0.3	0.3
		12m	34	3.2	-0.2	0.6	30.4	2.6	27.7	2.1	-	-	-	-	0.3	0.3
	URBAN	1.5m	0	0	0.4	0.1	-0.4	-0.1	0	0	2.9	1.8	-0.1	4.2	0.2	0.3
		12m	0.6	-0.4	-0.3	-0.6	0.8	-0.1	0.4	-0.7	2.8	-1.4	-0.2	-2.3	0.3	0.4
	LOCAL	1.5m	0	4.2	3	1.7	0.9	2.7	0	1.9	-1	7.7	34.7	81	-0.1	0.2
		12m	1.2	-2.4	-0.8	0.2	-0.5	-2.8	-0.6	-2	2	-3.2	21.1	-2.2	0.6	0.5
CCD 12m	RURAL	1.5m	1	0.3	0.3	-0.5	-0.5	0.9	-0.2	0.4	-	-	-	-	0.3	0.3
		12m	11.8	3.8	0.3	0.3	10.8	3.3	6.2	1.6	-	-	-	-	0.3	0.3
	URBAN	1.5m	0	0	0.6	-0.1	-0.7	0.1	-0.1	0.7	0.4	3.8	0.2	-1.3	0.3	0.4
		12m	0.3	-0.2	-0.4	-0.2	0	0	-0.3	-0.3	1.1	0.3	14.9	9.9	0.5	0.4
	LOCAL	1.5m	0	4.2	0.5	0	3.9	4.3	3.3	3.6	19.4	21.3	28.9	11.8	0.18	0.2
		12m	0.3	-2.1	-0.2	-0.6	-2.4	-1.9	-2	-1.5	-8.3	-4.7	-4.5	-6.8	0.8	0.7

RIGOUR TEST CAMPAIGN

Pseudorange Drift Reponse



Code-Carrier Divergence Response

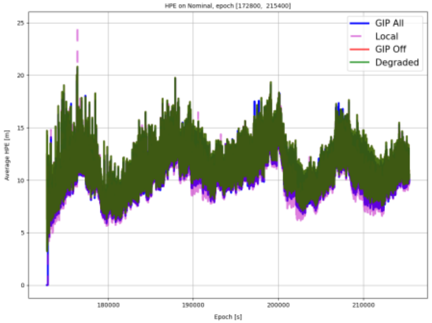


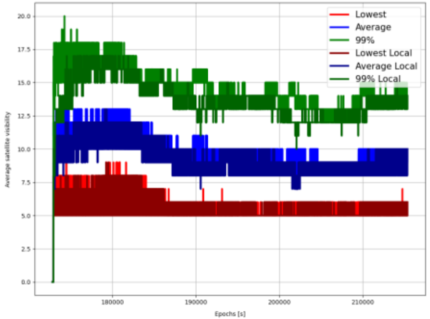
RIGOUR TEST CAMPAIGN

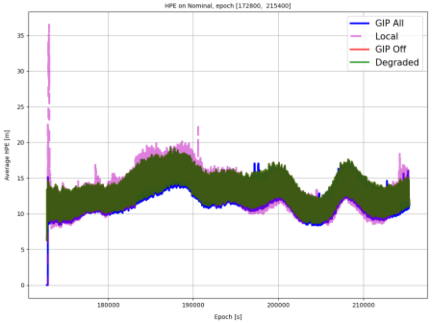
Availability impact by using a high density of users within a localized area

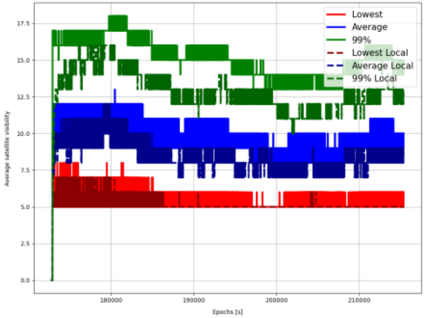
Local Users only

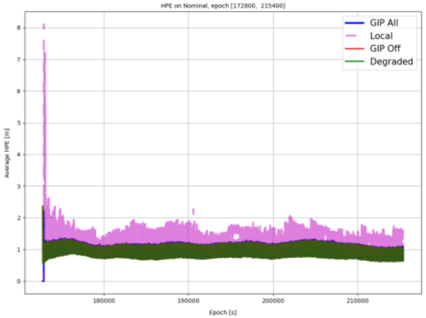
Local HPE, Satellite	Urban HPE, Satellite	Rural HPE, Satellite

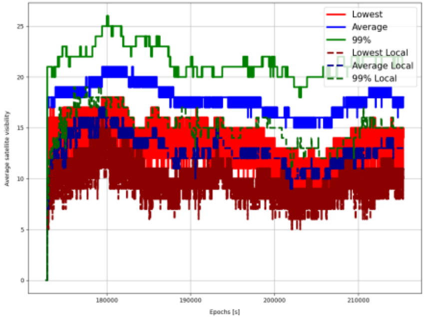












RIGOUR Conclusions and Recommendations - I

CONCLUSIONS	RECOMMENDATIONS	EXPECTED BENEFITS
➢ Pre-detection and Feared Event mitigation module has been successful in detecting moderate to high step events and is highly dependent upon continuously low-variance collected data. ➢ As such, eliminating urban-characteristic errors by processing only users in rural scenarios greatly improve detectability, even for low magnitudes.	➢ Implement a dedicated algorithm that can handle drift-driven Feared Events.	➢ Robust against Pseudorange Drifts and Code-Carrier Divergences.
	➢ Define and implement automatic nominal conditions recovery detection in Feared Events mitigation module.	➢ System being able to autonomously recover from Feared Events.
	➢ Review Feared Events amplitude ranges with respect to integrity requirements to identify maximum desired biases and relate to minimum detectable bias in dedicated study.	➢ Improved definition of integrity.
➢ Two main modules, the Fault Detection and Isolation + Global Exclusion module was shown to overlap in functionalities with the UDRE module, where the activation of the latter deactivates users' isolation of satellites, leading to inefficiency in the applied algorithms.	➢ Review GIP system design to grant more value to Fault Detection / Isolation and Global Exclusion functionality. ➢ Incorporate measurement characterization standalone capabilities.	➢ Development of parallel integrity streams architecture, enhancing integrity performance.
➢ The UDRE module and sigma UDREs, as the main output of the satellite integrity functionality, have been successful in protecting the users against all impactful types of Feared Events. However, widespread simulated stations were critical for monitoring.	➢ Implement a larger service areas with widespread users to improve satellite observability.	➢ Proof of concept for integrity based on user-only measurements.
➢ The local Integrity algorithm goal is granting additional protection to local environmental sources of error in areas with high density of users. The results show an improvement over urban users, but the service was found insufficient to provide protection for some high-magnitude local effects such as NLOS. Since they happen at user level, little difference is seen by using GIP products. User-level Sensor fusion is encouraged.	➢ Enhance local user’s environmental simulations that takes into account local geometry, obstructions and multipath spatial correlation between users.	➢ Enhancement of simulation realism, enabling innovative approaches making use of spatial discretization.
	➢ Improve local integrity algorithm, enabling the obtention of over bounding parameters irrespective of the occultation of satellites between local users. Measurement error merge after clock removal, clusterization, usage of more complex statistical overboundings.	➢ Enhancement of local integrity concept.

RIGOUR Conclusions and Recommendations - II

RECOMMENDATIONS	EXPECTED BENEFITS
Multithreading techniques usage and optimization of parallelization tasks for user measurement simulation.	Flexibility, reduction of simulator execution time.
The assessment of TTA derived requirements for SoL (6 seconds) of the real-time operating system, considering all latencies present in the integrity chain.	Definition of infrastructure and communication requirements.
The assessment of non-referenced receivers' measurement desynchronization impact on the GIP algorithms, also considering communication failures, outages and discontinuities in the raw input data.	Upgrade prototype to be aligned with the operational system.
Capture a list of aims for RIGOUR service requirements related to performance-based navigation for projected potential opportunities (i.e.: integrity for GNSS-based road/rail transport, tolls, UAV navigation…) to iterate on useful and realistic specific performance requirements	Adaptation of performance requirements, opportunity for user engagement.
Improvement of the demonstrator platform with simulated raw measurements, correction models and errors, including improved time/space correlations, and improving the zero-order approach used here. Address the importance of real GNSS data collection.	Enhancement of simulation accuracy and applicability. Development of an upgraded GIP prototype closer to the operational system. Capture of future risks (data privacy, user engagement).

Benefits of Working with ESA

- Thanks to the support provided by ESA and the NAVISP Element 1 programme we have developed the RIGOUR system which is an innovative integrity prototype.

- ESA has provided guidance along the different stages of the project and validated our technical approach which is much appreciated.

GMV would like to thank ESA for their support in this activity.

AoB

Thank you

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