

# MAGIE (REAL-TIME BIG DATA PROCESSING FOR GNSS INTEGRITY)

FINAL PRESENTATION

OHB AUSTRIA GMBH, 27.01.2026



# AGENDA

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1. Project introduction
2. System concept and technical scope
3. GNSS Integrity Processor tuning
4. Simulation and processing
5. Presentation of simulation results
6. Conclusions & way forward

**1**  
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# PROJECT INTRODUCTION

# PROJECT OVERVIEW

## FACTS AND FIGURES

### MAGIE: Mobile-Application-based GNSS Integrity Engine

#### Programme

- NAVISP-EL1-053
- A new concept for GNSS Integrity (real-time big data approach)

#### Duration

- 01/2022 – 11/2025

#### Project Team

- OHB Austria GmbH (OHB)
- Science & Technology (S&T)
- IntegriCom (IC)

### Project Goals

- Prototype a GNSS integrity service based on crowd-sensed data
- Demonstration of the feasibility and a quantification of the benefits (with respect to existing Integrity systems) using large-scale simulations

### Heritage

- GNSS simulator XPLORA (formerly GIPSIE)

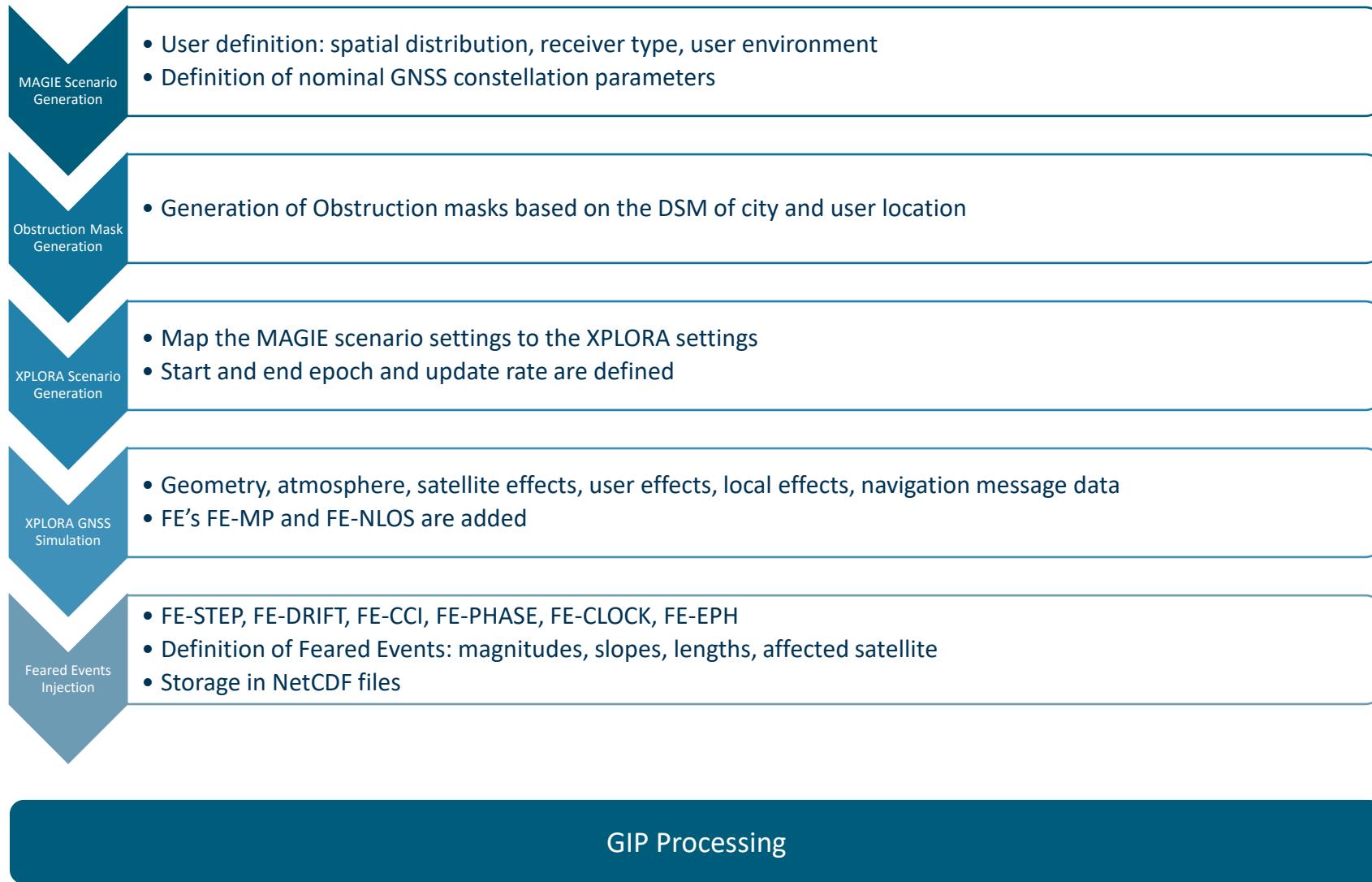
# 2

## SYSTEM CONCEPT AND TECHNICAL SCOPE

- Main objective: prototype a GNSS integrity service based on crowd-sensed data
- Solutions shall be scalable (number of users can vary strongly)
  - Reducing computational complexity is key
- Demonstrator will be simulation based:
  - Realistic, but simple user-equipment performance models
  - Realistic, but simple environment models
  - Based on nominal error models + (near) worst-case feared-event impact

# SIMULATION STRATEGY

## BASIC ARCHITECTURE



# FEARED EVENTS 1/2

ID	Feared event	Effect Model	Simulation of the effect on the receiver measurements	Worst-case impact
<b>FE-STEP</b>	Pseudorange Step Error	Step response $f_{resp}(t)$ on the pseudorange	The effect of FE-STEP on the pseudorange is modelled as a step response of a first-order, a second order DLL or as a random transient reaction.	<p>Detectable with 'step' detector (using behaviour over time) and 'instantaneous range error' detector ('per epoch').</p> <p>Impact on ranging is similar to all users, but will depend somewhat on receiver's DLL filtering.</p> <p>Larger range errors will have larger impact on users but will be easier to detect. Worst-case step is expected to be somewhat smaller than the MDB. Simulate 70%/80%/90%/100% of MDB.</p>
<b>FE-DRIFT</b>	Pseudorange Drift Error	Ramp $f_{ramp}(t)$ on the pseudorange	The FE-DRIFT is modelled as a ramp on the pseudorange with the slope of the ramp being equal to the pseudorange drift in the satellite signal.	<p>Detectable with 'drift' detector (using behaviour over time) and 'instantaneous range error' detector ('per epoch').</p> <p>Impact will grow over time, and so does detectability. The worst-case profile will greatly depend on autocorrelation properties of the test statistic.</p> <p>Proposal: when the 'per epoch' detector has a certain MDB, it is reasonable to simulate slopes significantly smaller than MDB/T (with T the time between samples). Could simulate 10%/20%/30% of MDB/T, compare impact of these cases and adjust when needed.</p>
<b>FE-EPH</b>	Erroneous Broadcast Ephemeris (orbits)	Errors introduced to the orbit parameters of the ephemeris data	<p>No direct effect on the pseudorange/carrier-phase measurements.</p> <p>As this FE is intended to model errors at navigation data generation level it will not be detected by a CRC check.</p>	<p>Detection is based on comparing est. satellite position with the ephemeris-based position. Worst-case satellite position error <del>wrt</del> impact on integrity is hard to establish.</p> <p>Nominal errors (standard deviation):</p> <ul style="list-style-type: none"> <li>radial: 0.16 m</li> <li>along-track: 1.04 m</li> <li>cross-track: 0.42m</li> </ul> <p>Projection to worst-case user location (TN2):</p> $R_{total, \max \epsilon  \in [0^\circ, 90^\circ]} \approx \max \left\{ \underbrace{0.97 \cdot  \epsilon_r  + 0.24 \cdot  \epsilon_t }_{WUL \text{ on edge off footprint}}, \underbrace{\sqrt{(\epsilon_r^2 + \epsilon_t^2)}}_{WUL \text{ in footprint}} \right\}$ <p>Along-track error is likely to be the 'worst' in terms of impact. Radial errors have 4 times larger effect on the range at the WUL, but 6.5 times larger standard deviation.</p> <p>So: simulate along-track errors of size somewhat smaller than the associated MDB?</p>

# FEARED EVENTS OVERVIEW 2/2

ID	Feared event	Effect Model	Simulation of the effect on the receiver measurements	Worst-case impact
<b>FE-CLOCK</b>	Erroneous Broadcast Clocks	Errors introduced to clock parameters of the ephemeris data	<p>No direct effect on the pseudorange/carrier-phase.</p> <p>As this FE is intended to model errors at navigation data generation level it will not be detected by a CRC check.</p>	<p>Similar to FE-STEP and FE_DRIFT. The full bias is observed by all users. Simulate as biases somewhat smaller than associated MDB.</p>
<b>FE-PHASE</b>	SV Degraded Carrier Phase [Navarro2016]	Additional Random noise $f_{noise}(t)$ on the carrier phase	The effect of the FE-PHASE is modelled as an increased noise on the carrier phase measurements.	As other cases, but based on 'minimal detectable variance degradation' MDVD: simulate degradations somewhat smaller than the MDVD.
<b>FE-CCI</b>	SV Code Carrier Incoherence	Ramp on carrier phase and pseudorange $f_{ramp}(t)$	The effect of FE-CCI on the code and carrier measurements is simulated as a ramp with different slopes on carrier phase and pseudorange measurements.	<p>Impact on CMC and ranging measurement will depend somewhat on receiver architecture [Gomez2020]</p> <p>Impact expected to be largest for 'intermediate values' of the ramp (very small and very large ramps will have lesser impact).</p> <p>[Gomez2020] uses slopes of same size and opposite sign on carrier and code phase. Is this the expected behaviour? Worst case could be range-only slope.</p>

- Previous list contained GLOBAL feared events
  - Satellite-based
- LOCAL feared events:
  - Severe Multipath
- Local feared events are visible to the GIP: “receiver data is bad” -> receiver to be excluded
- Local feared events are more visible to the receiver itself
  - Receiver shall deal with these itself

- Range-bias detector (should detect steps and slopes – step is worst-case slope. Includes satellite clock failures)
  - Bias estimated based on residuals (scaled to compensate for geometry)
- Ephemeris detector
  - The 3d Satellite position deviation wrt ephemeris estimated
  - Uses robust estimation (not median, but iterative robustly weighted least squares – computationally more efficient)
  - Worst-case feared event: purely radial error
  - Pre-filtering: included a multipath indicator to remove high-multipath sources
- Code-carrier divergence
  - Uses GBAS-based estimator/filter to estimate CCD.
  - Needs convergence time of at least 150s. Hence, raw data is collected from all receivers, then robustly averaged, then filtered (instead of filtering per receiver)
- Phase-noise detector
  - Estimates variance of (white) phase-noise over a window (trade-off between accurate estimation and potential delay)

- Mechanism: provide statistical bounds to residual error components
  - Non-local: based on centralized processing by a central processing engine-based
  - Local: based on local processing by the users (mobile app-based)
- Big Data and Scalability:
  - Too much data to handle optimally
  - Additional data should still contribute
- High-level design strategy for non-local faults:
  - Reduce data at the earliest possible point in the architecture
    - Remove bad geometry data, low SNR data, high multipath data...
    - Each reduction shall improve the quality of the remaining data
  - Rely on the presence of large amounts of data rather than accurate errors models
    - error modeling for low-quality sensors really hard

- **Global Integrity Concept is based on:**
  - Separate detectors for each of the feared events
  - Flagging the likely presence of feared events
  - No differential corrections -> hence low-frequency errors will not be removed
- **GIP provides the user with (a subset of) this information from the detectors:**
  1. A flag that indicates whether the test statistic exceeded a certain threshold value
  2. The threshold used to produce the flag
  3. The test statistic (or estimated errors) themselves (note: *could* become a differential system with these)
  4. Information on the uncertainty associated with the test statistic/estimated errors in the form of (parameters of) a probability distribution function
- **Supplying more than just a flag allows for more flexibility on the user side**
  - Different trade-offs required as per the SoW

- **General Approach:**

- Describe all measurement errors by a mixture, of which each component represents a ‘system state’ and is weighted by its likelihood.
    - For example: likelihoods 99.97% nominal, 0.01% clock error, 0.02% orbit error, standard deviations: 1m, 5m, 10m, biases: 0m, 2m, 1m.
    - Can derive PVT error distribution from the measurement distributions in principle, but not computationally

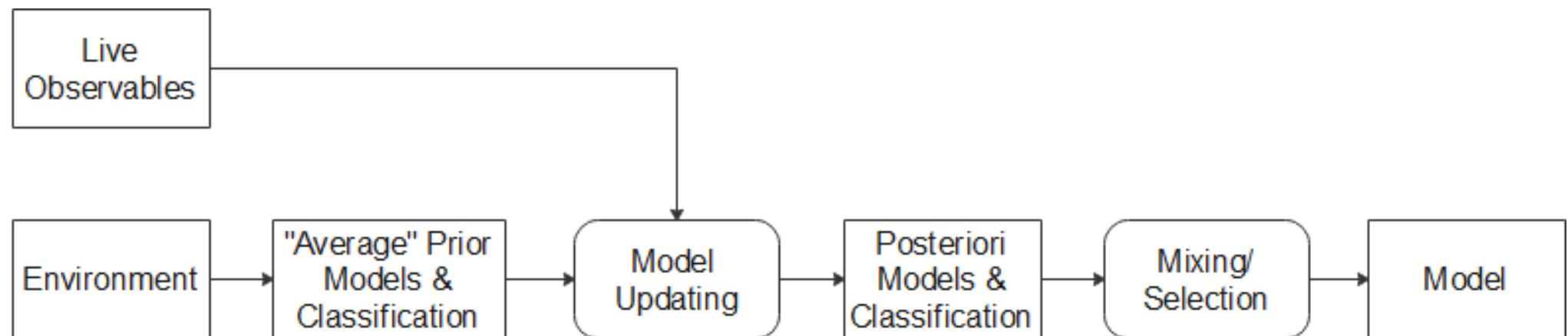
- **Need a simple/simplified description of the measurement errors**

- Overbounding
  - Use of fault detection and flags

- **Foreseen approach:**

- Overbound local errors by a normal distribution ‘per range’
  - Overbound global errors by a normal distribution ‘per range’
  - Combine local+global errors ‘per range’ and translate to PVT domain in an SBAS-like fashion

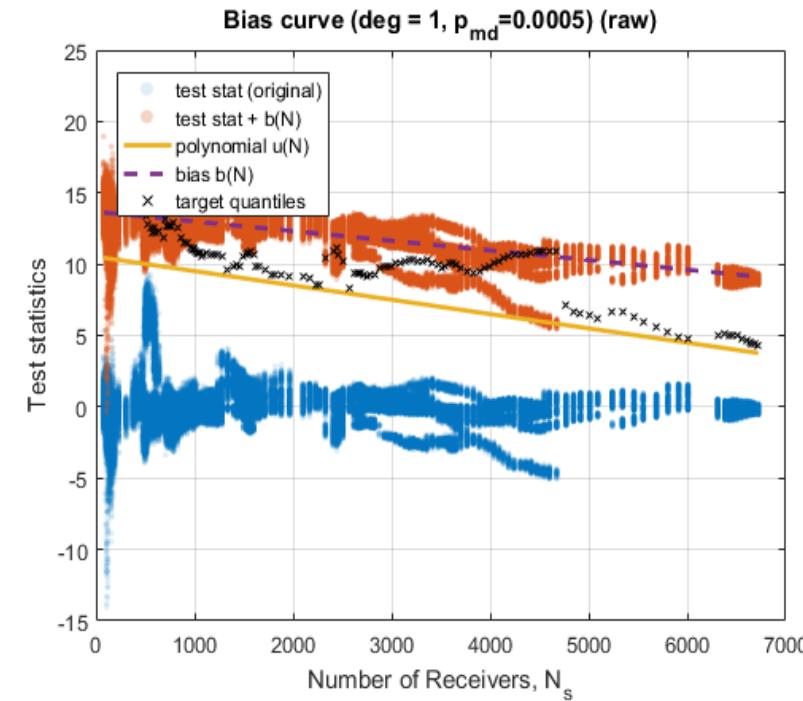
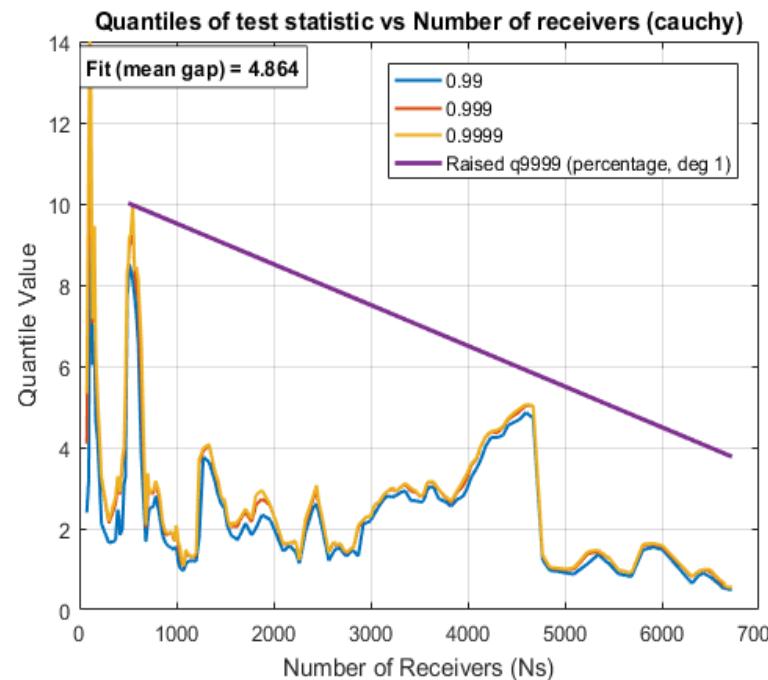
- Bound local measurement errors based on:
  - Environment -> prior models
  - Actual observables -> update to prior models based on
    - (1) classification of signal reception conditions
    - (2) (overbounding) models of local measurement errors (could be receiver-type specific)



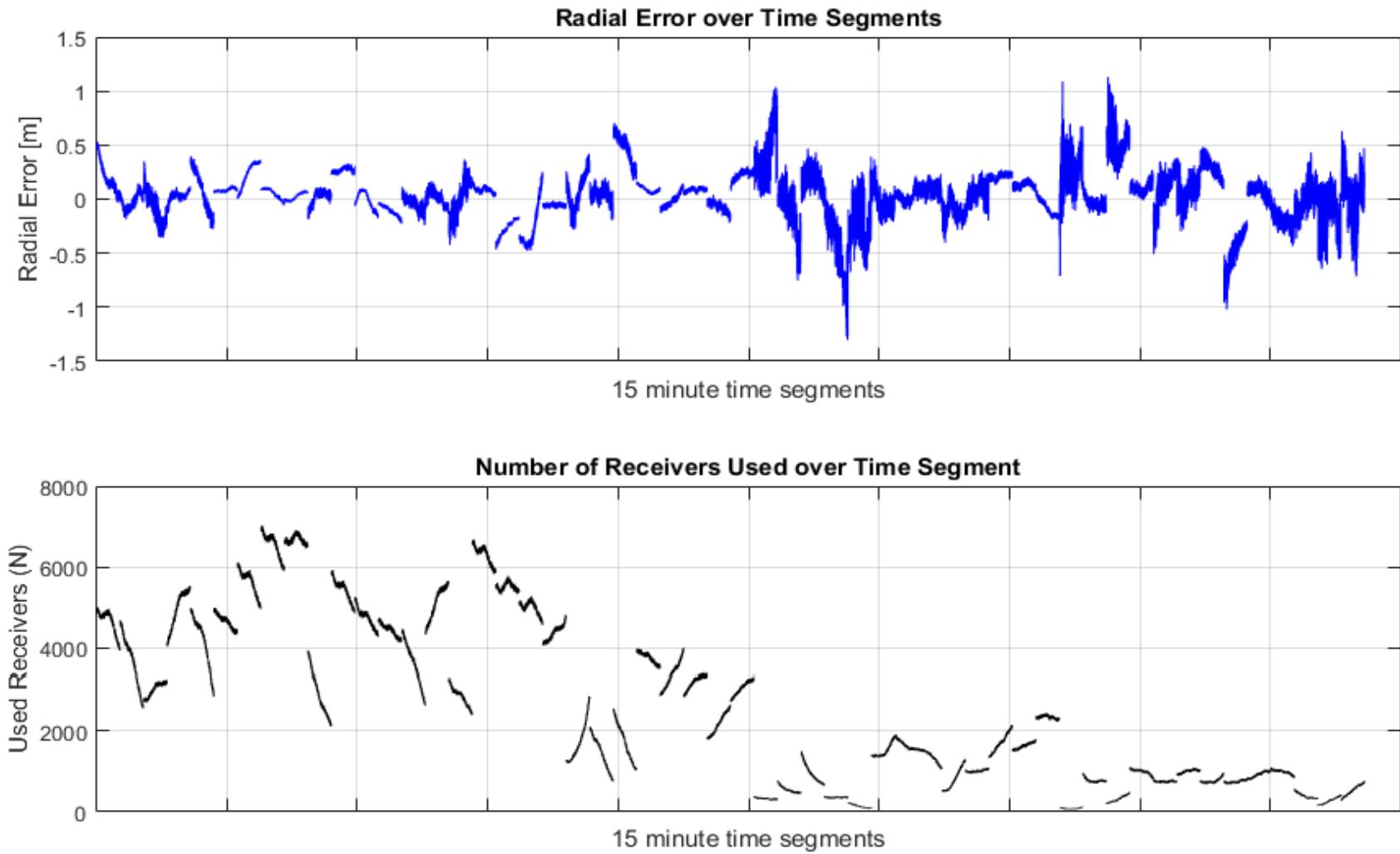
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# GNSS INTEGRITY PROCESSOR TUNING

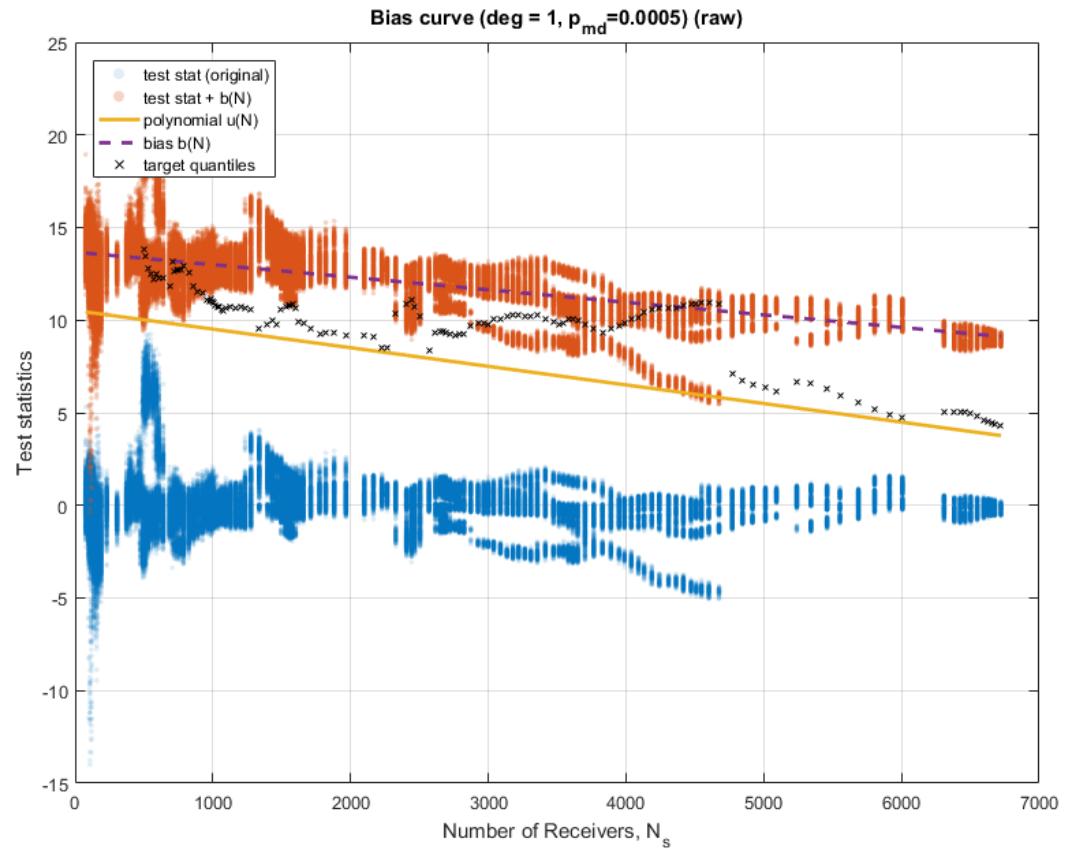
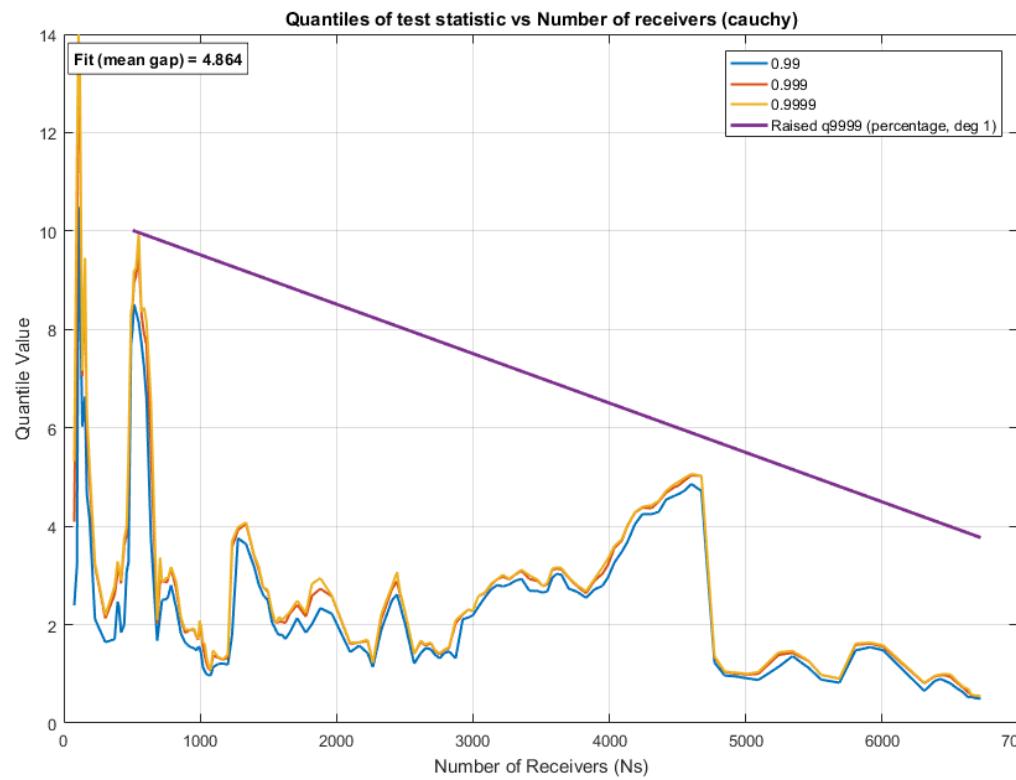
- Behaviour found:
  - Test statistic seemingly depends on  $N_s$  in strange way
  - Caused by undersampling of orbital errors, which vary only VERY slowly over time
  - Increase around 4000 receivers actually reflects a period of large, but actually present, orbital errors, not estimation uncertainty!



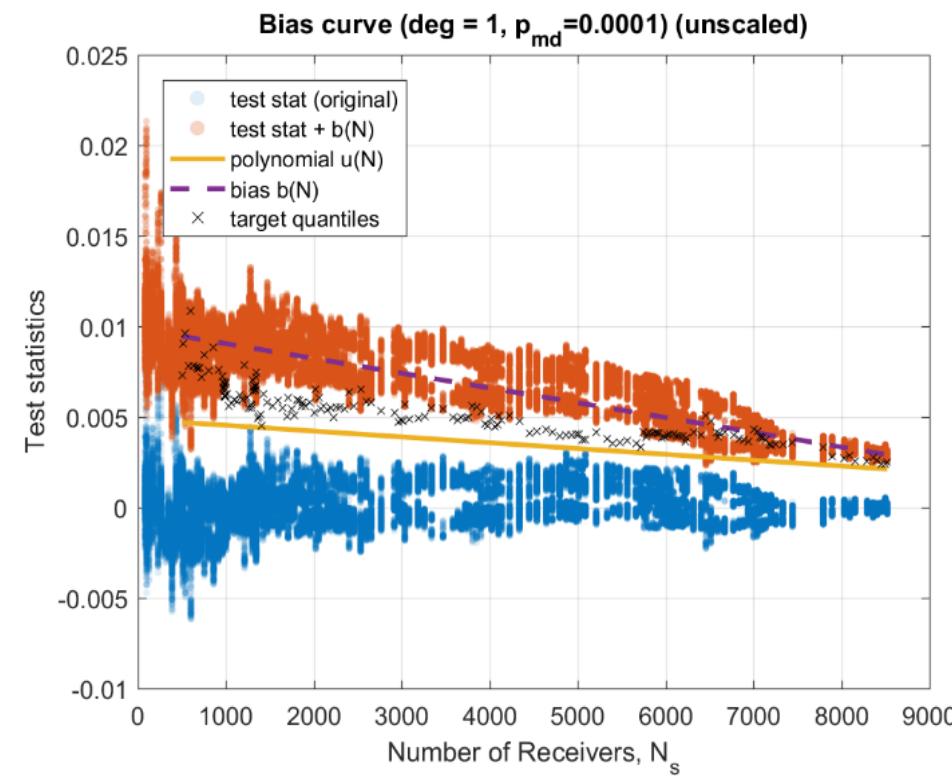
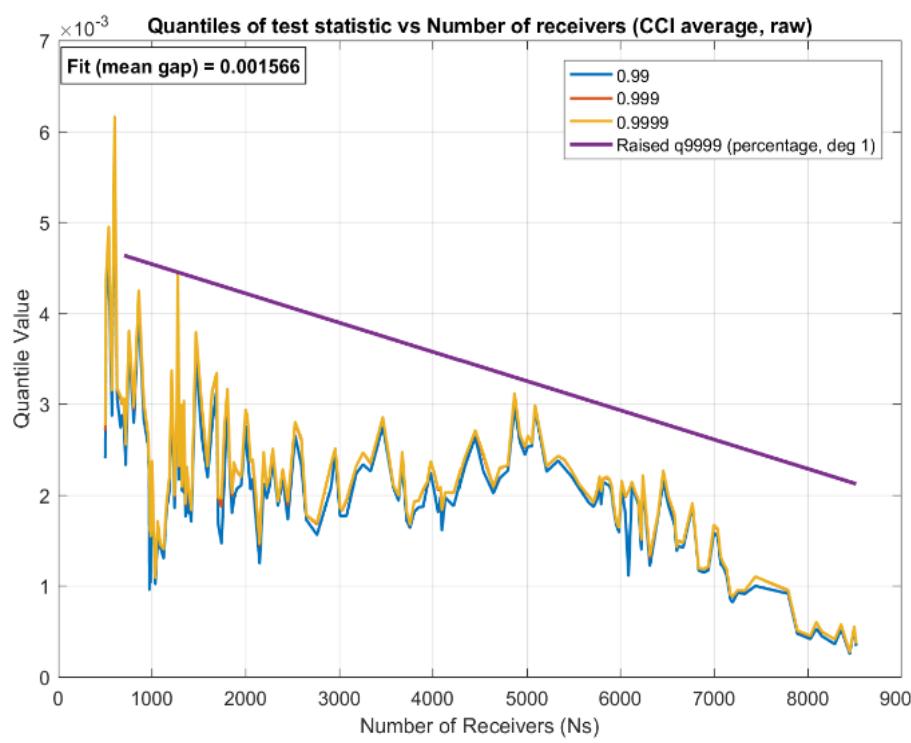
- Behaviour found:
  - Estimation uncertainty can be seen as 'noise' on the estimates
  - Noise high when  $N_s$  is small, but can go down to cm level for larger  $N_s$
  - Nominal Radial Error (and Error Rates) can become high for some data segments
    - Slope with random steepness
  - Detection thresholds need to take that into account



- Very similar to ephemeris detector (see below)
- Reason: can exploit that bias is the same for all receivers, no geometry dependency, but high correlation with radial error still

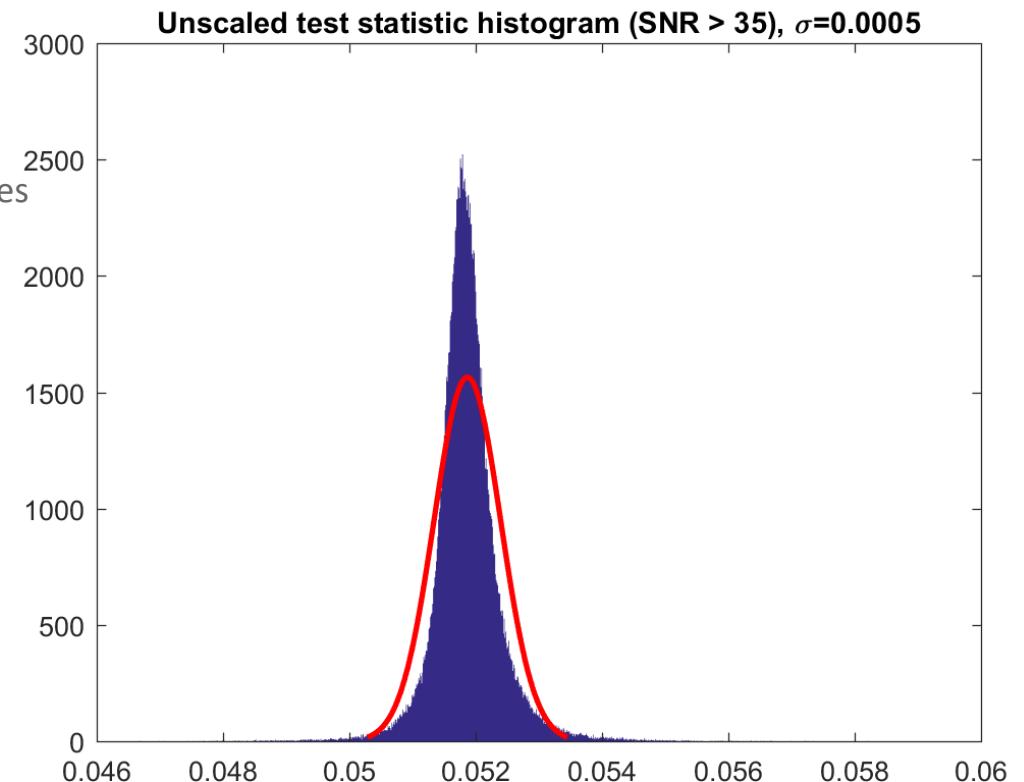
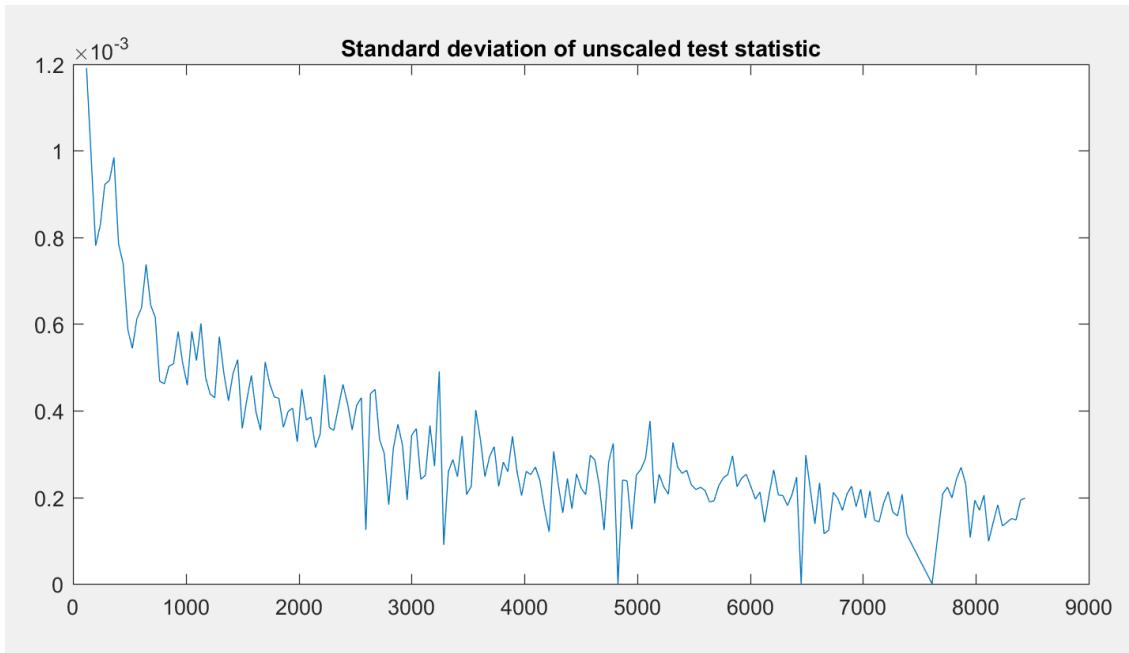


- Improving accuracy with larger number of receivers
- Some impact of large (radial) range error rates visible here too



# PHASE NOISE DETECTOR

- Clearly shows  $1/\sqrt{N_s}$  behaviour expected of white noise
- Phase noise is estimated to have a standard deviation of around 5 cm
- Estimation noise has standard deviation of 0.5 mm overall, and lower than that for values of  $N_s > 1500$ , hence deviations of a few mm can be detected reliably

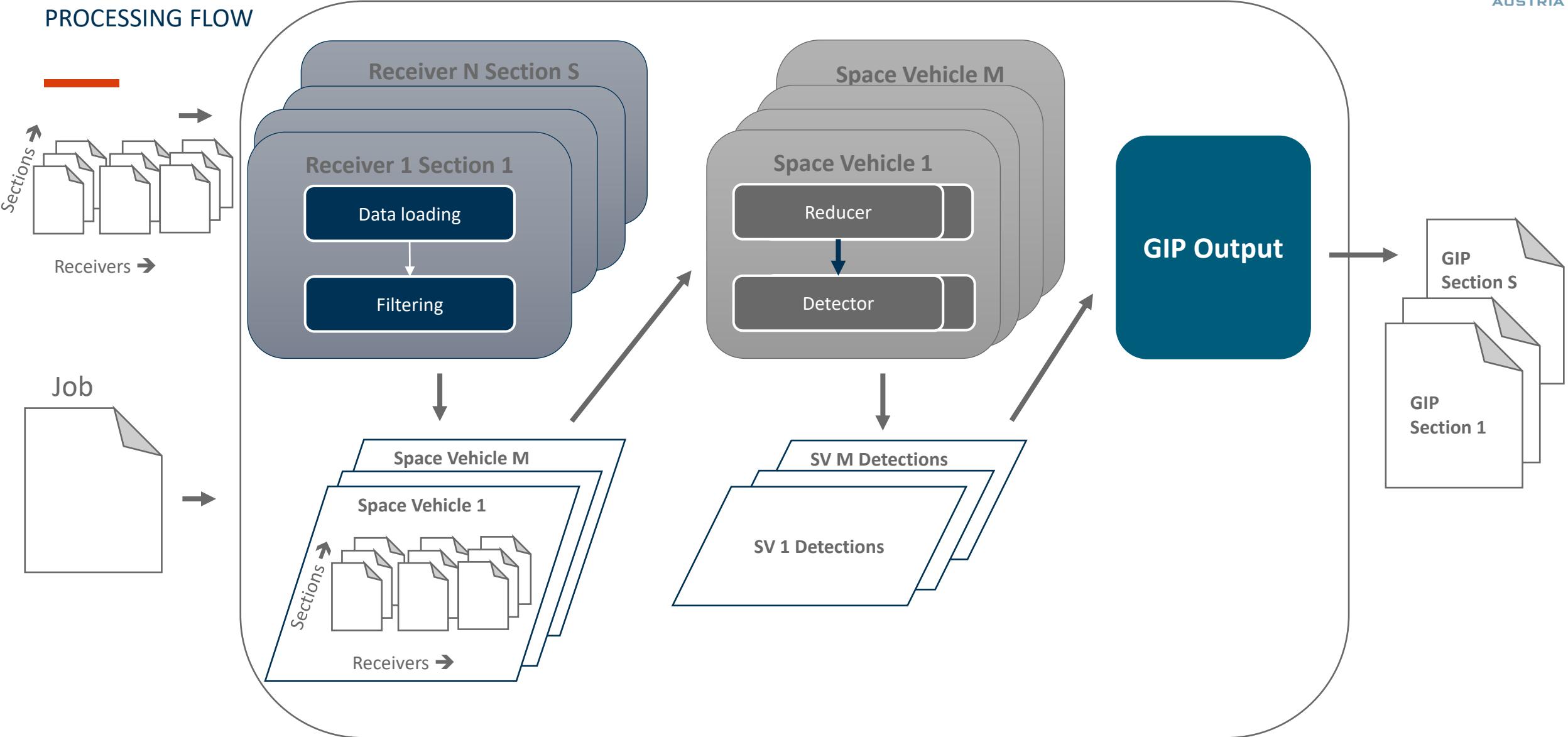


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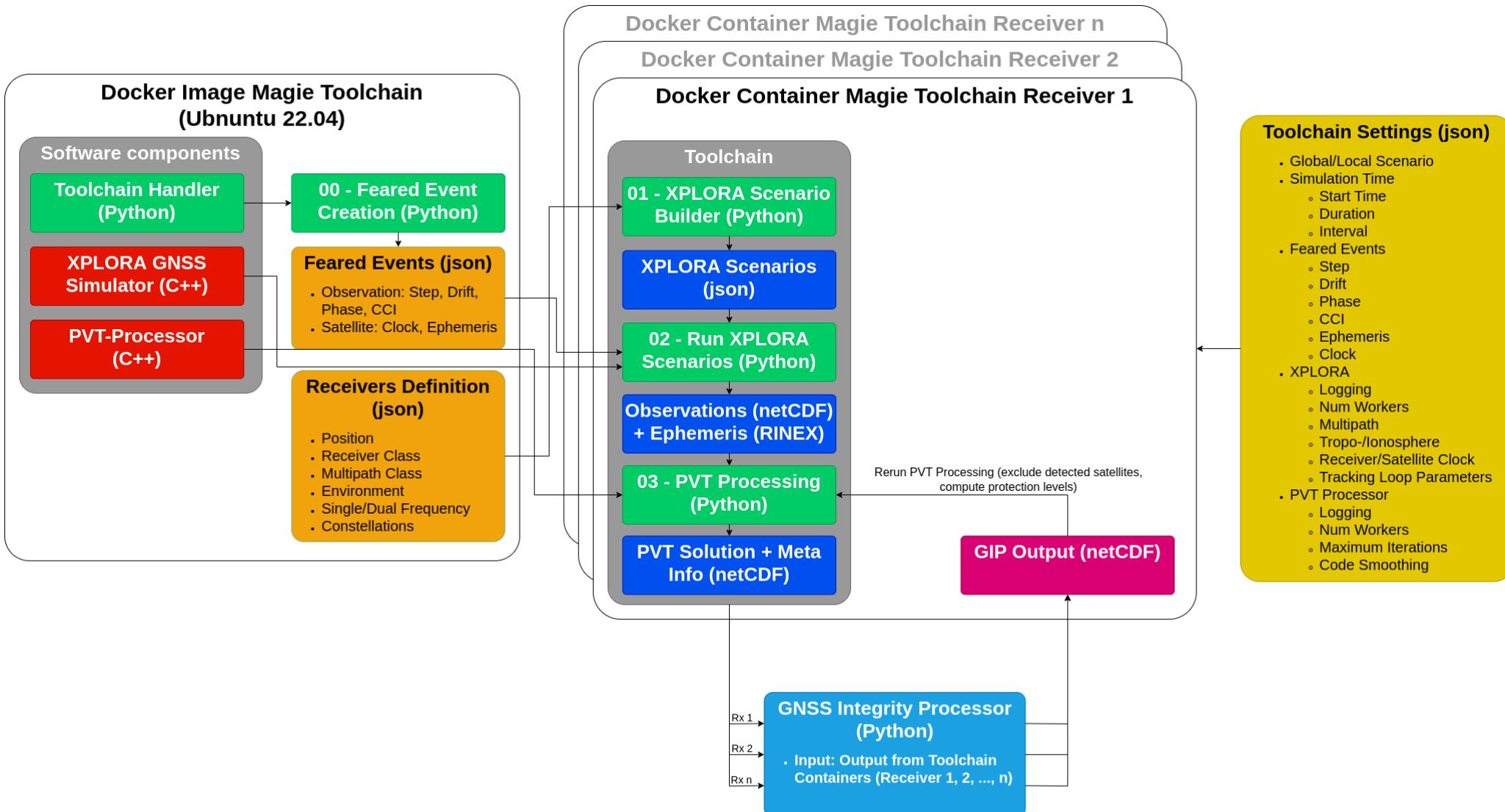
## SIMULATION AND PROCESSING

- **Two main tasks:**
  1. **Receiver simulation** - operates per receiver, fully parallel
  2. **GNSS Integrity Processor (GIP)** - operates over all receivers and 15-minute segments
- **Rationale:**
  - Optimisation & parallelisation → faster computation
  - 15-minute sections → ensure realistic computation resources



# MAGIE TOOLCHAIN (DOCKERIZED)

## OVERVIEW



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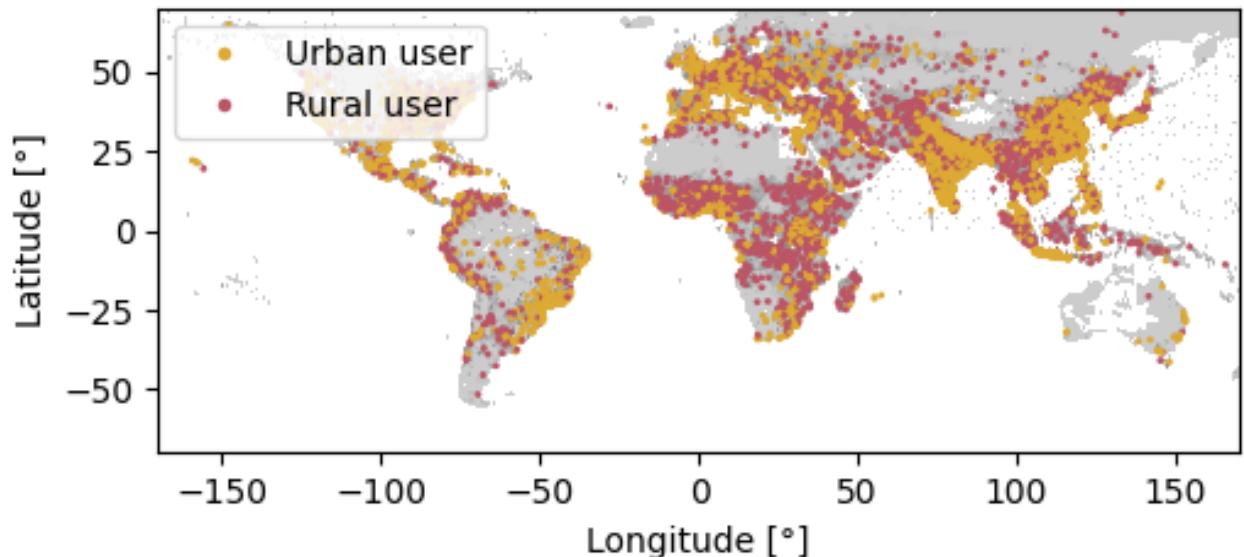
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# PRESENTATION OF SIMULATION RESULTS

# INTEGRITY RESULTS

## GLOBAL SCENARIO OVERVIEW

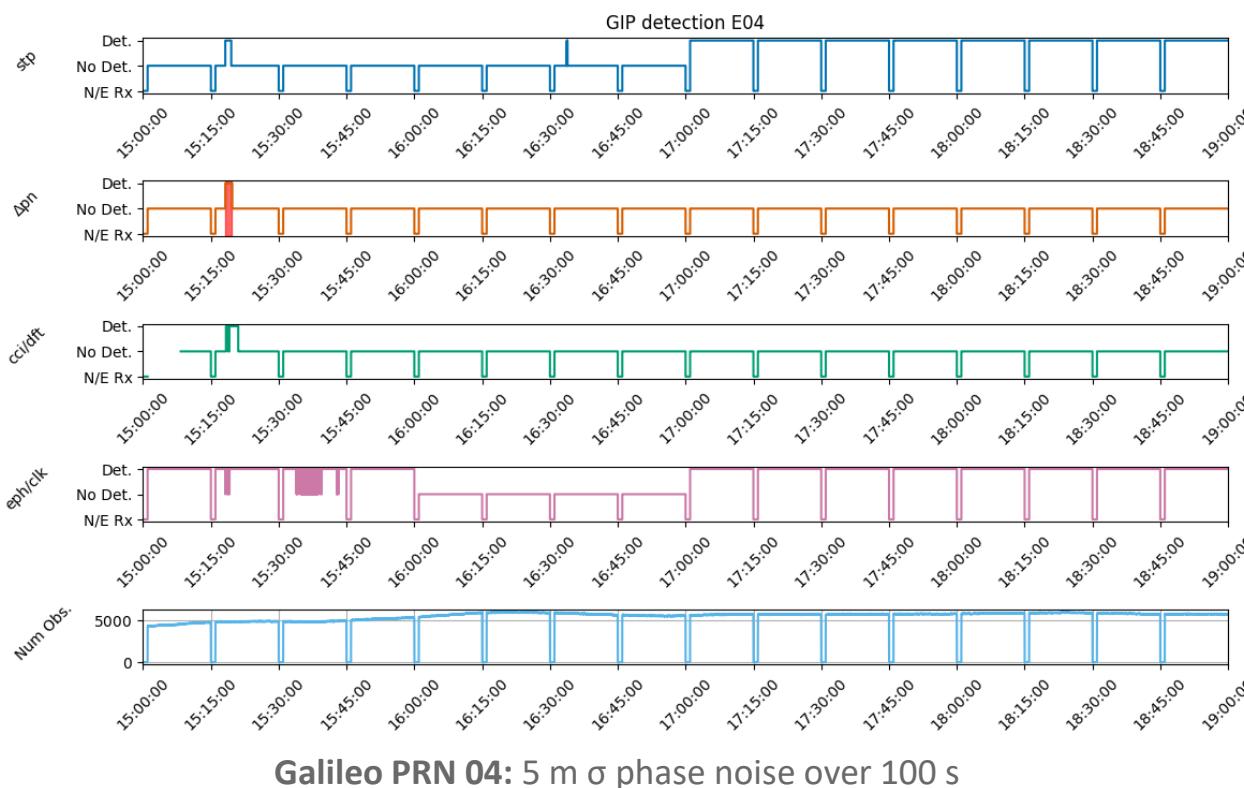
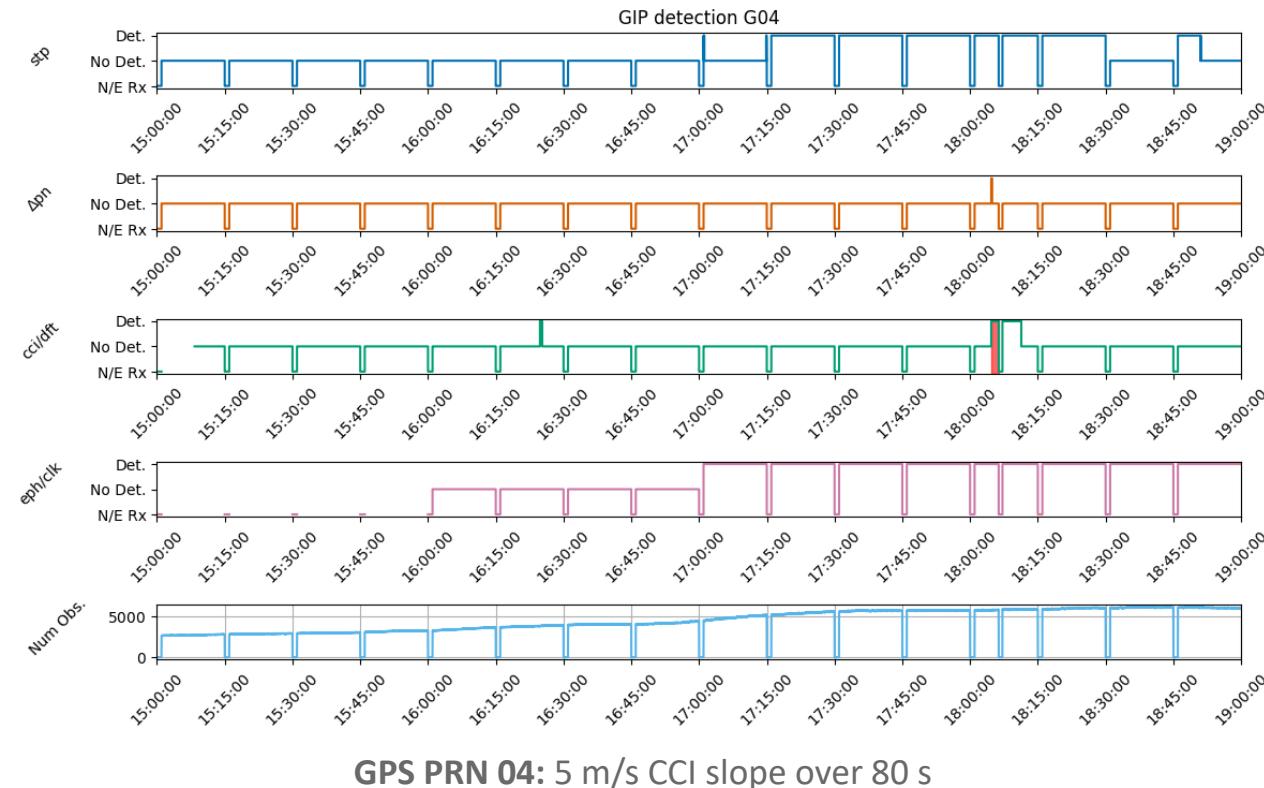
- 10,000 globally distributed receivers (clustered)
- Different receiver types (mass-market vs. professional vs. high-end)
- Different environments (rural vs. urban)
- Different multipath levels (weak vs. medium vs. severe)
- User measurements used as input for generating GIP products



- **Simulation duration:** As agreed, a duration of 4 hours was processed (2023/6/29 15:00:00 – 19:00:00)
  - 16 sections per receiver, 16 GIP outputs (15 minutes per section)
- **Feared Event Injection:** Based on the outcome during the detector tuning phase, the following magnitudes for the FEs have been defined
  - Step / Phase Noise: 5 meters
  - Drift / CCI: 5 meters per second
  - Ephemeris: 25 meters in radial component (5 meters added to  $SQRT\_A$  Kepler parameter)
  - Clock: Change of scale factor due to bit flip in LSB 0 or 1
- **Toolchain Runs:**
  - Globally distributed receivers delivering user measurements to GIP
  - Local receivers (city of Melbourne) with high multipath
  - GIP products computed (detection flags, MDBs, number of observers)
  - User results (PVT, HPL), computed via GIP products and user measurements for global/local scenario

# GIP RESULTS

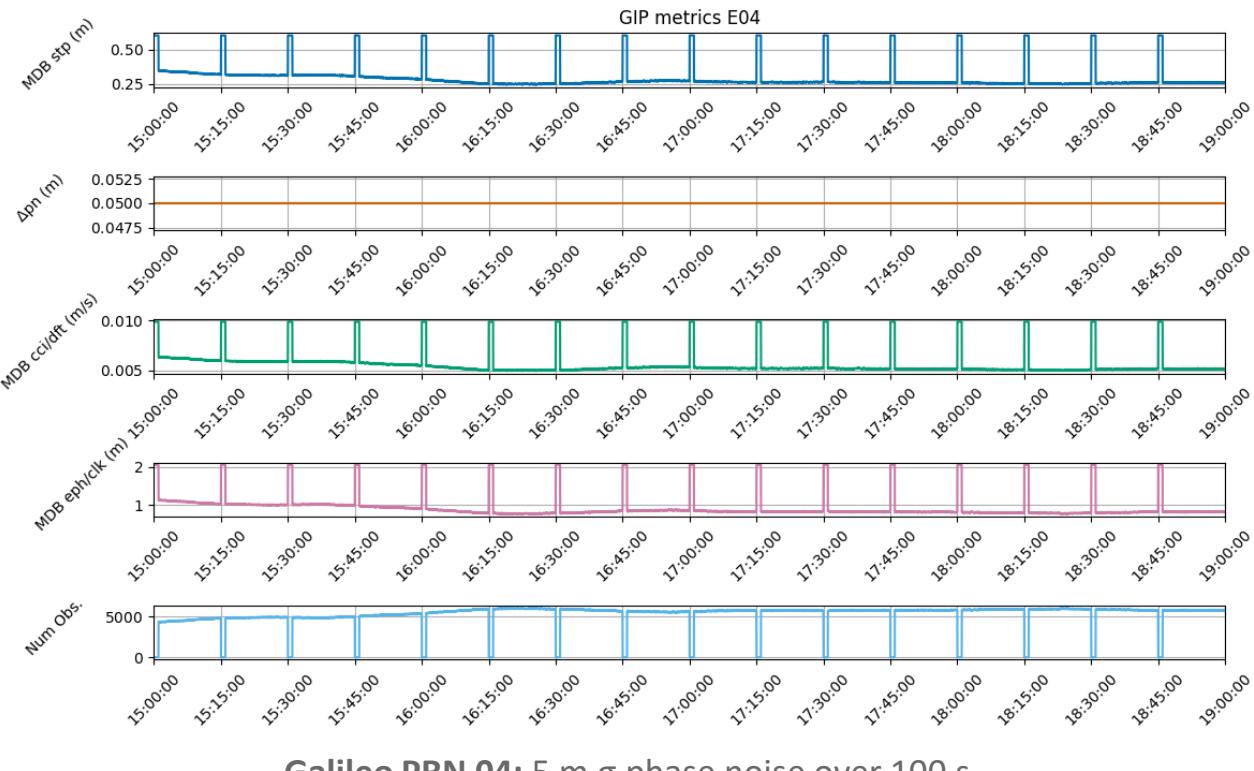
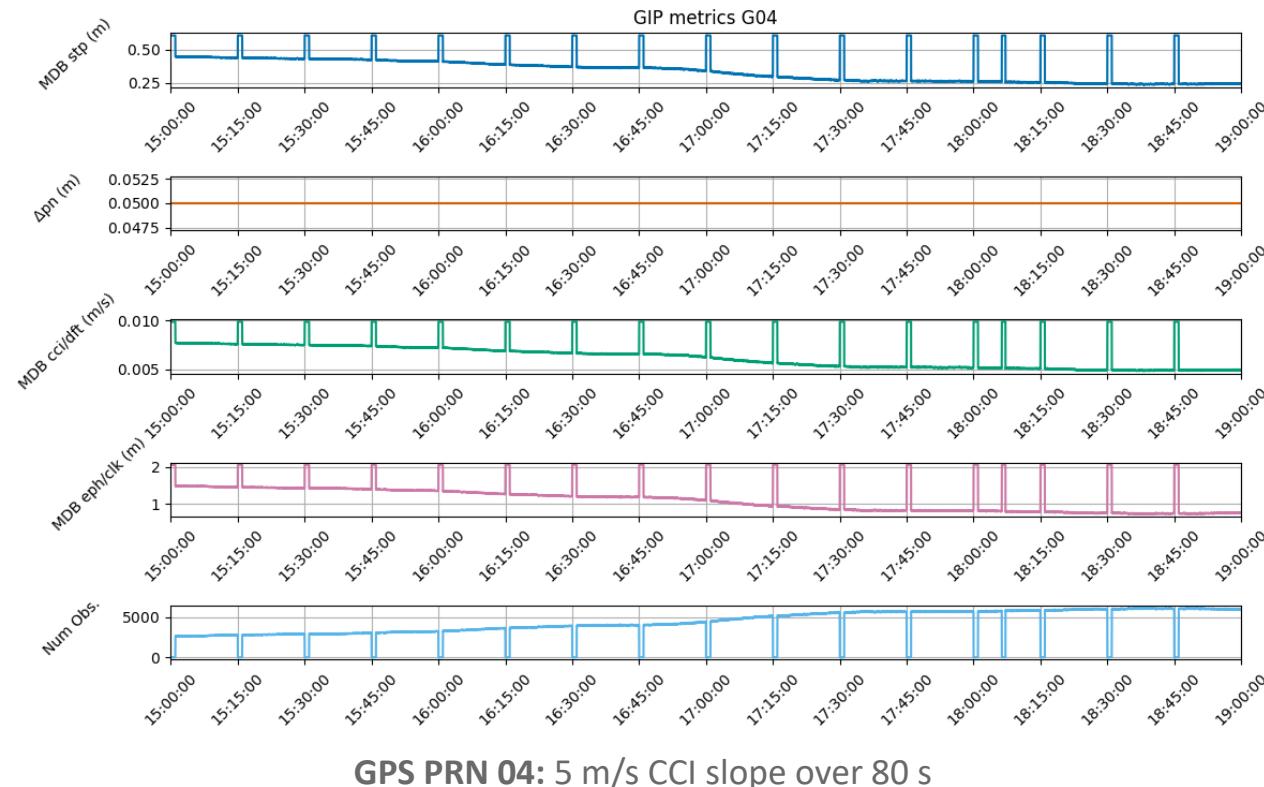
## DETECTION FLAGS



- 4 detectors covering 6 types of FE
- Detection flag depicts 3 states: *Detection vs. No Detection vs. Not enough receivers*

# GIP RESULTS

## MINIMAL DETECTABLE BIASES



- Correlation between number of observers (receivers) and MDB
- MDBs used for Protection Level Computation
  - Step, CCI/Drift and Eph/Clock for "Global" PL
  - $\Delta$  phase noise (not a MDB per definition) for SBAS PL (DO-229F-MOPS)

# GIP RESULTS

## PERFORMANCE

FE	Start	Duration	PRN	Magnitude	Detection	TTA
<b>Step</b>	15:05:00	100 s	GPS 23	5 m	Yes	0 s
<b>Phase</b>	15:18:10	80 s	GAL 04	5 m	Yes	0 s
<b>Phase</b>	15:22:00	70 s	GPS 27	5 m	Yes	0 s
<b>Phase</b>	15:36:30	70 s	GPS 15	5 m	N/E Rx.	-
<b>Drift</b>	15:44:10	90 s	GPS 23	5 m/s	N/E Rx.	-
<b>Phase</b>	15:56:10	120 s	GAL 03	5 m	Yes	0 s
<b>CCI</b>	16:04:10	120 s	GPS 24	5 m/s	N/E Rx.	-
<b>Phase</b>	16:16:00	100 s	GAL 08	5 m	N/E Rx.	-
<b>Step</b>	16:29:00	60 s	GAL 05	5 m	Yes	0 s
<b>Step</b>	16:32:40	70 s	GAL 12	5 m	Yes	0 s
<b>Drift</b>	16:55:50	60 s	GAL 25	5 m/s	N/E Rx.	-
<b>Drift</b>	16:59:10	70 s	GPS 11	5 m/s	Yes	0 s
<b>CCI</b>	17:25:50	70 s	GPS 19	5 m/s	Yes	0 s
<b>CCI</b>	17:57:10	80 s	GAL 26	5 m/s	N/E Rx.	-
<b>Drift</b>	18:01:10	80 s	GAL 03	5 m/s	Yes	0 s
<b>CCI</b>	18:04:40	100 s	GPS 04	5 m/s	Yes	0 s
<b>Step</b>	18:23:30	80 s	GPS 07	5 m	Yes	0 s
<b>CCI</b>	18:26:50	100 s	GPS 03	5 m/s	Yes	0 s
<b>Drift</b>	18:37:40	120 s	GAL 07	5 m/s	N/E Rx.	-
<b>Drift</b>	18:45:30	60 s	GPS 08	5 m/s	Yes	1 s

Observation-based Feared Events

FE	Start	PRN	Magnitude	Detection	TTA
<b>Eph</b>	15:32:00	GAL 05	25 m	Yes	0 s
<b>Eph</b>	17:32:00	GAL 33	25 m	N/E Rx.	-
<b>Eph</b>	18:02:00	GPS 22	25 m	Yes	0 s

Ephemeris-based Feared Events

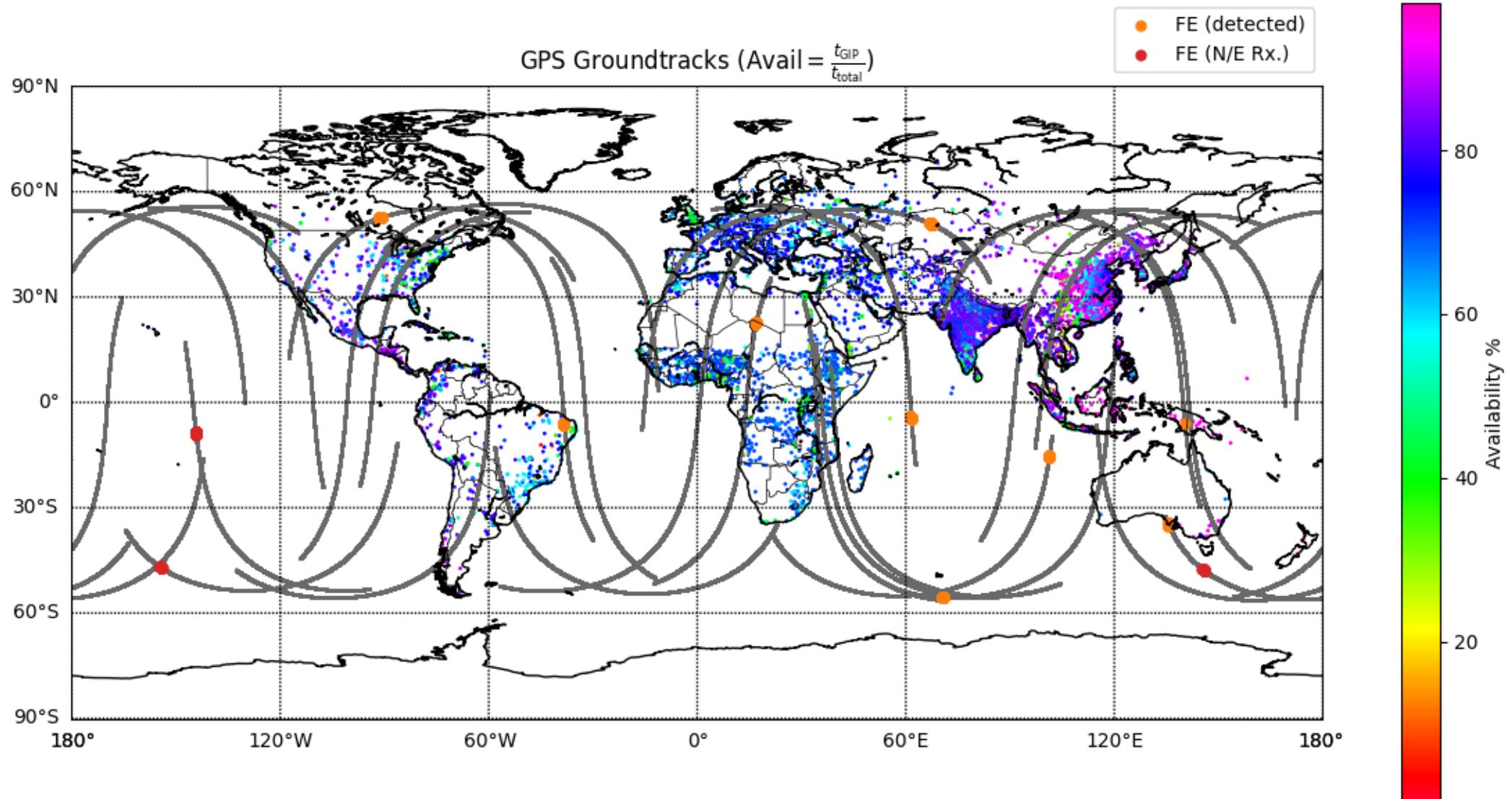
Detection Rate (incl. N/E Rx.)	Detection Rate	FA rate step	FA rate Δpn	FA rate cci/dft	FA rate eph/clk
65.2%	100%	24%	0%	4%	27.9%

GIP Performance (covering all satellites)

- Clustering of globally distributed receivers has big influence
- False alerts are affecting individual satellites (thus making them unavailable) and not the service as a whole
- Moreover, consecutive FE detection flags over a period of time should be seen as only one alert

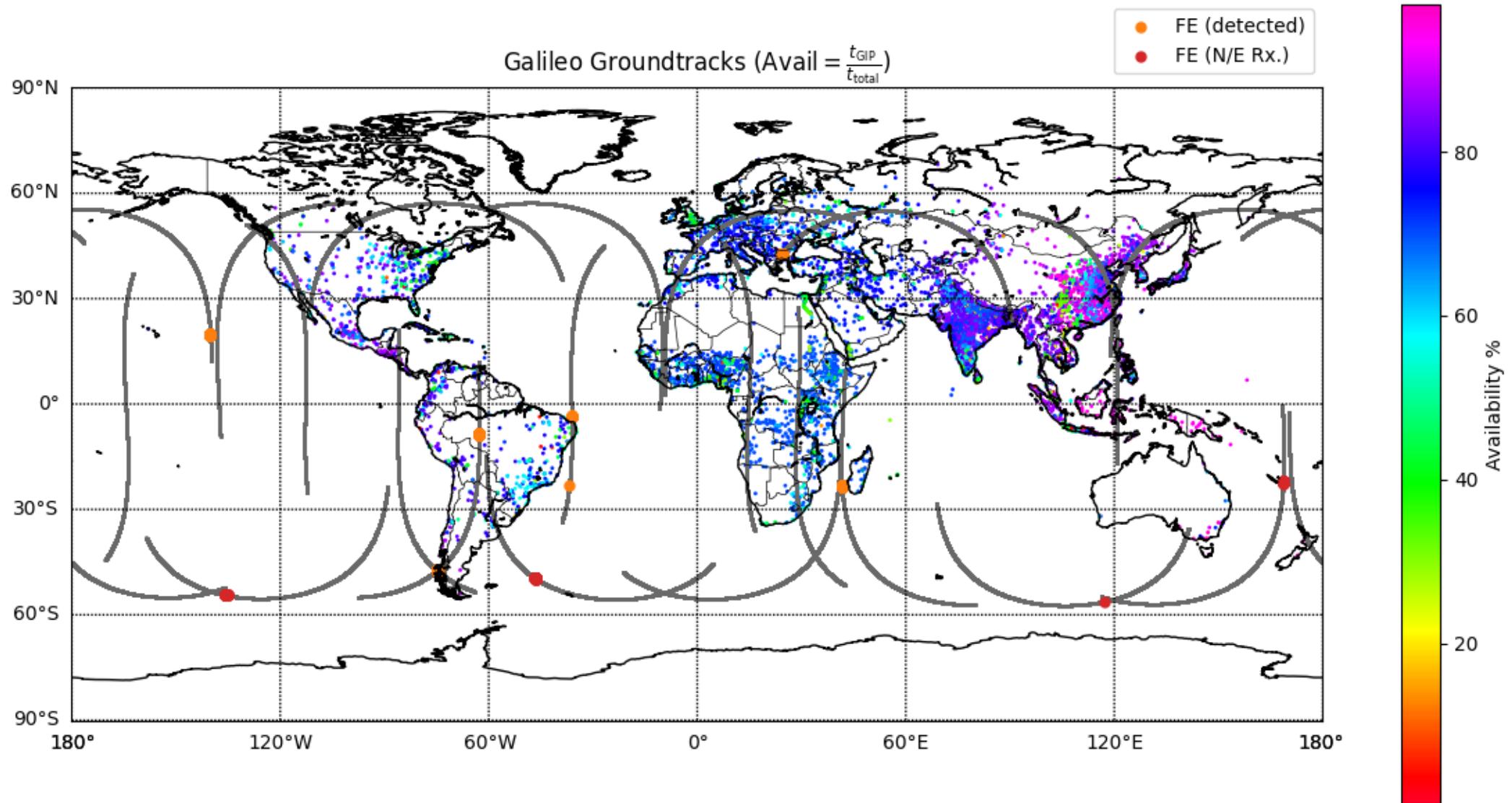
# INTEGRITY RESULTS

## GPS SATELLITE GROUND TRACKS WITH AVAILABILITY



# INTEGRITY RESULTS

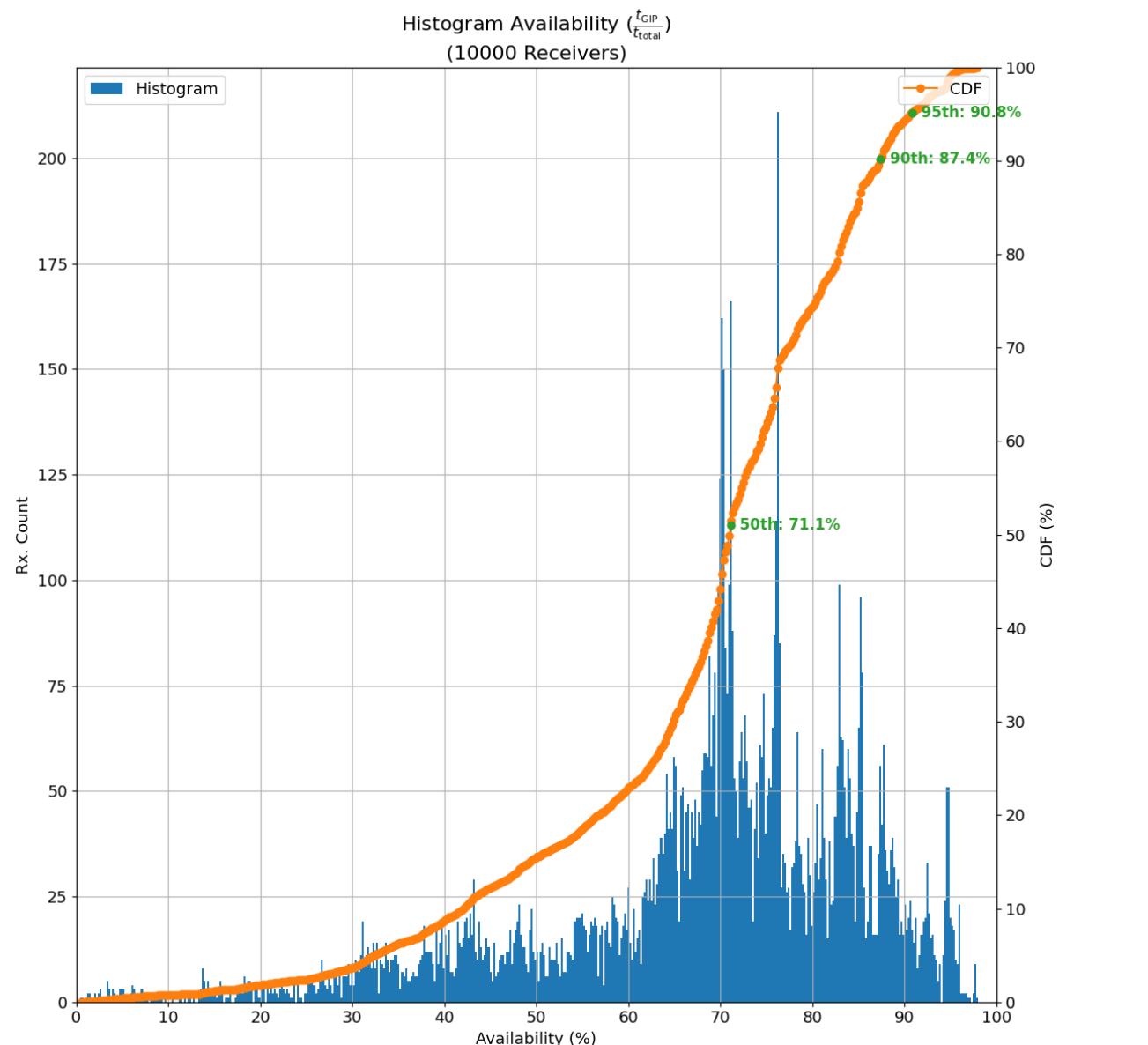
## GALILEO SATELLITE GROUND TRACKS WITH AVAILABILITY



# INTEGRITY RESULTS

## GLOBAL SCENARIO AVAILABILITY

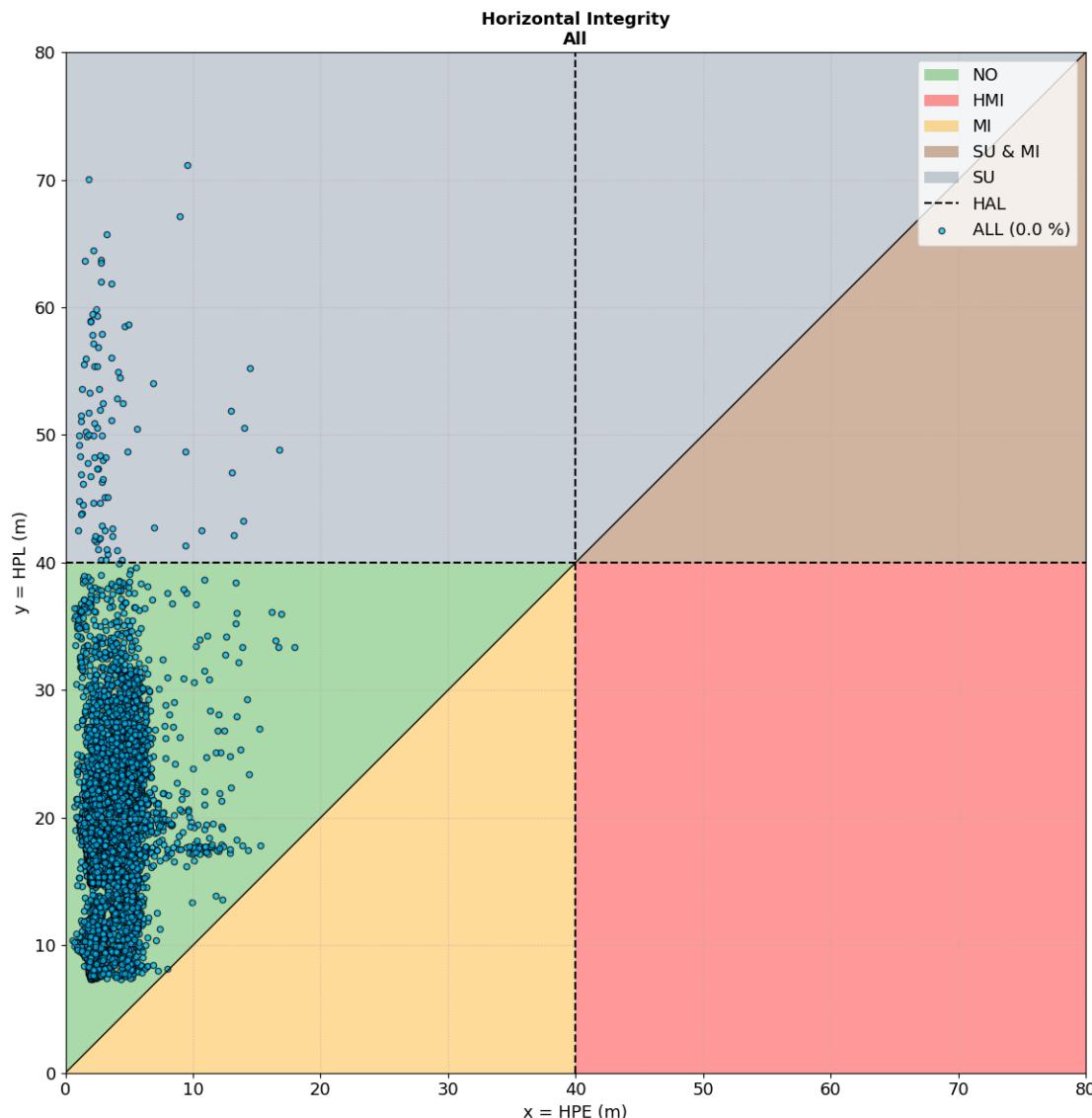
- Availability defined as GIP epochs vs. total number of epochs
- 50% of all receivers 71.1% availability
- 90% of all receivers 87.4% availability
- 95% of all receivers 90.8% availability



# INTEGRITY RESULTS

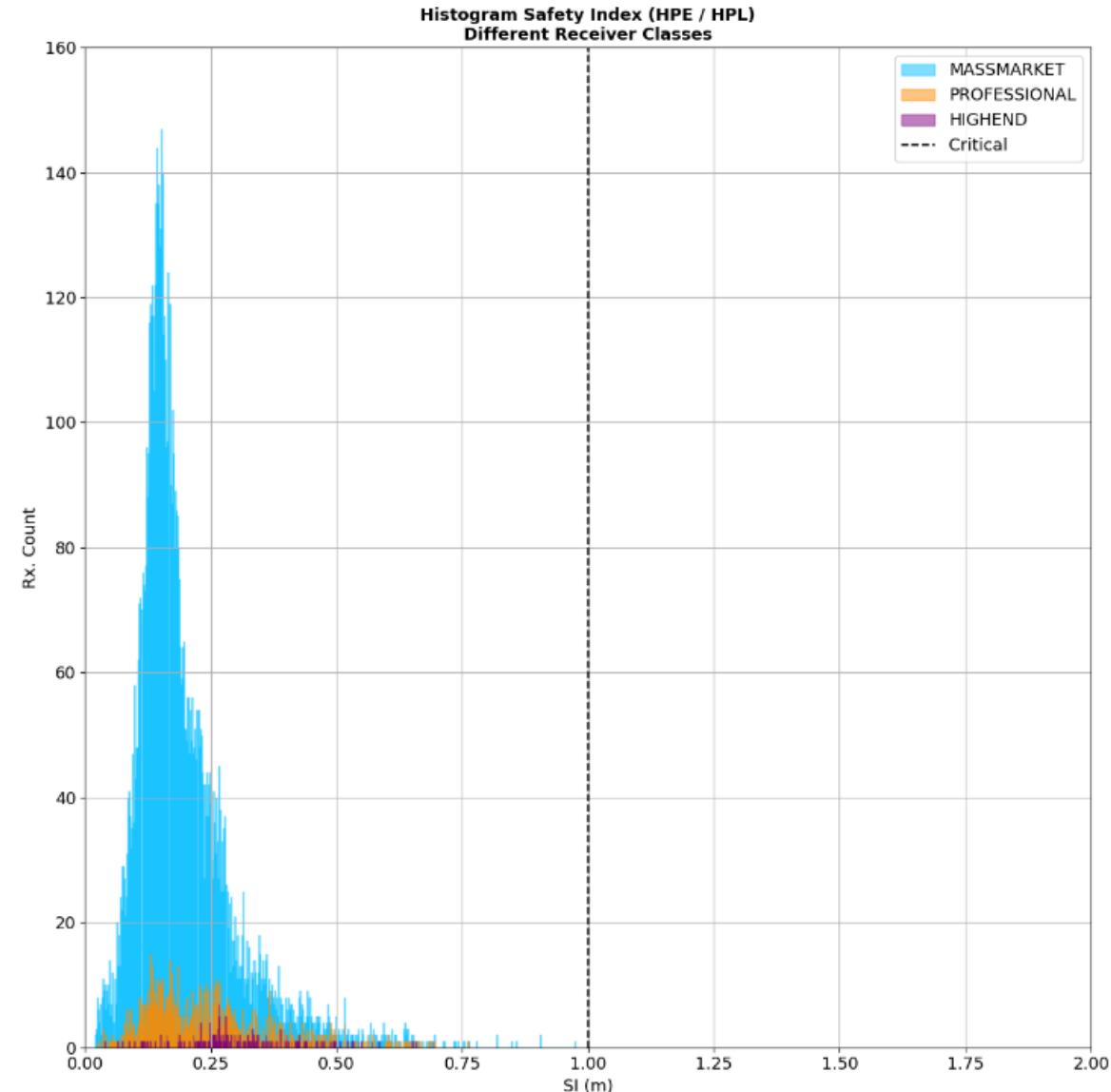
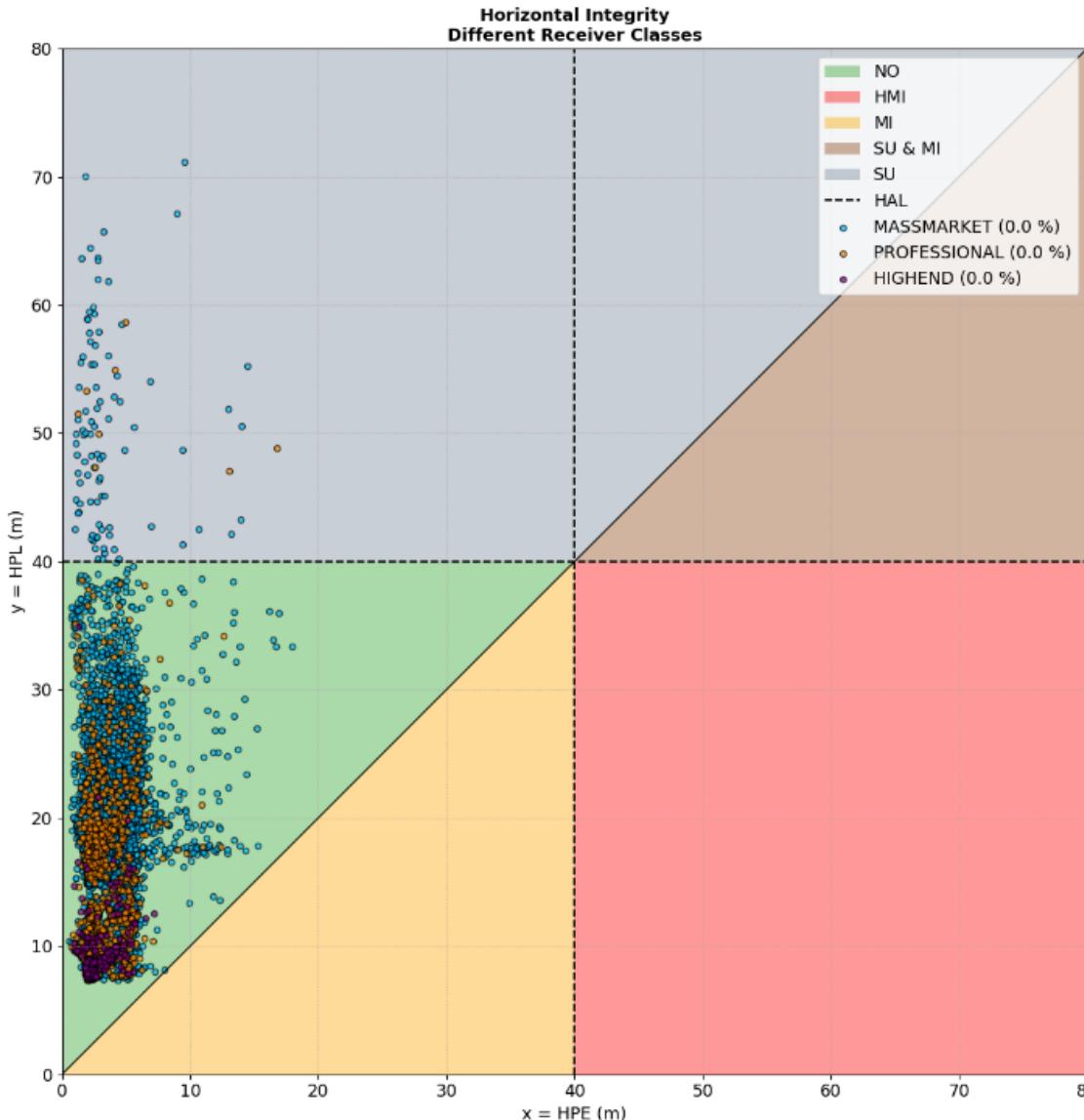
## GLOBAL SCENARIO ALL RECEIVERS

- Integrity performance by comparing horizontal position error (HPE) with horizontal protection level (HPL)
- Stanford plot
  - **Horizontal Alert Limit (HAL)** at 40 m (EGNOS LPV-200)
  - **Nominal Operations (NO)**:  $HPE < HPL < HAL$
  - **Misleading Information (MI)**:  $HPL < HPE < HAL$
  - **Hazardous Misleading Information (HMI)**:  $HPL < HAL < HPE$
  - **System Unavailable (SU)**:  $HPE < HAL < HPL$
  - **SU & MI** (combination of SU and MI)
- No Integrity Violations ( $HPE > HPL$ )



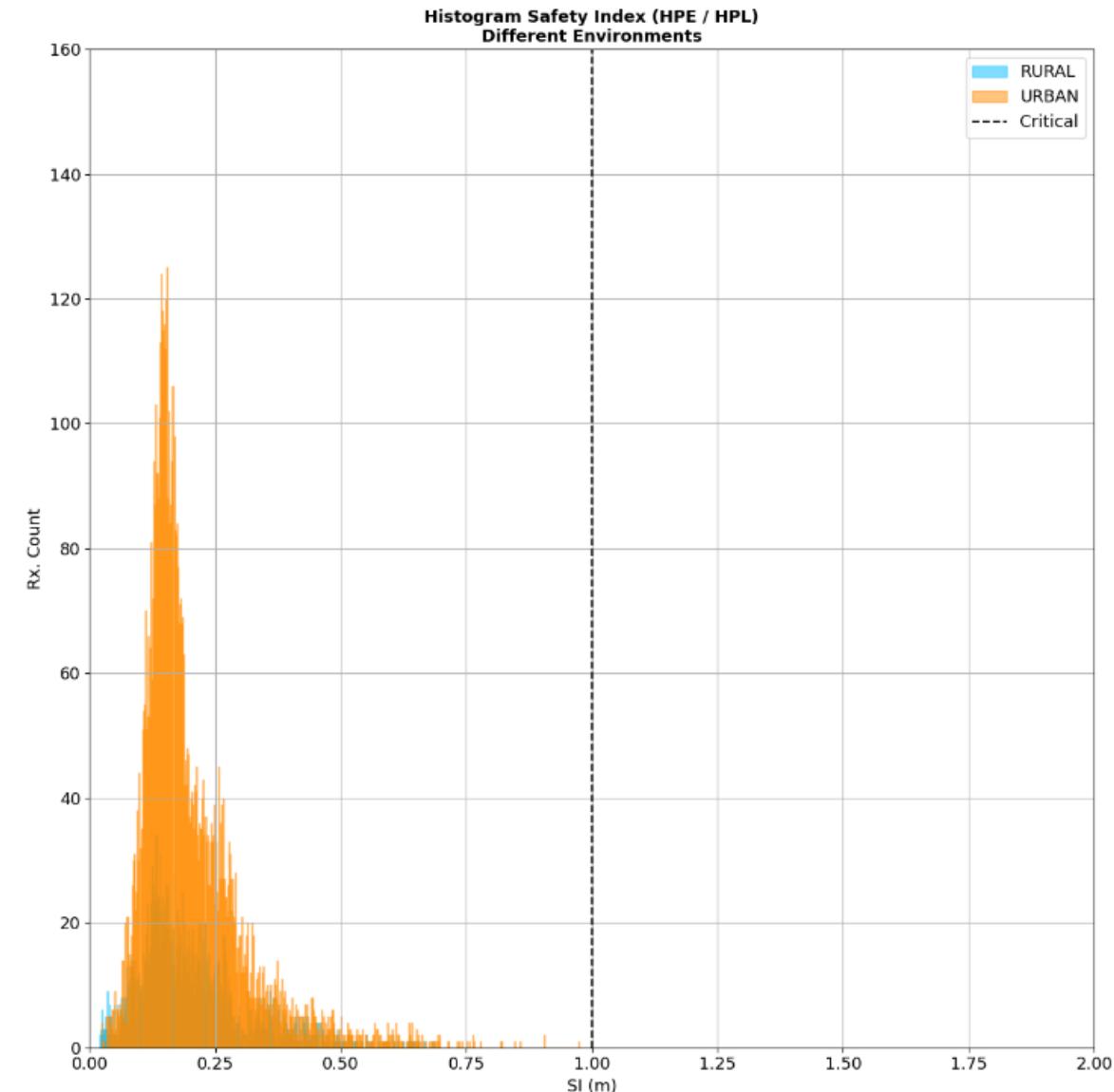
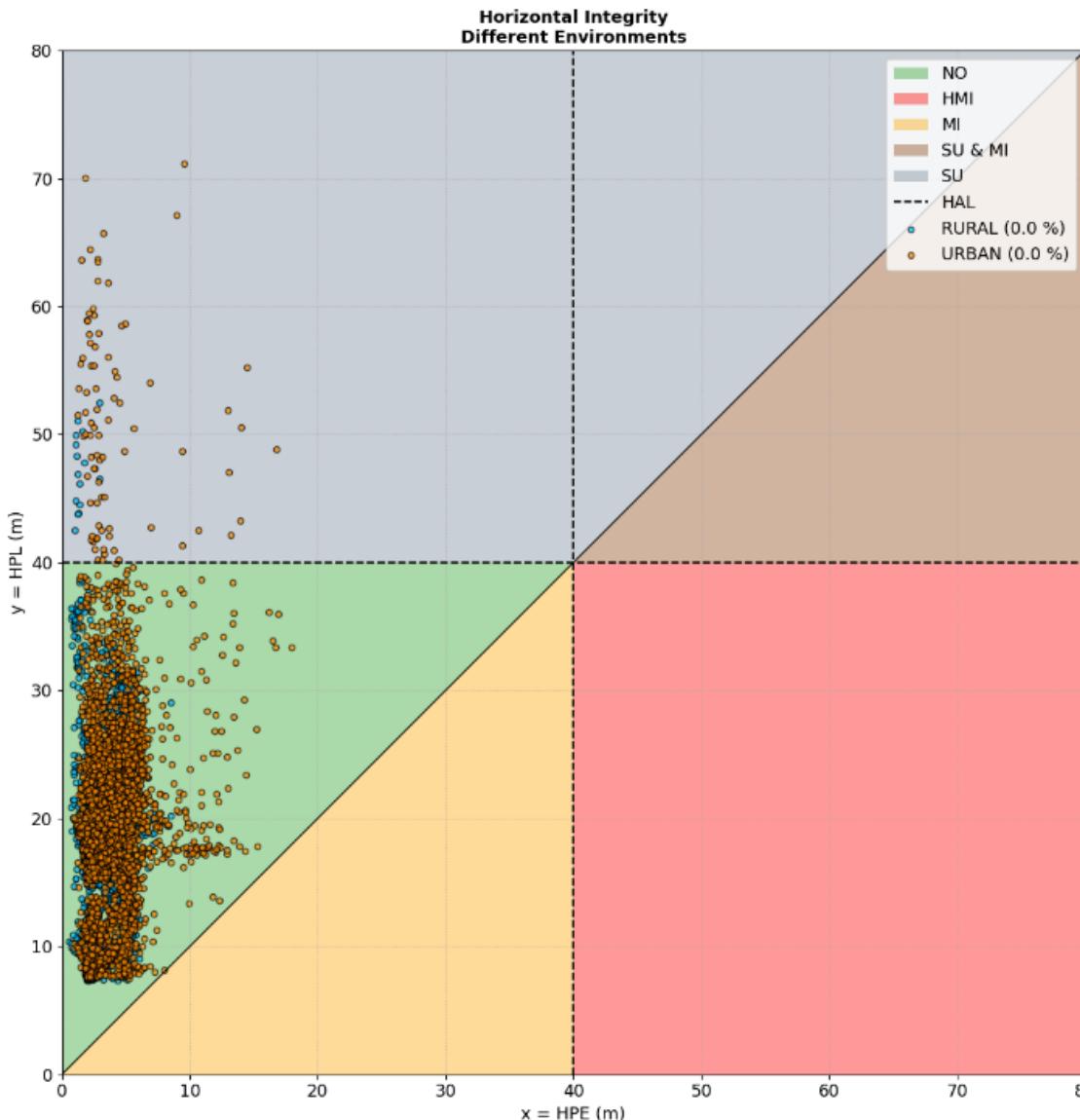
# INTEGRITY RESULTS

## GLOBAL SCENARIO DIFFERENT RECEIVER TYPES



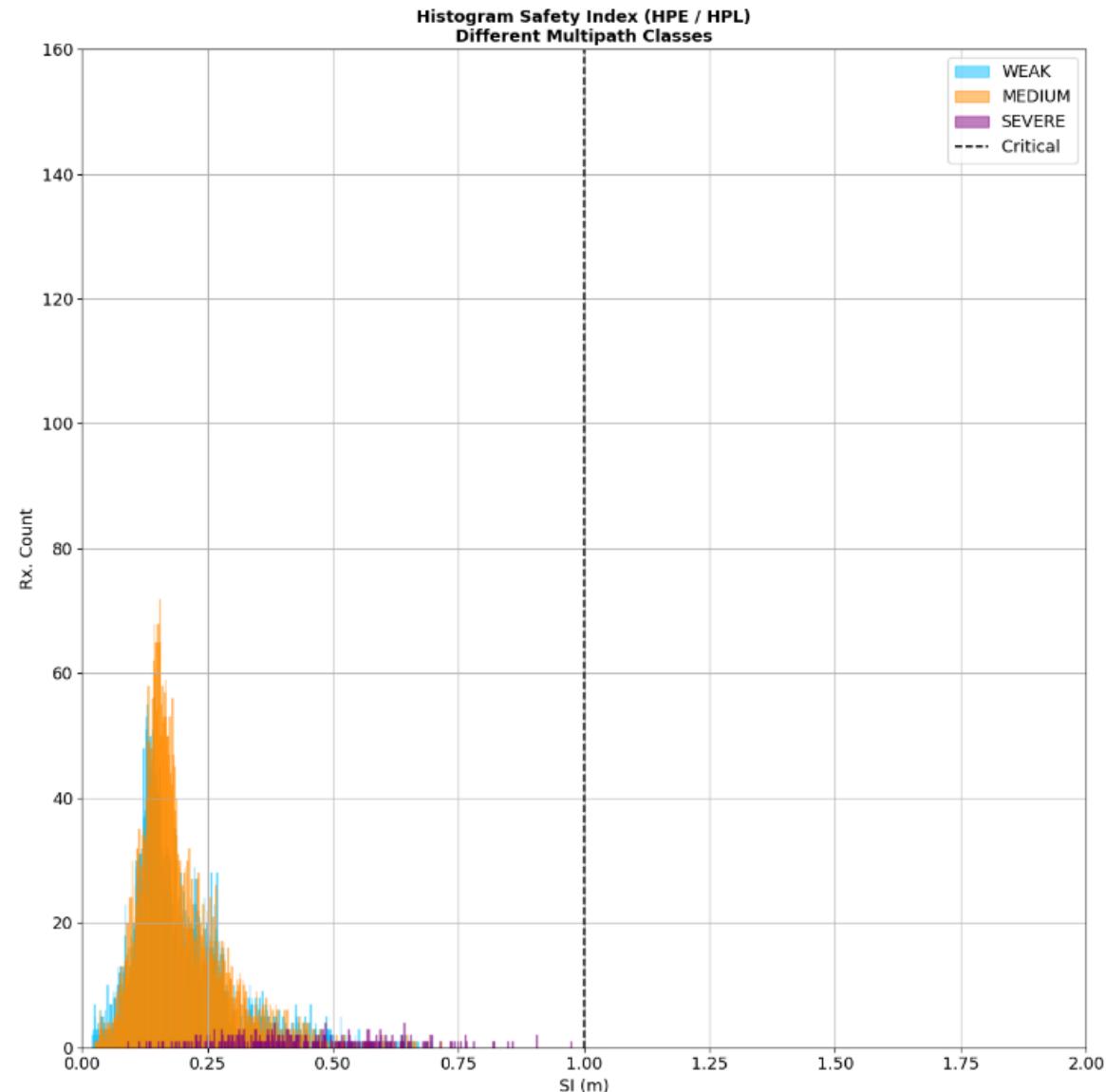
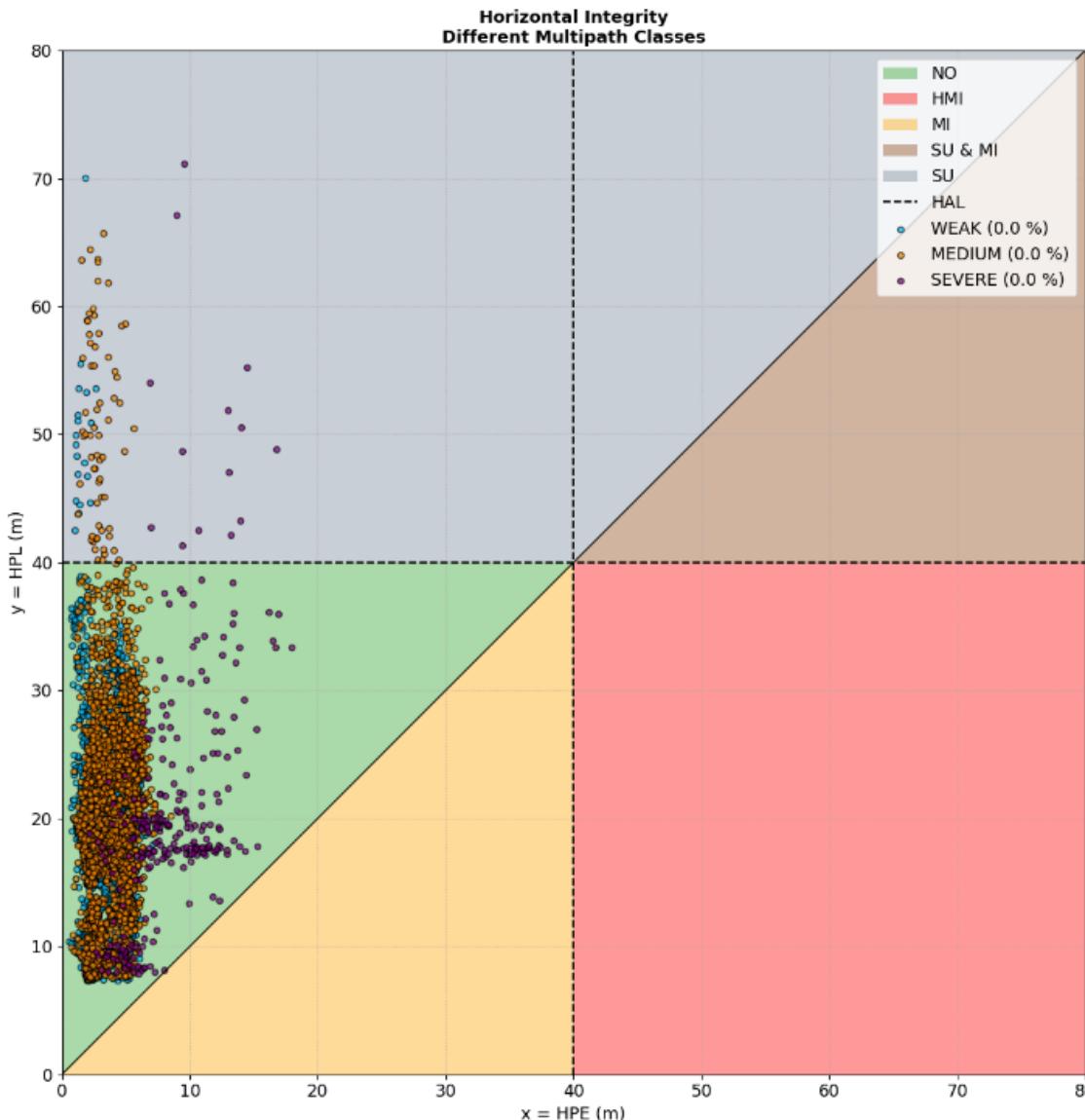
# INTEGRITY RESULTS

## GLOBAL SCENARIO DIFFERENT ENVIRONMENTS



# INTEGRITY RESULTS

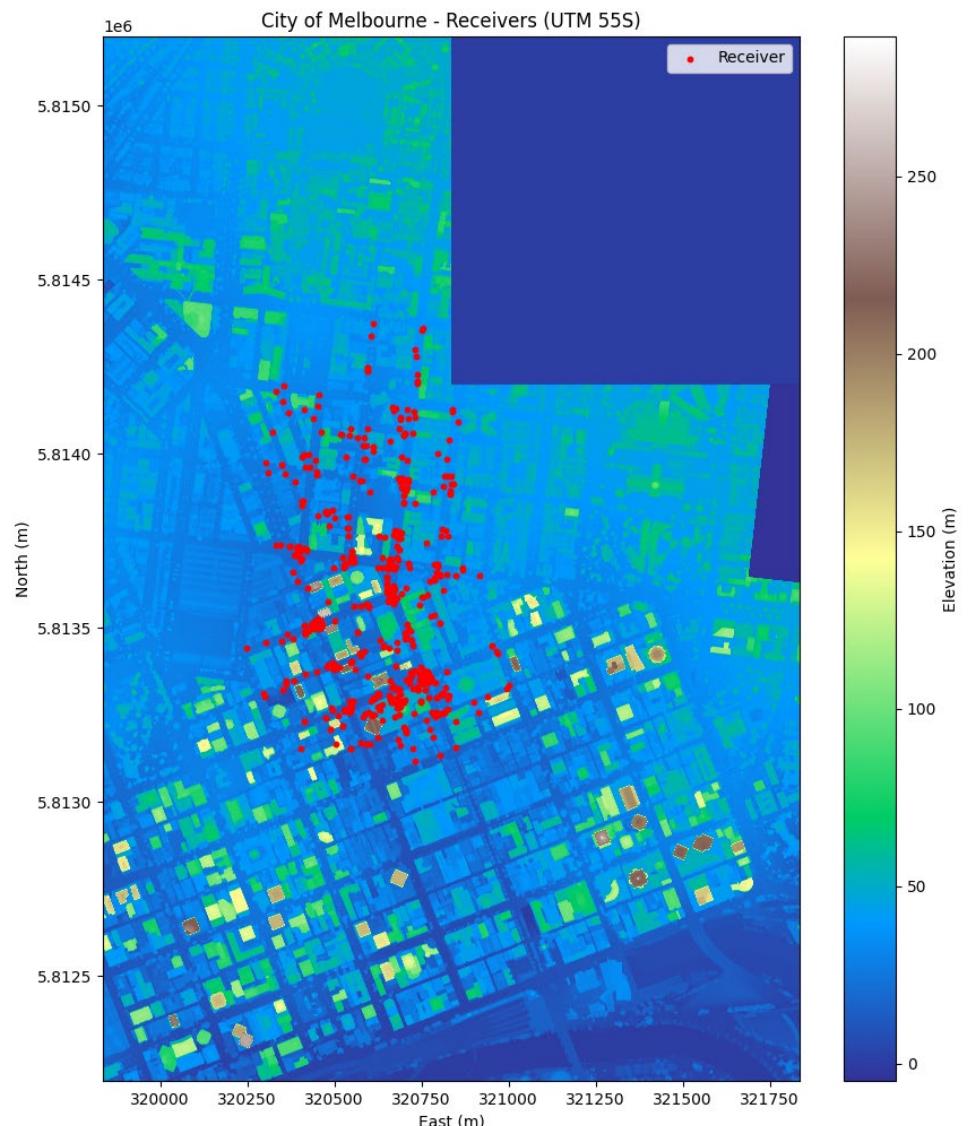
## GLOBAL SCENARIO DIFFERENT MULTIPATH LEVELS



# INTEGRITY RESULTS

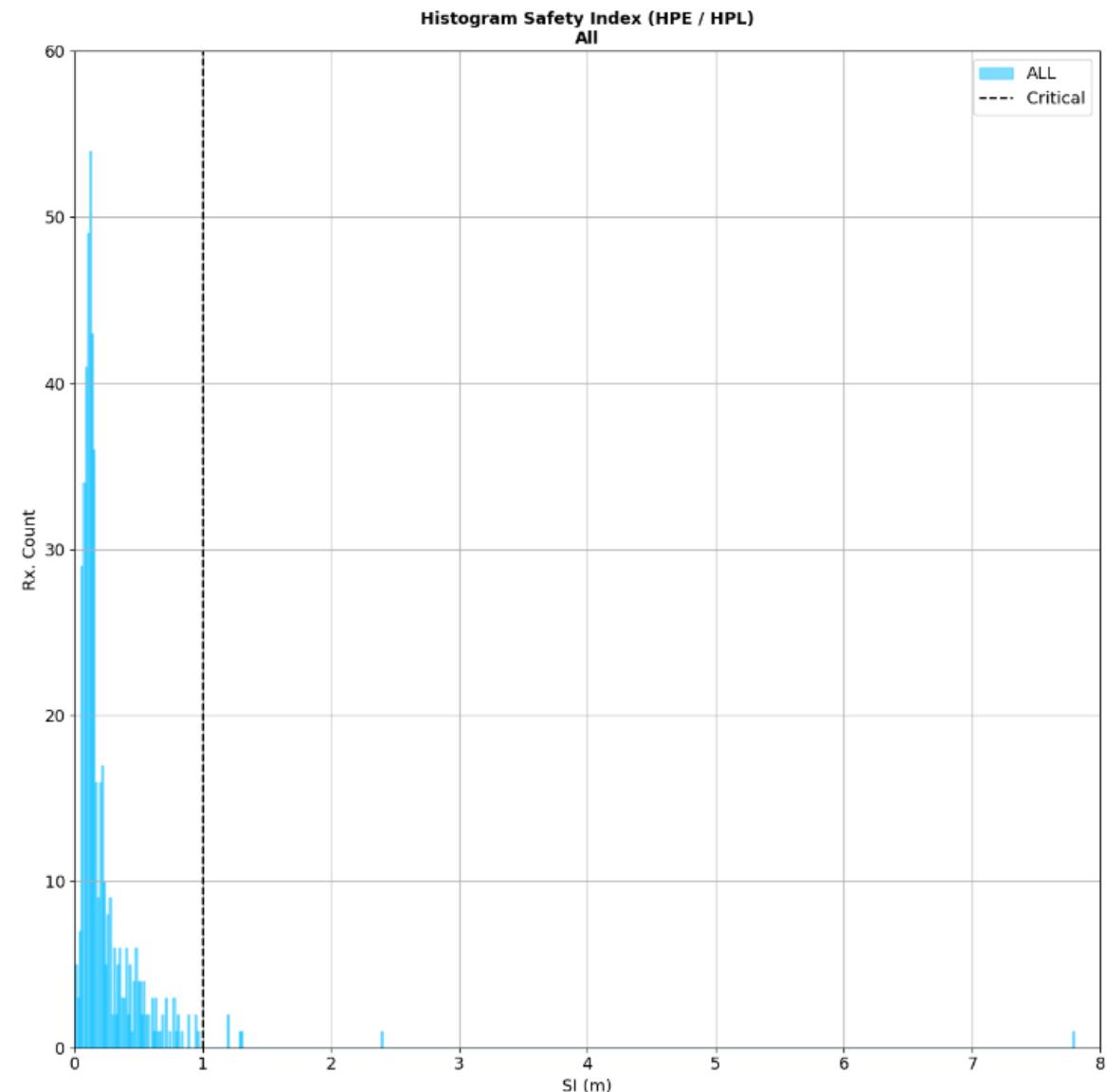
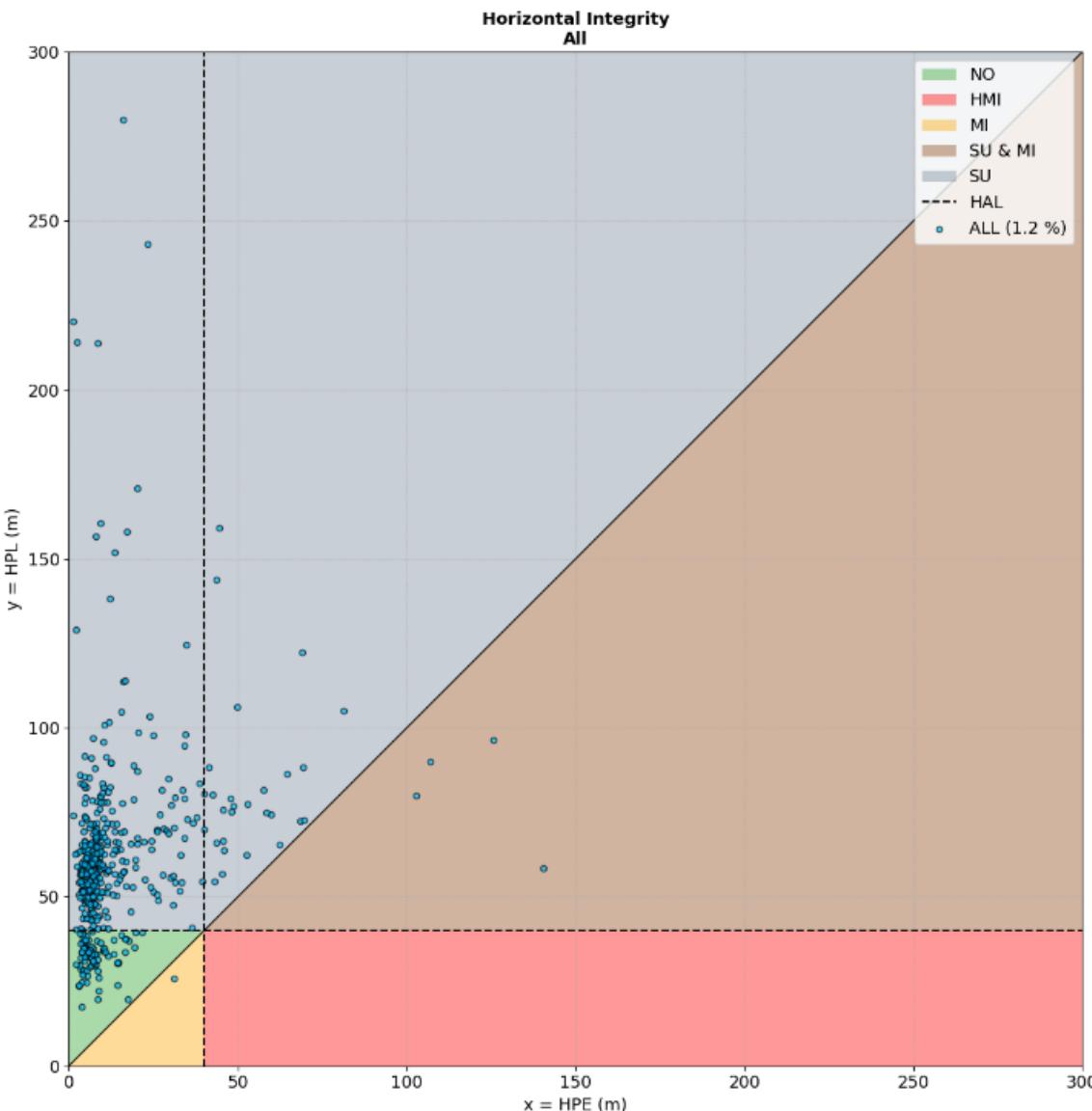
## LOCAL SCENARIO (CITY OF MELBOURNE)

- 500 locally distributed urban receivers in the streets of Melbourne
- Different receiver types (mass-market vs. professional vs. high-end)
- Different multipath levels (weak vs. medium vs. severe)
- Using GIP products for integrity computation
- Receiver locations and obstruction masks generated via publicly available DSM tiles (simplified ray-trace algorithm)
  - <https://data.melbourne.vic.gov.au/explore/dataset/digital-surface-model/information/>



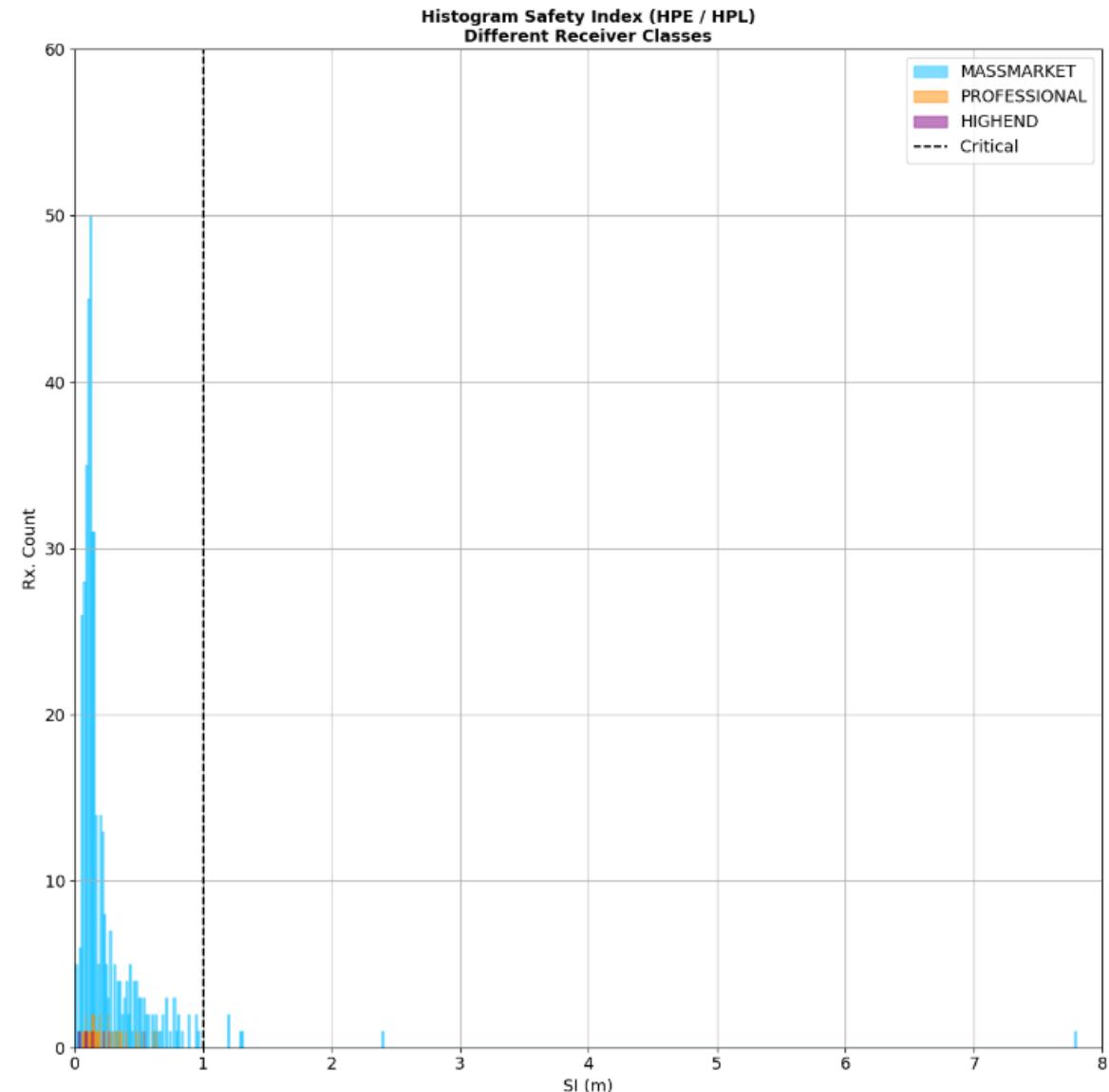
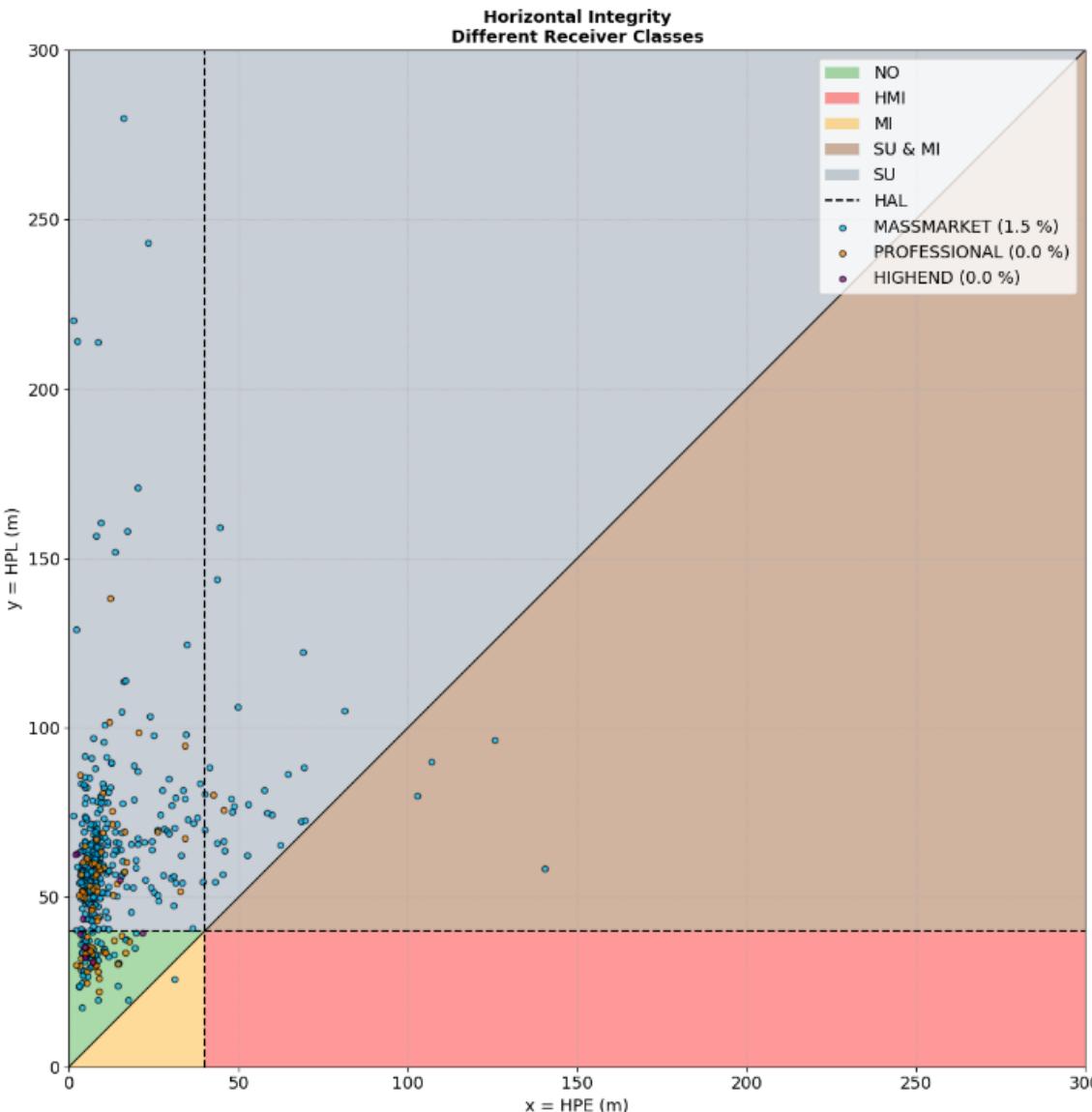
# INTEGRITY RESULTS

## LOCAL SCENARIO (CITY OF MELBOURNE)



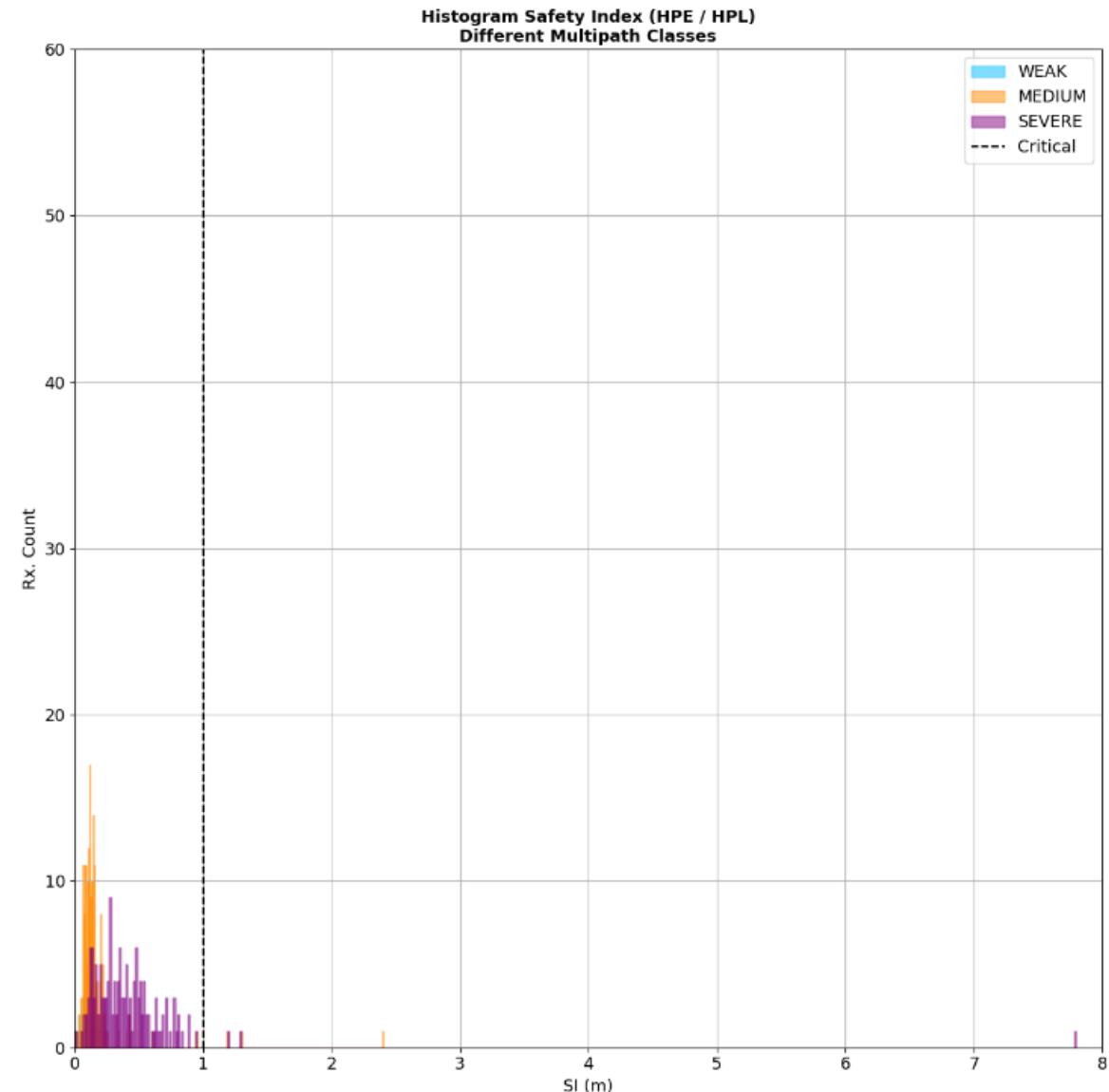
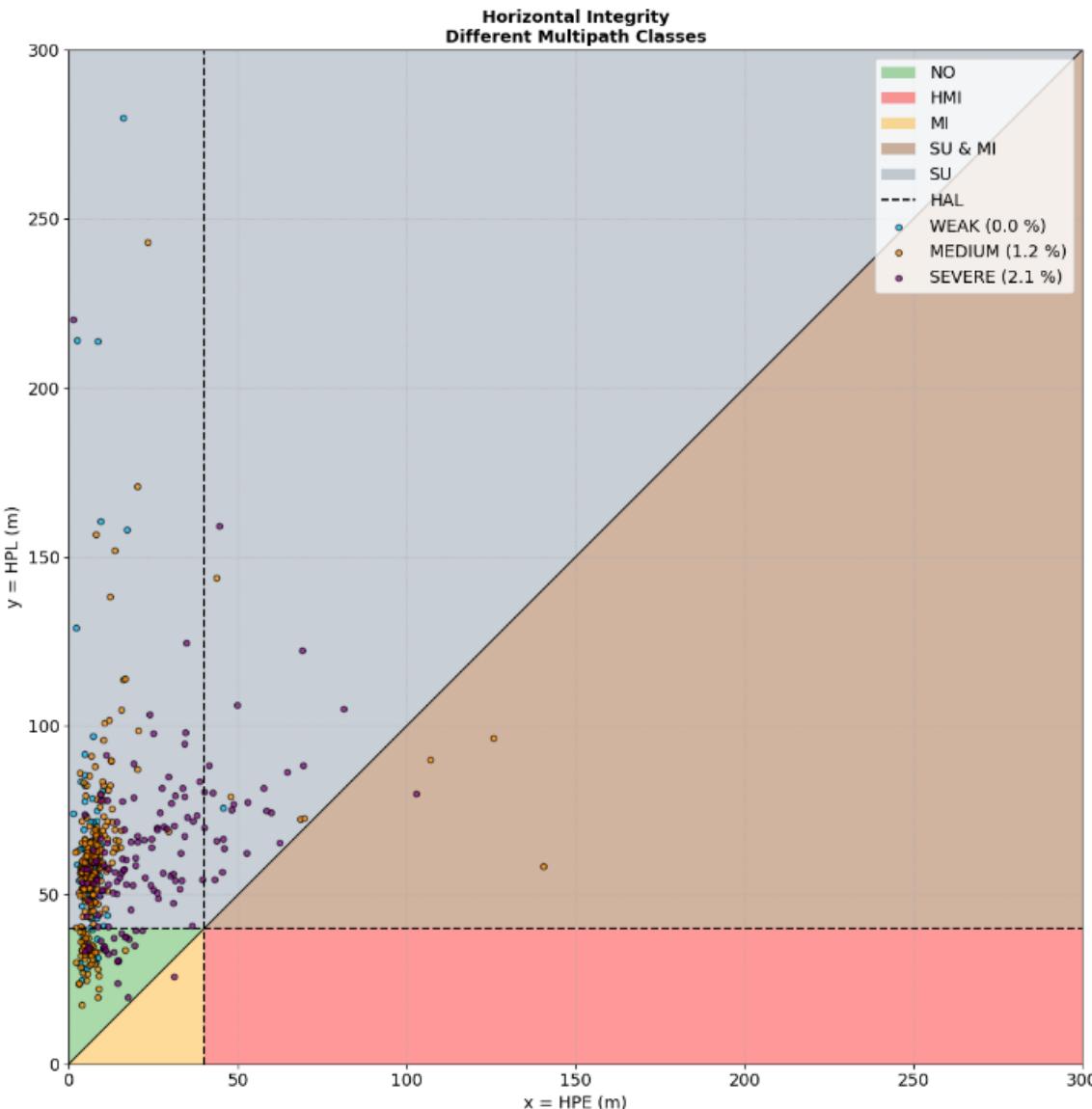
# INTEGRITY RESULTS

## LOCAL SCENARIO (CITY OF MELBOURNE) DIFFERENT RECEIVER TYPES



# INTEGRITY RESULTS

## LOCAL SCENARIO (CITY OF MELBOURNE) DIFFERENT MULTIPATH LEVELS



# 6

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## CONCLUSIONS & WAY FORWARD

- Nominal conditions show good integrity performance among all receiver/multipath classes/environments
- Feared events can reliably be detected based on user data
- Clustered distribution of global user receivers is significant
- GIP provides effective integrity information with/without feared events (proof of concept of big data-based integrity)
- Heavy multipath is the main negative effect impacting integrity across the service
  - Not only affects the contributions to the GIP but also results in a higher safety index

- Properly use prior information from environmental maps and combine it with live-observables from users
- Clustered receiver distribution
  - Can lead to lower-than-expected rates of availability
  - For a future service, a high number of professional users is crucial, specifically from maritime domains to support the coverage area
- Modelling of multipath within the GIP is crucial and it could make sense to differentiate the service for various classes of receiver types (e.g. high-end receivers, which are less susceptible to multipath can have lower PLs and alert limits)
- Ephemeris-based feared events are heavily affecting the receivers as well as service availability. Thus, for future work the handling of such feared events could further be improved, which would result in lower false alert rates and thus better overall availability of the service
- MAGIE could be enhanced by Machine Learning
  - presents significant opportunities and challenges in anomaly detection
  - Large datasets can be used to train models
  - Suitable anomaly detection tasks: multipath, non-line-of-sight (NLOS) signals, cycle slips

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# THANK YOU!

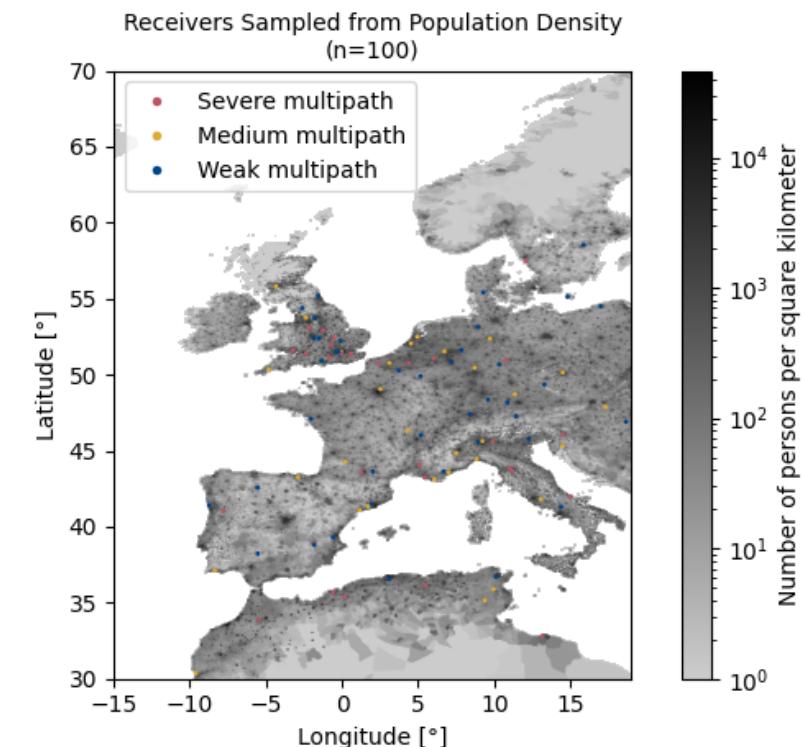
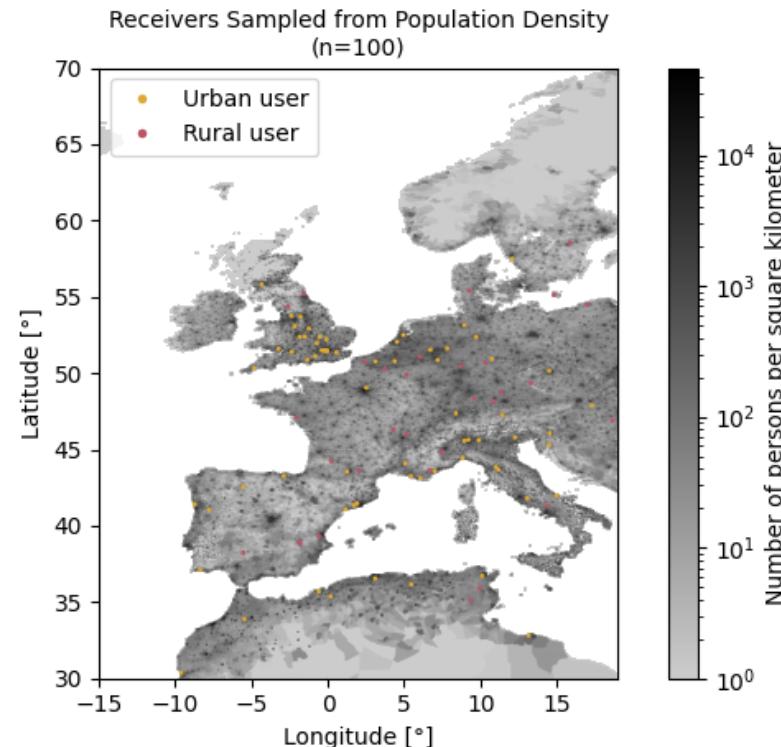
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# SIMULATION SCENARIOS (1)

## GLOBAL TEST SCENARIO

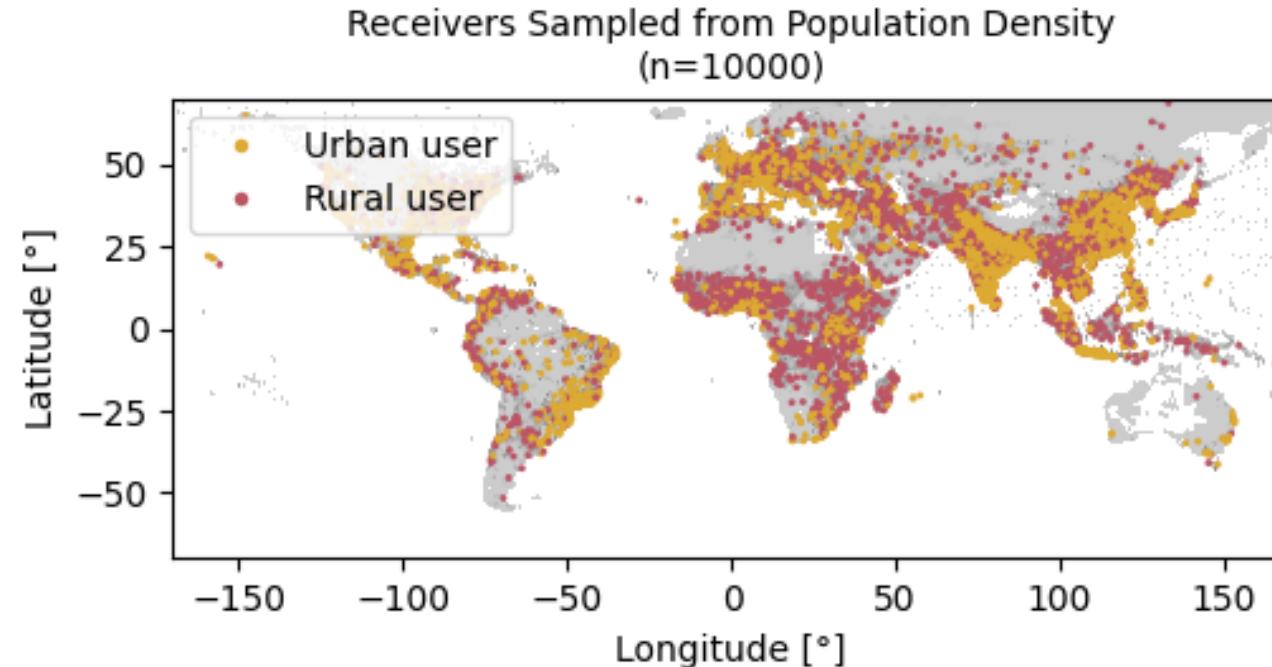
- 100 receivers
- Europe
- 10 hours
- 1 Hz



# SIMULATION SCENARIOS (2)

## FINAL GLOBAL SCENARIO

- 10.000 receivers
- worldwide
- 10 days
- 1 Hz



# SIMULATION SCENARIOS (3)

## LOCAL SCENARIO

- 2500 receivers
- 3x3 km grid in the city of Melbourne (Australia)
- 1 hour
- 1 Hz

