CAT III GBAS with evolution towards DFMC

NAVISP-EL2-100 Final Presentation

8-Oct-2025

INDRA

01

Company Background and Project Overview

Indra Air Navigation

- 8,000 installations in more than 180 countries
- The most complete and trusted range of navigational aids
- Proven reliability in all climatic conditions

Pioneering satellite technology for safe landings

- Fatal air accidents at Brønnøysund and Namsos lead to a Parliament resolution to improve landing safety at Norway’s short-field airports
- First installation and operational approval for use under CAT-I conditions at Brønnøysund in 2007
- SCAT-I in daily use at 17 Norwegian short-field airports
- Ground Based Augmentation System (GBAS) is the international successor to SCAT-I, standardised by ICAO.

Normarc 8100 GBAS

- Efficient & Safe user operation
- Remote & Local operation
- Up to 48 approaches
- Fanless, robust design, high reliability
- Low maintenance costs
- Familiar user interfaces for users of ILS
- Up to 4 VHF for all runways coverage
- Developed by Indra in Norway (Indra Navia)
- Prototype installations at Frankfurt, Oslo and Tenerife Norte airports

NAVISP-EL2-100

- After the covid-19 pandemic, there was less GBAS interest in the market. Instead of pursuing certification of a Category III GBAS system based on GBAS Approach Service Type (GAST) D using GPS, Indra Navia decided to start developing towards a future Dual Frequency Multi-Constellation (DFMC) GBAS ground station.
- This lead to the NAVISP-EL2-100 project which started in November 2021 and finished in 2025.
- The main objective for the project was to contribute into the ICAO standardisation process and thereby create a good basis for a DFMC GBAS Ground Station based on Indra Navia's existing platform, including the completion of the GAST C and GAST D specific features needed to provide a DFMC GBAS ground station.
- During the project ESA provided valuable feedback and access to their experts which improved the project results.

02

GBAS and Integrity Threat Mitigation

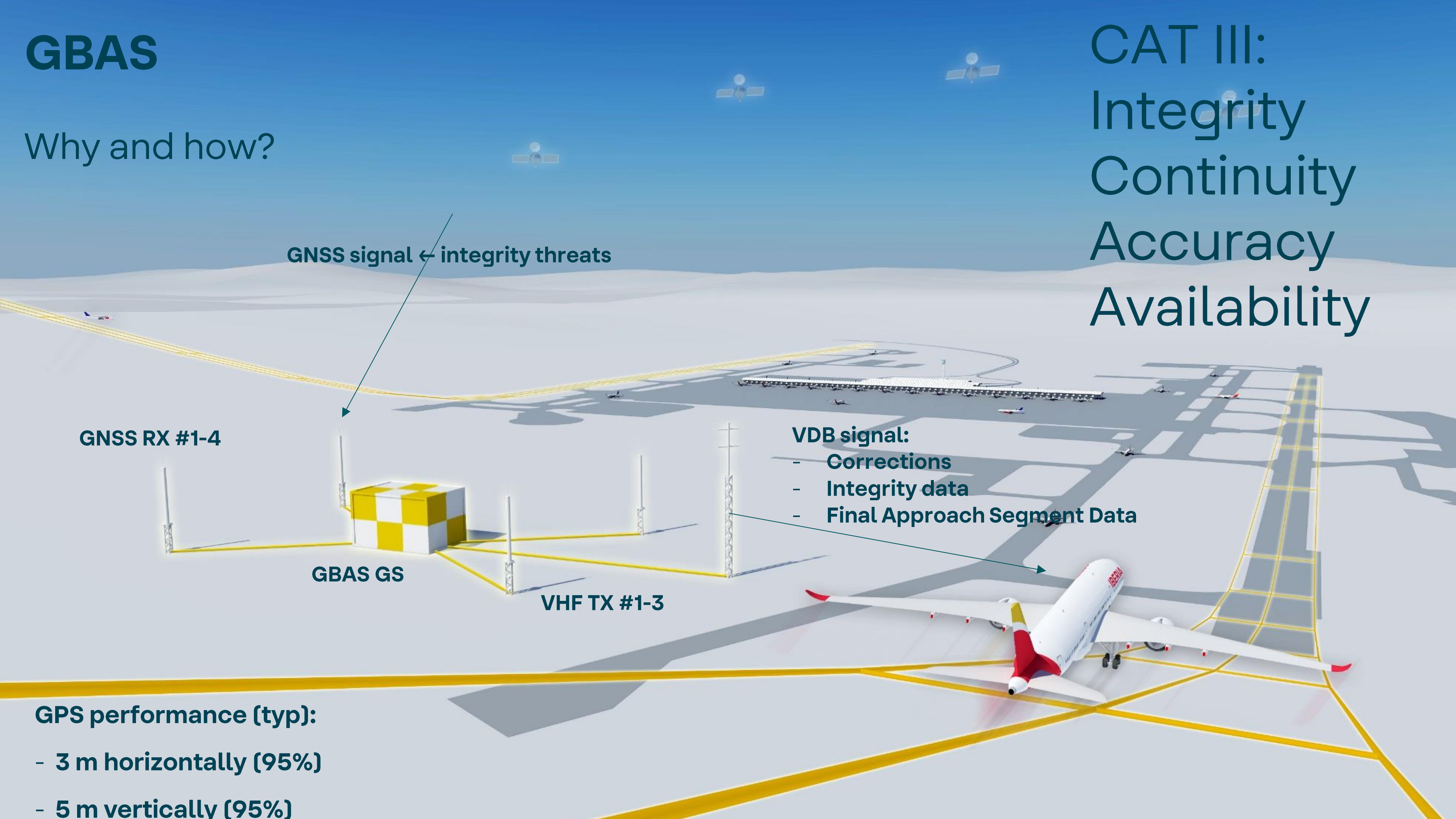
What is GBAS?

- Ground Based Augmentation System – local augmentation at the airport
- ICAO Standardised (Annex 10)
- Supports approach, landing up to CAT IIIb, and take-off

GBAS

Why and how?

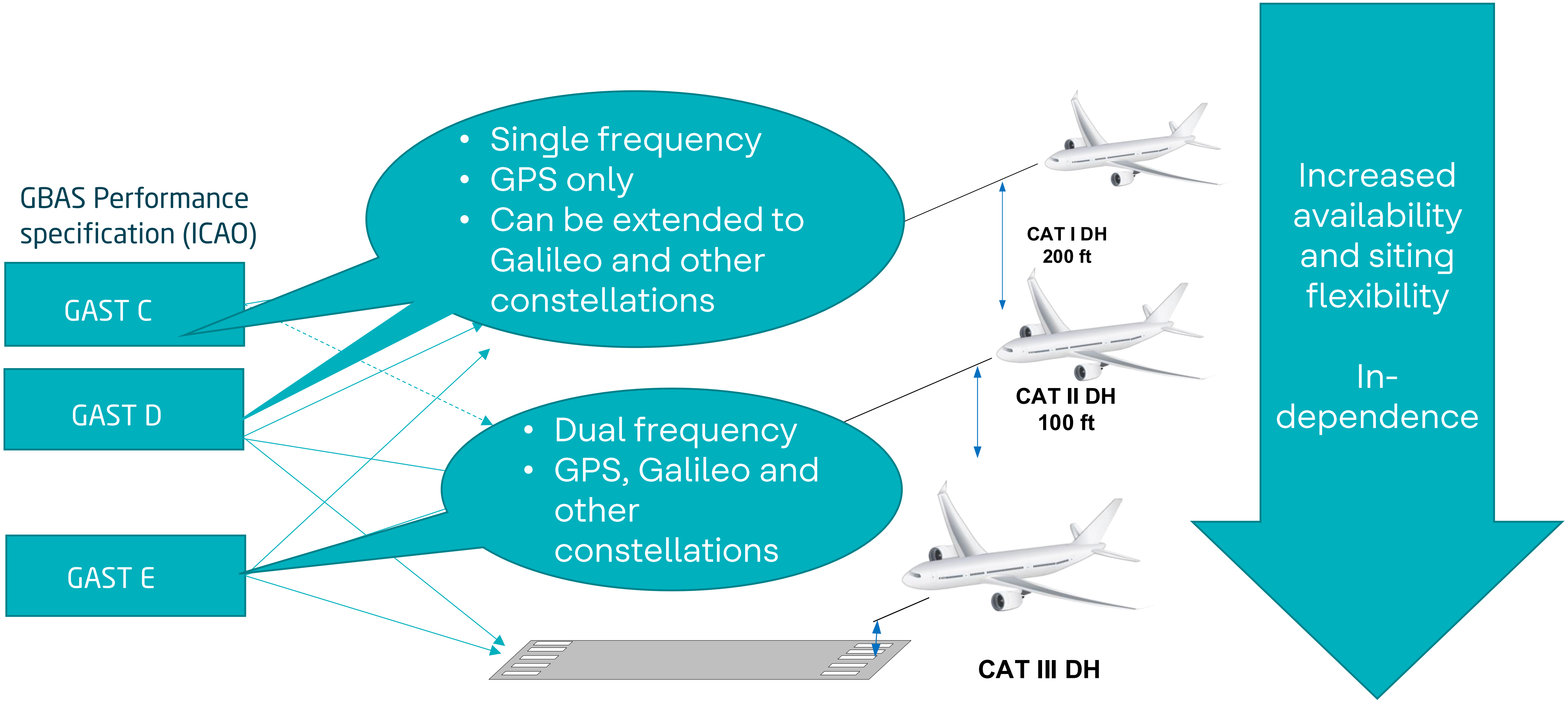
CAT III:
Integrity
Continuity
Accuracy
Availability



GPS performance (typ):

- 3 m horizontally (95%)
- 5 m vertically (95%)

GASTs and CATs



General Integrity Requirements (Cat I)

- Integrity risk: *probability that the GS provides information which when processed by a fault-free receiver, results in an out-of-tolerance lateral or vertical relative position error without annunciation for a period longer than TTA (1.5s).*

$2 \times 10^{-7}/app$

$0.5 \times 10^{-7}/app$
PLs

$1.5 \times 10^{-7}/app$
SV faults
RR faults+Environment

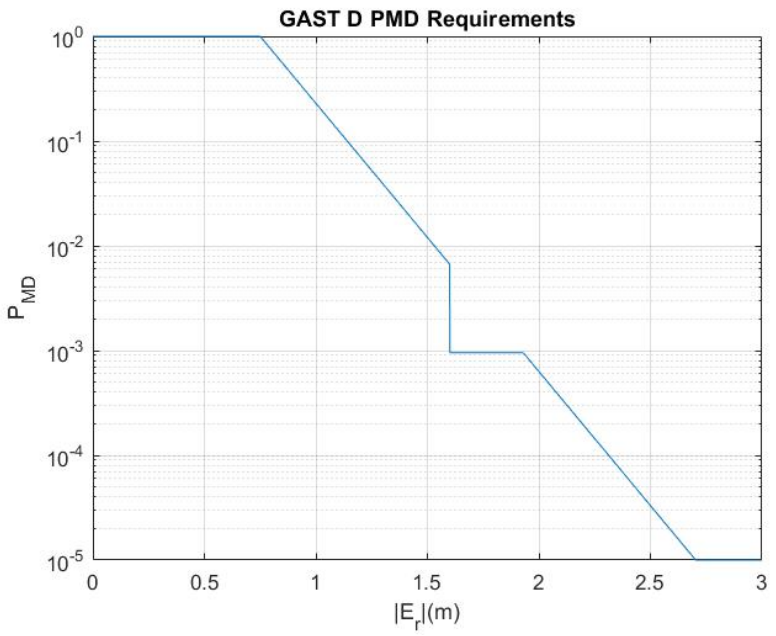
GAST C	GAST D	GAST E
Mandatory	Mandatory but Iono threats excluded	Mandatory but Iono threats excluded
Approach 150s (CAT I)	Landing 15s (CAT III)	Landing 15s (CAT III)

- *Double faults on a GPS SV can be neglected (low prior probability), but not for GAL.*

Additional Integrity Requirements (CAT II/III)

- Derived from the airworthiness requirements (Limit and malfunction conditions) of safe landing for CAT II/III approaches.
- These requirements are formulated in the range domain for the ground subsystem.
- The requirements should not be violated for more than TTD (1.5s).

GAST C	GAST D	GAST E
Not required	Mandatory (includes satellite faults and ionospheric gradients)	Mandatory (some threats may move to the airborne subsystem)



The proposed DFMC (GAST E)

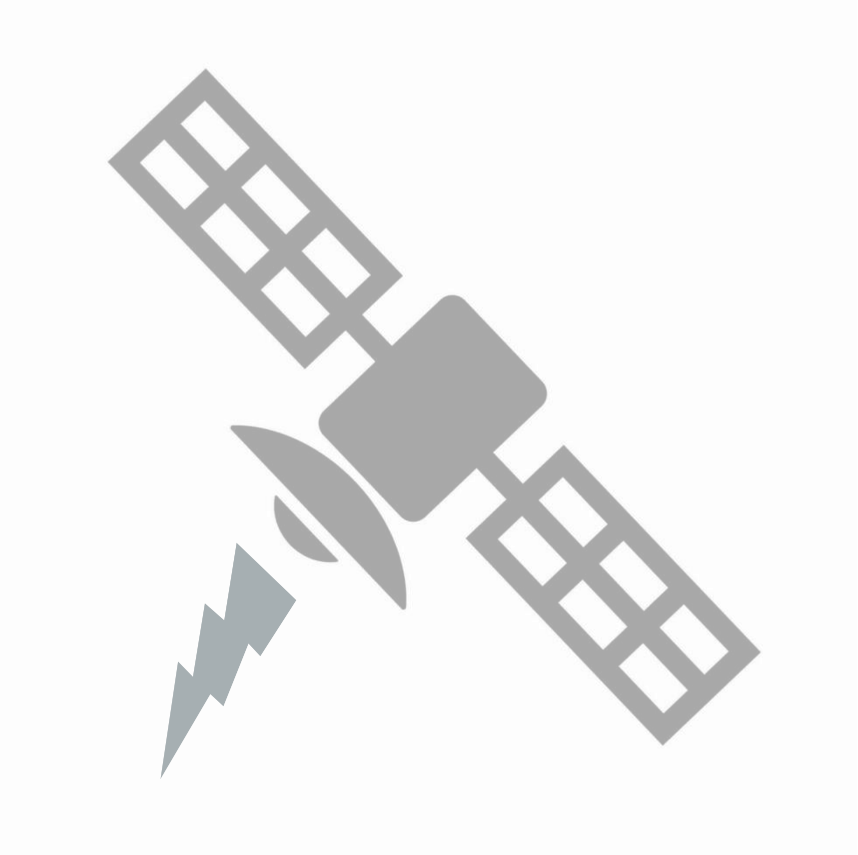
- Still under development
- Uses DFMC
- Covers CAT II/III approaches
- In case of losing a frequency, it is supposed to switch to GAST D* or C* (slightly different from legacy GAST D or C)
- In the new type, it is envisioned that
  - Raw measurements will be broadcast in MT23 instead of corrections (MT1 and MT11). Most probably, at lower rate to accomodate the capacity of the VDB link
  - Smoothing of the GS measurements is done in the avionics. The avionics decides the type of smoothing and the time constant.
  - Monitoring will be done in the GS, and the alerts of hazardous events will be sent in separate message (MT50) broadcast at a high rate
  - Responsibility for the ionospheric gradient threat will be moved to the avionics for GAST E, while responsibility is shared for GAST C*/D*.
  - The integrity requirements should be similar to GAST D

03

Signal Deformation Monitoring

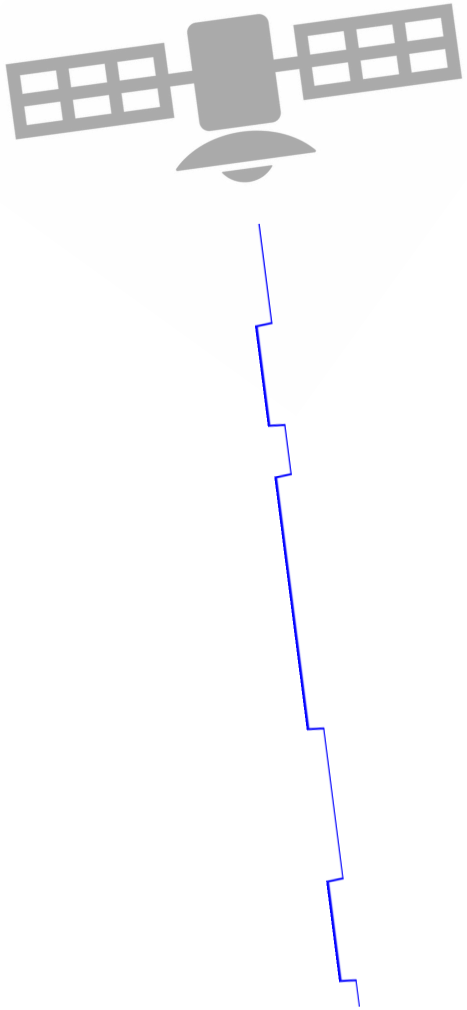
Content

- Signal deformation events
- DFMC threat models
- DFMC user space and threat space
- Multipath mitigation
- Signal Deformation Monitor
- Results for GAST C, GAST D and DFMC

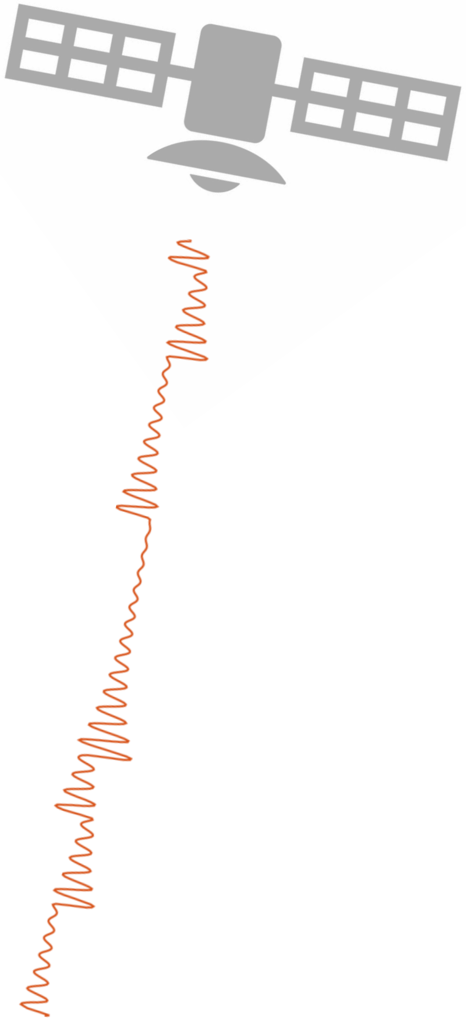


Signal deformation events

GPS



- PRN 19 incident in 2004:
  - Hardware malfunction, specifically with signal generation equipment
- PRN 23 incident in 2016:
  - Signal modulation, irregularities in the way signal was encoded and transmitted



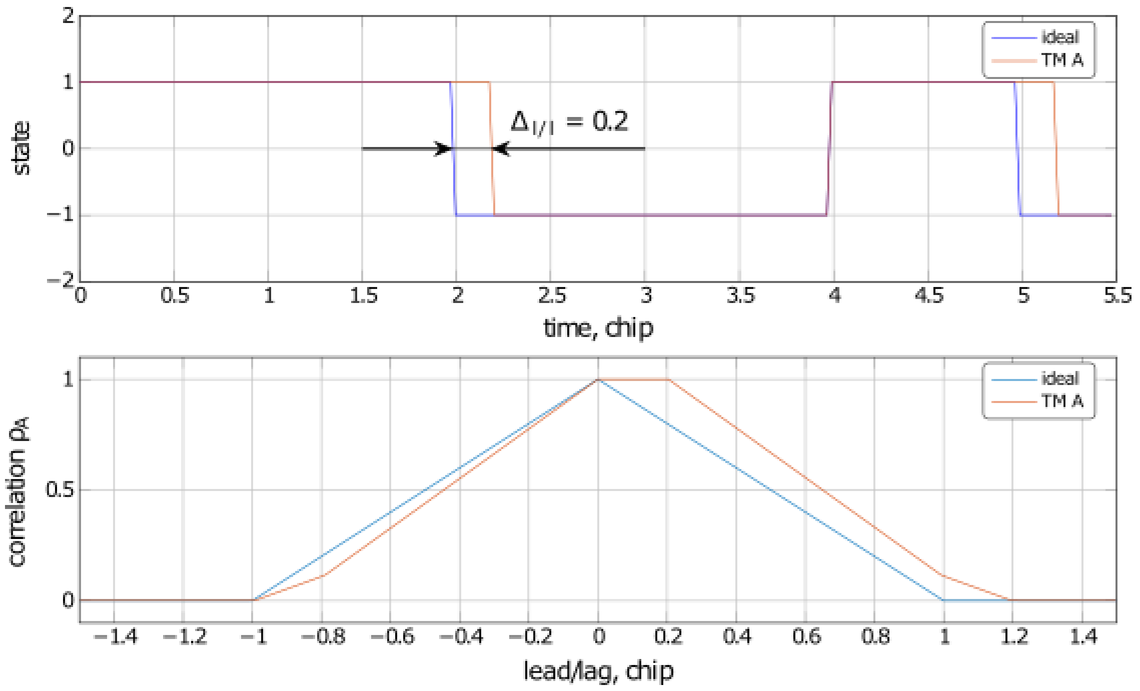
Galileo

- Early operational stage issues in 2014-2015
  - Integration challenges between hardware and software including calibration errors and synchronisation of onboard systems

Threat models for Signal Deformation Monitor

Threat Model A

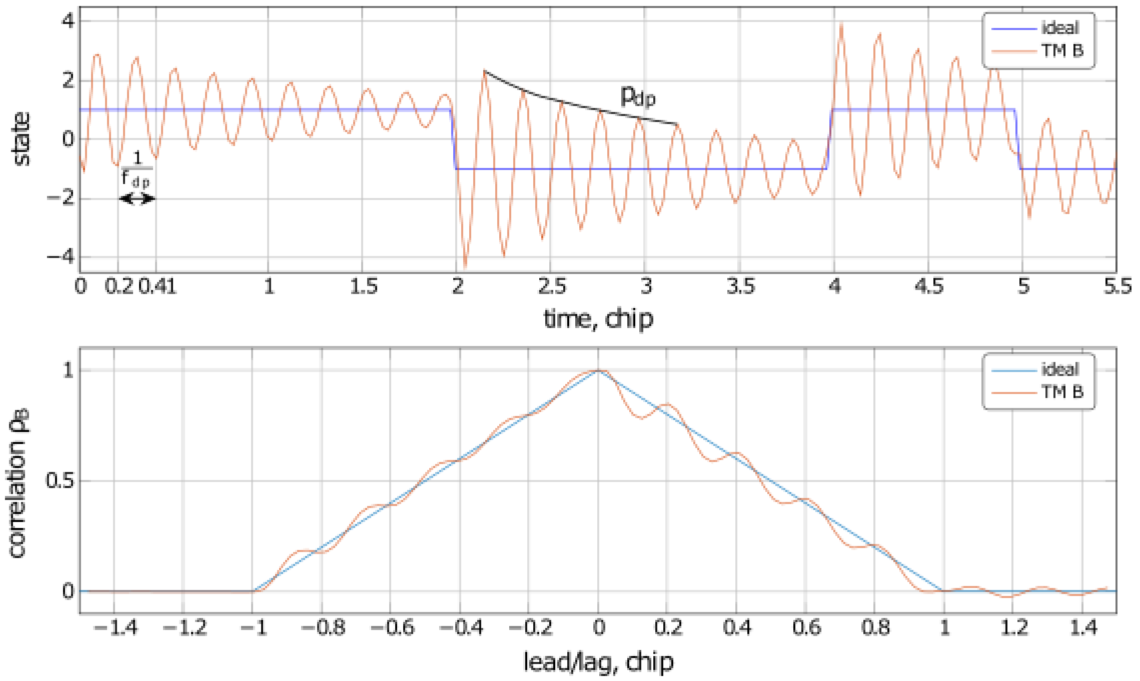
- Digital distortion
- Lead/lag of the falling edge of binary signal
- Correlation function having plateau – challenging for determining true peak (prompt).



Threat models for Signal Deformation Monitor

Threat Model B

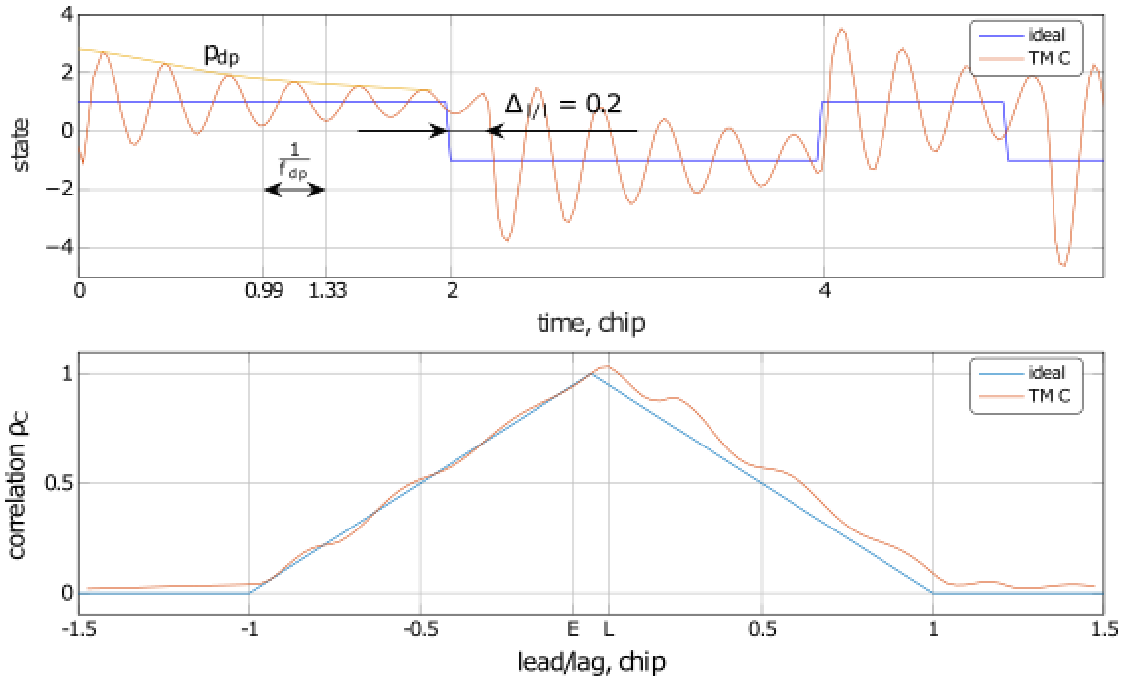
- Analog distortion
- Damping effect after switching states defined by two parameters
- Correlation function affected by the damping effect might generate false peaks.



Threat models for Signal Deformation Monitor

Threat Model B

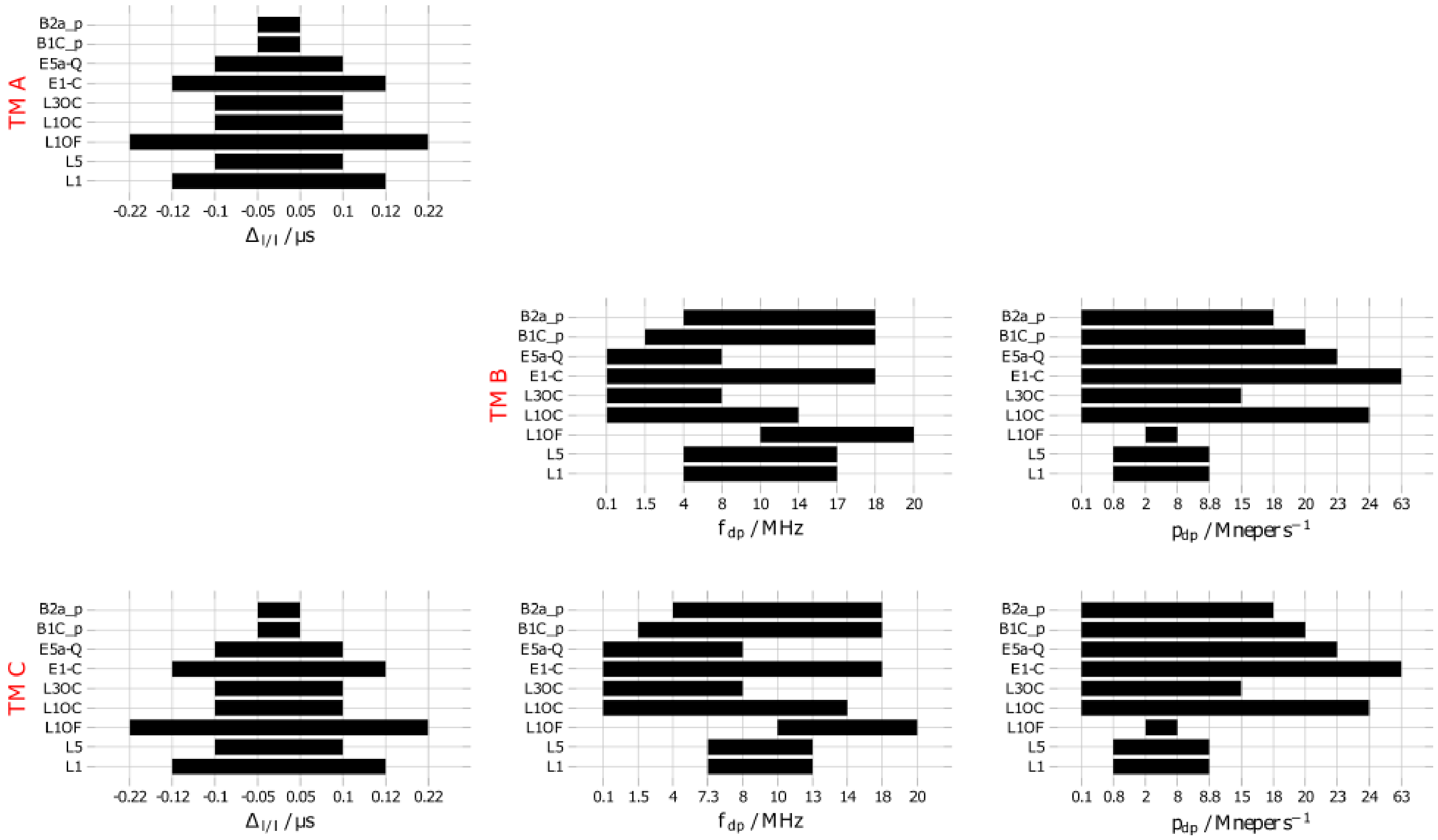
- Digital and analog distortion
- Lead/lag and damping effects affecting binary signal
- Correlation function with shifted peak and possible multiple peaks



DFMC Threat space

Threat parameters across bands

- Used to generate all possible threat combinations to test resilience of the monitor
- Parameter's domain are limited by the generative capabilities of onboard equipment

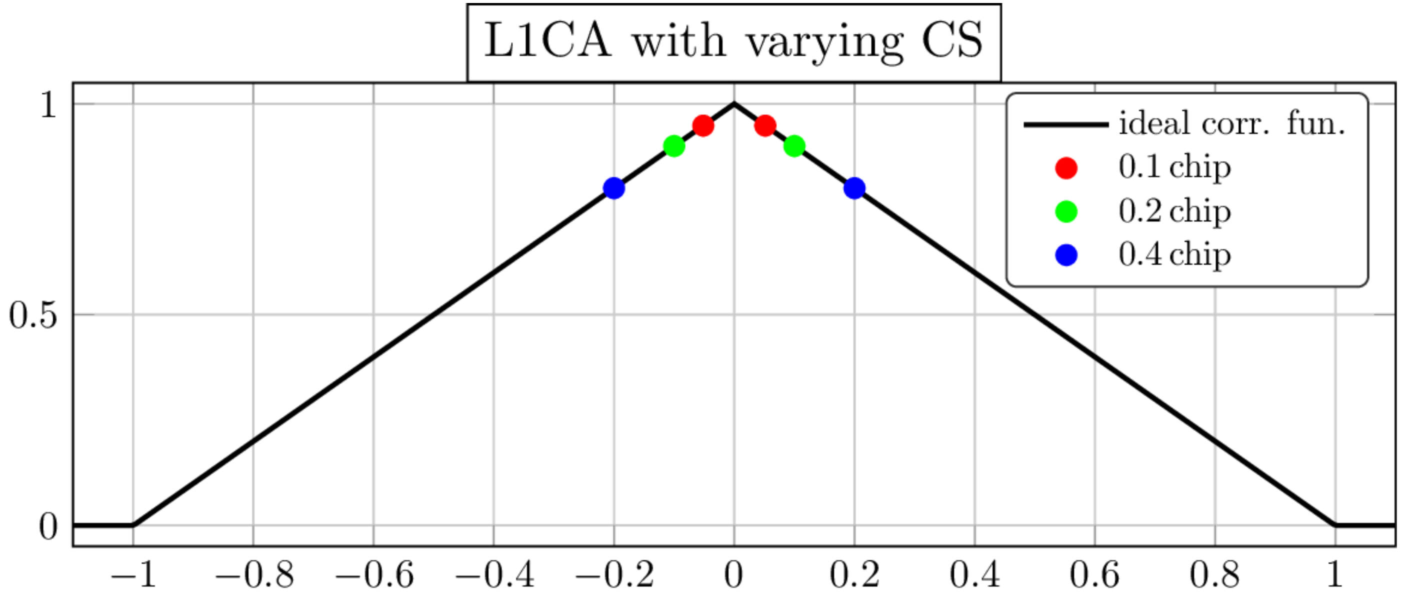


DFMC user space

Three parameters defining airborne receiver

1. Correlator spacing CS

- Space between tracking correlators
- Shorter the spacing the better resilience to multipath effect
- Based on the correlators the prompt and therefore the error is estimated

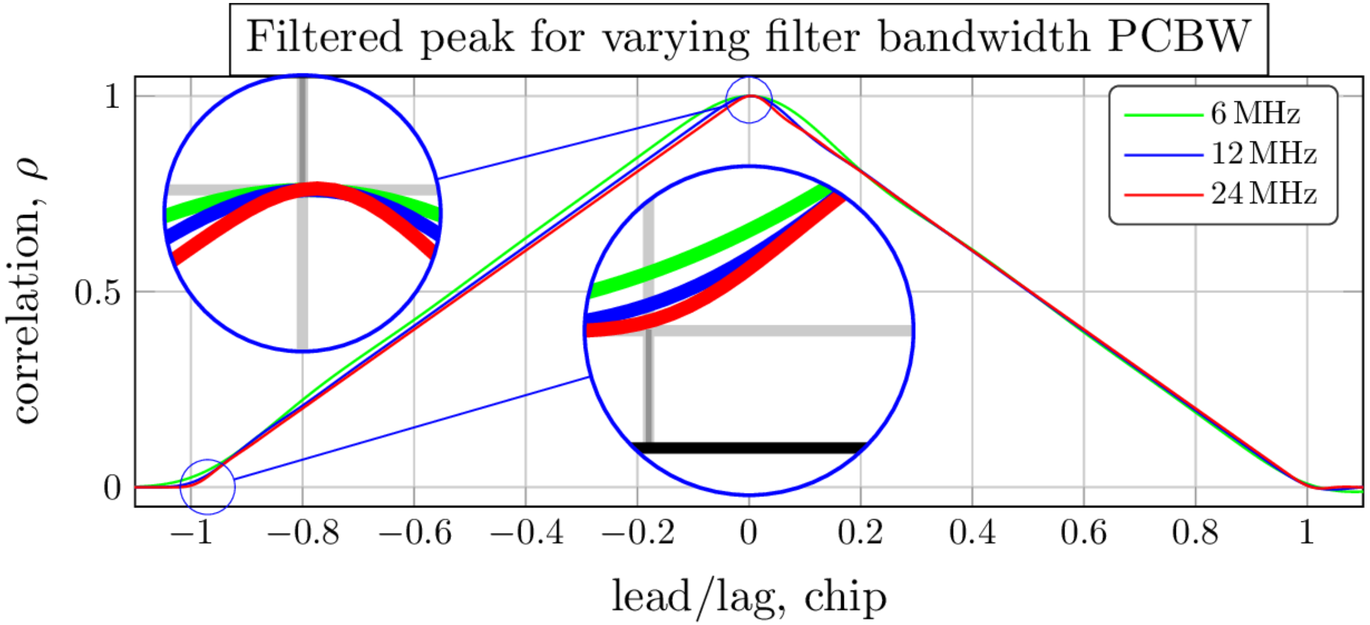


DFMC user space

Three parameters defining airborne receiver

2. Precorrelation filter bandwidth PCBW

- Wider the bandwidth brings sharper peak and therefore better prompt estimation
- Narrow bandwidth results in uncertainty in prompt location especially with E-L discriminator



DFMC user space

Four types of airborne filters

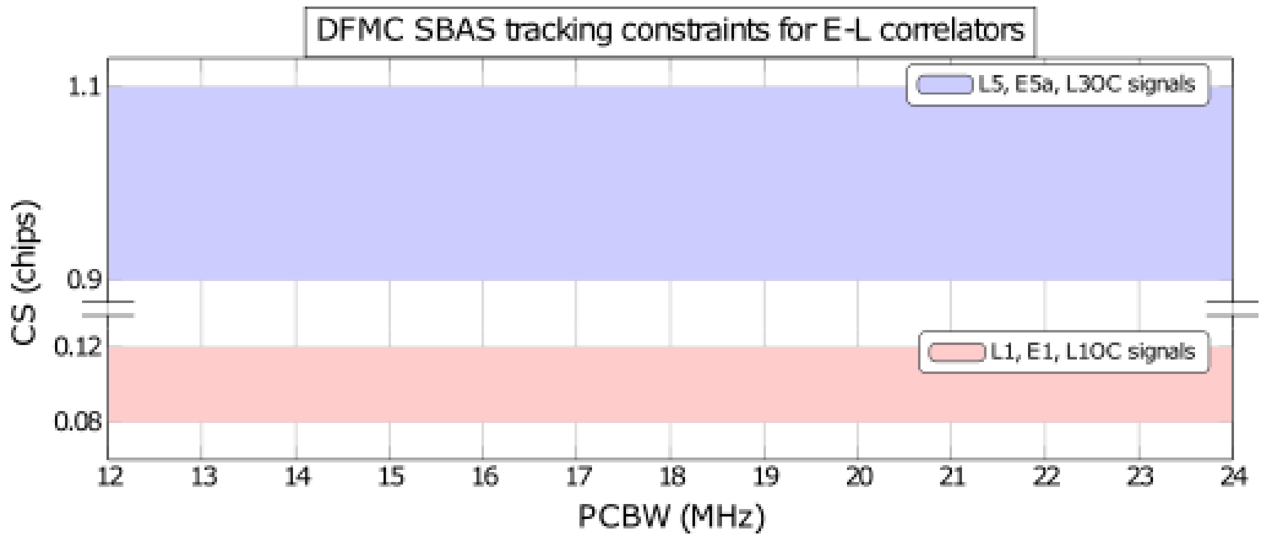
3. Precorrelation filter types

- Filter 1: 6th-order Butterworth.
- Filter 2: resonator filter type with a constant group delay equal to zero. The design of this filter is based on the
    - full definition of the transfer function:
    - The amplitude response is 1 within the desired filter bandwidth. The filter roll-off outside of the filter
    - bandwidth is set to 30 dB/octave.
    - The phase response is such that the group delay is constant and equal to 0.
- Filter 3: resonator filter type with a concave group delay and a 150 ns maximum differential group delay. The design of this filter is based on the full definition of the transfer function:
    - The amplitude response is 1 within the desired filter bandwidth. The filter roll-off outside of the filter bandwidth is set to 30 dB/octave.
    - The phase response is such that the differential group delay reaches 150 ns at the edge of the filter bandwidth following a 3rd order function and then goes back down following a 9th order function.
- Filter 4: the amplitude response is that of a 6th-order Butterworth filter. The phase response is that of smallest order Butterworth filter leading to a differential group delay greater than 150 ns.

DFMC user space

Three parameters defining airborne receiver

Pairs of (CS,PCBW) needs to be tested covering entire user space

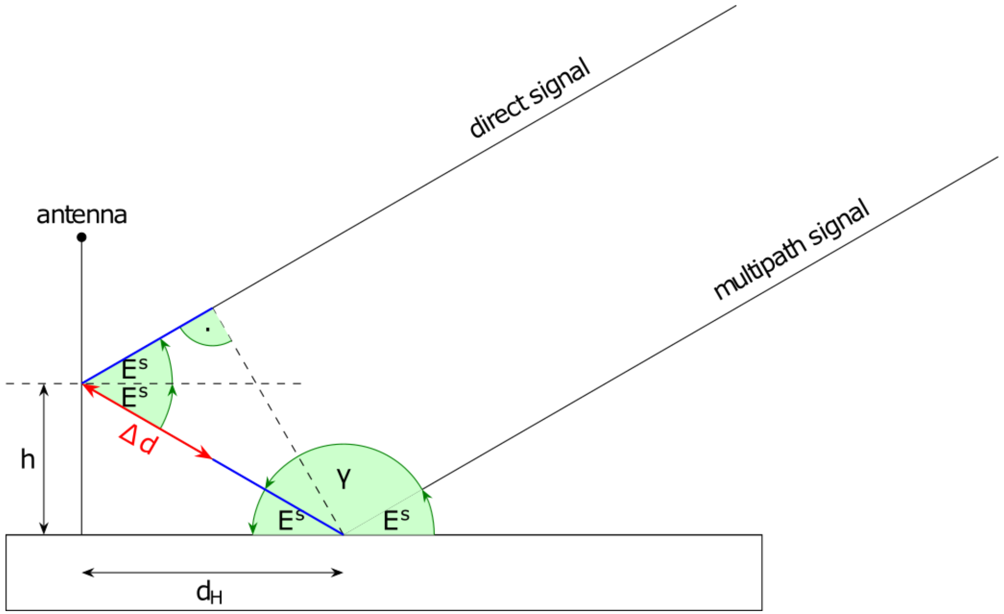


MP mitigation

Low pass filter

The bandwidth for low pass filter was estimated based on a MP ground-reflection theoretical model.

Such model assumes single ray reflection.

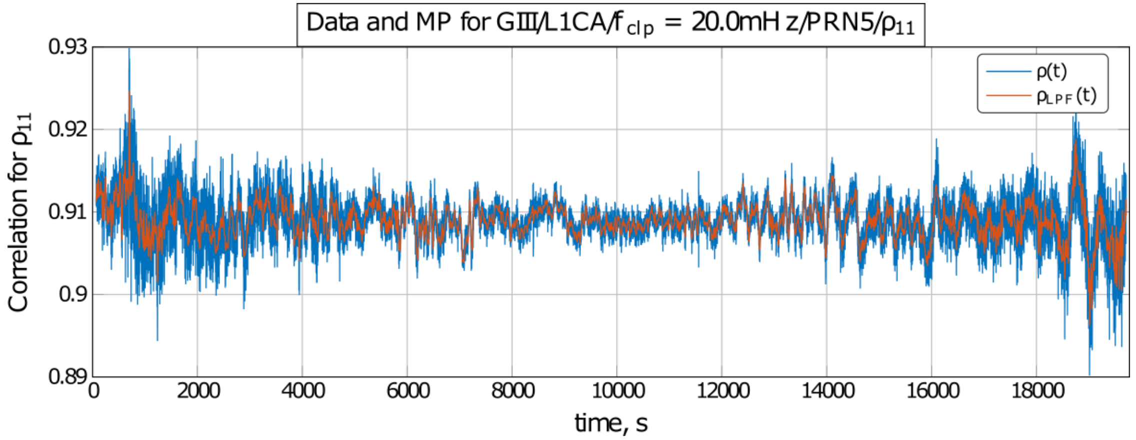


MP mitigation

Low pass filter

Purpose of MP mitigation is to remove low frequency component from each correlator measurements.

Example shows time series for correlator and its MP component.

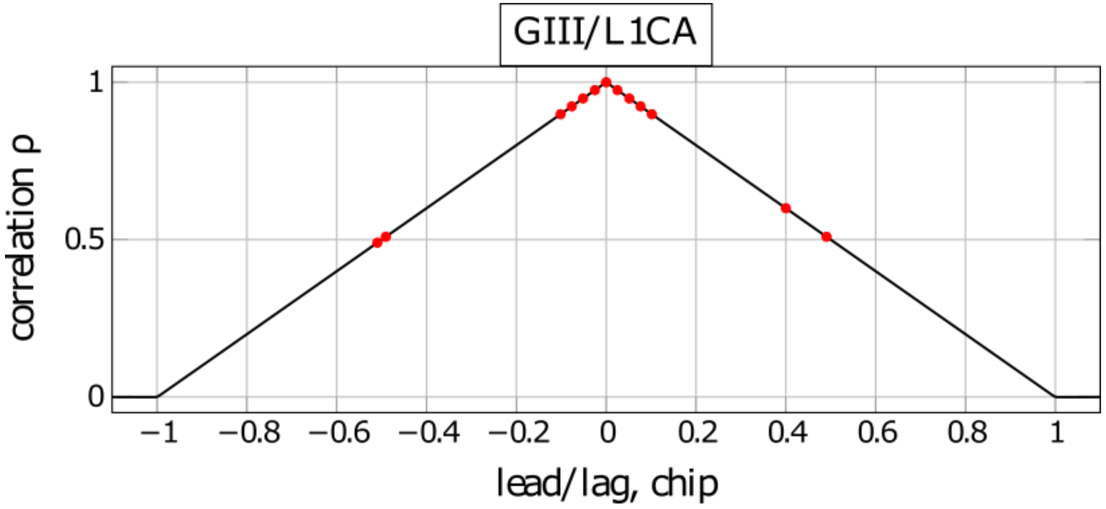


Signal Deformation Monitor

Adjacent differences

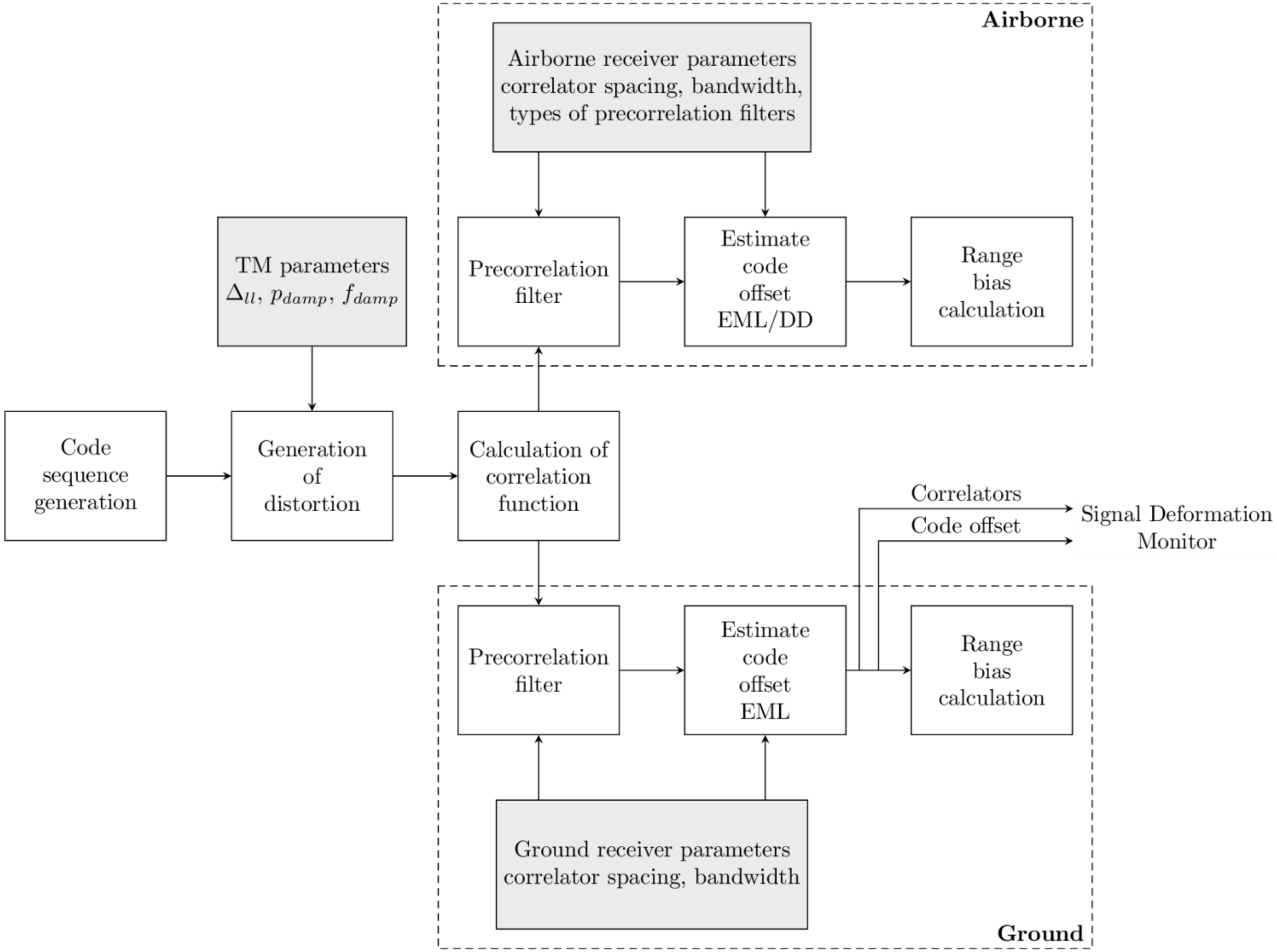
- Correlation differences between each neighboring correlators
- These differences are gathered along considerable time span
- Covariance matrix is taken to grasp variability between these differences

- Use covariance matrix to detect deformation in correlation function



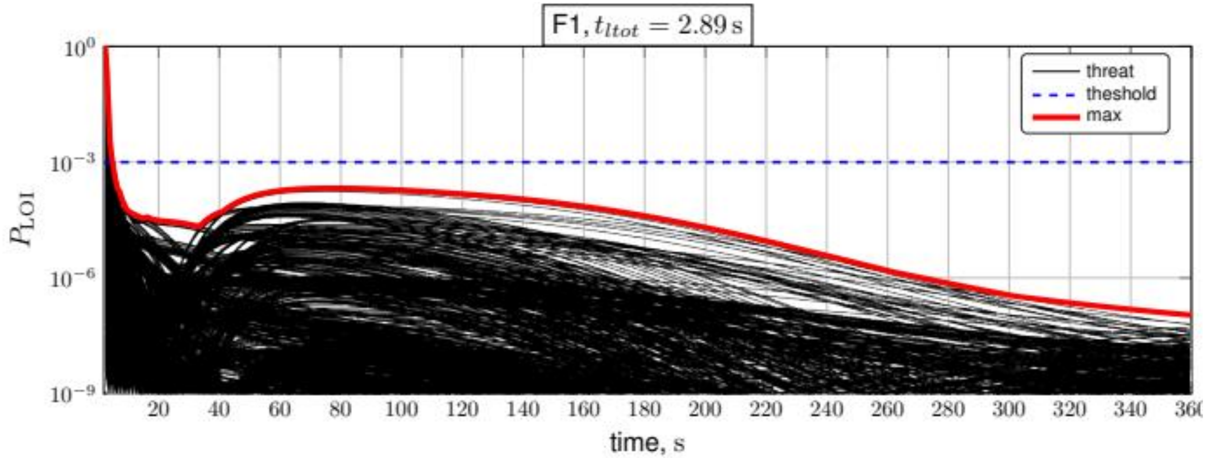
Signal Deformation Monitor

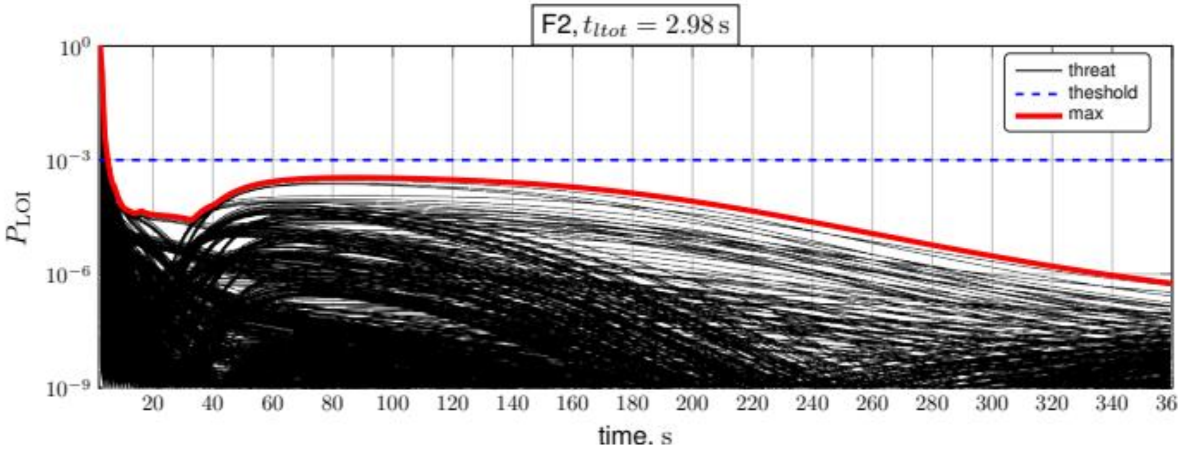
Evil Waveform generation

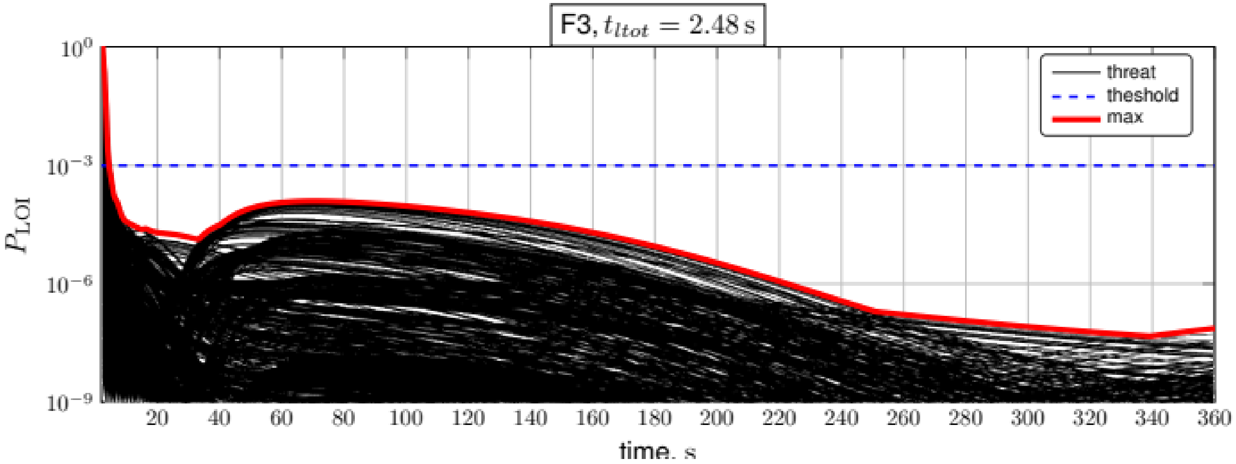


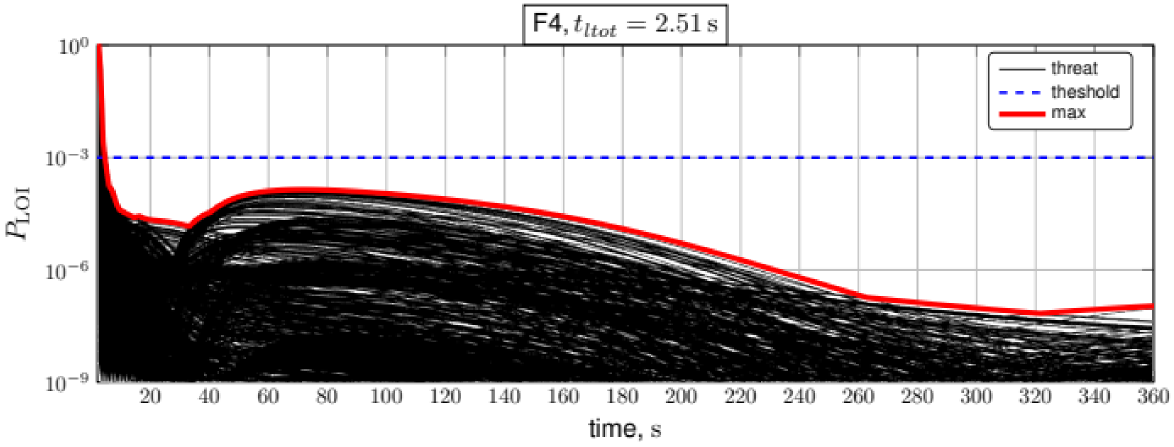
Results for Probability of Loss of Integrity

GAST C



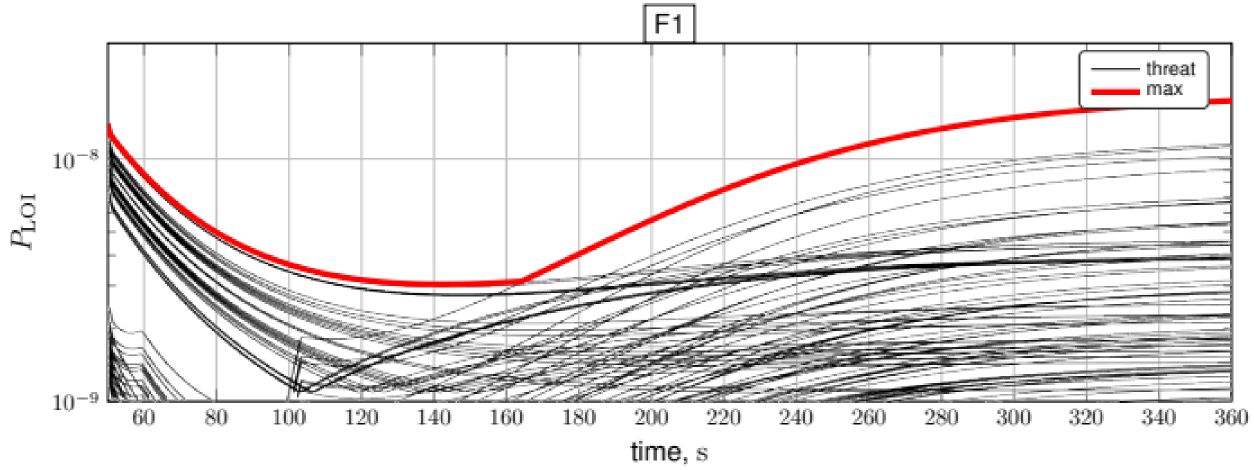


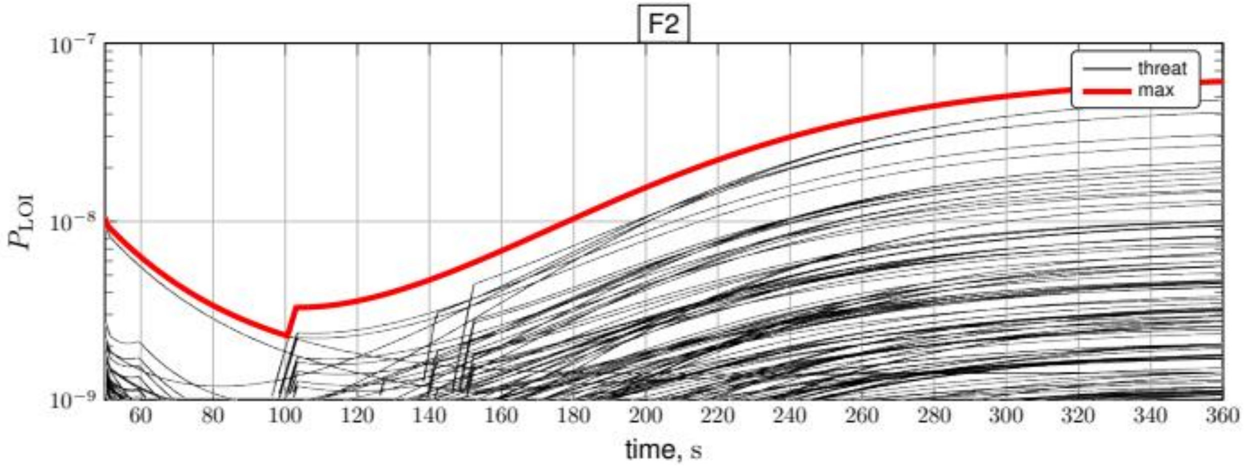


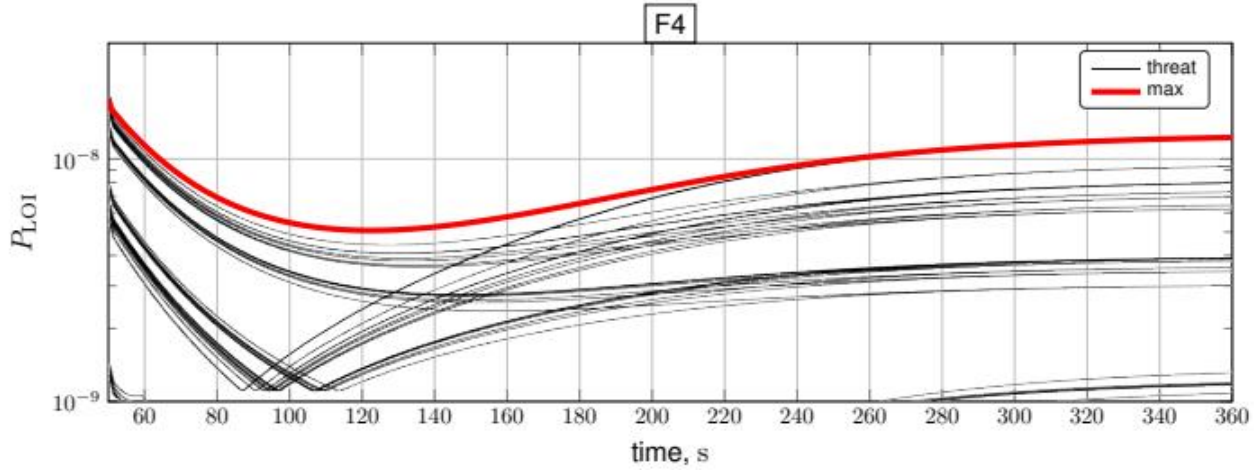


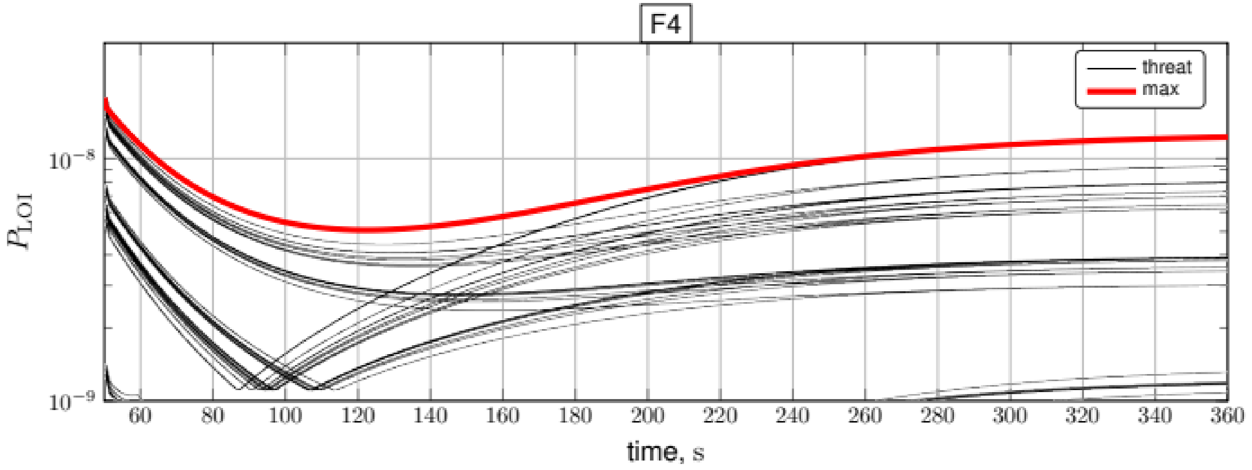
Results for Probability of Loss of Integrity

GAST D



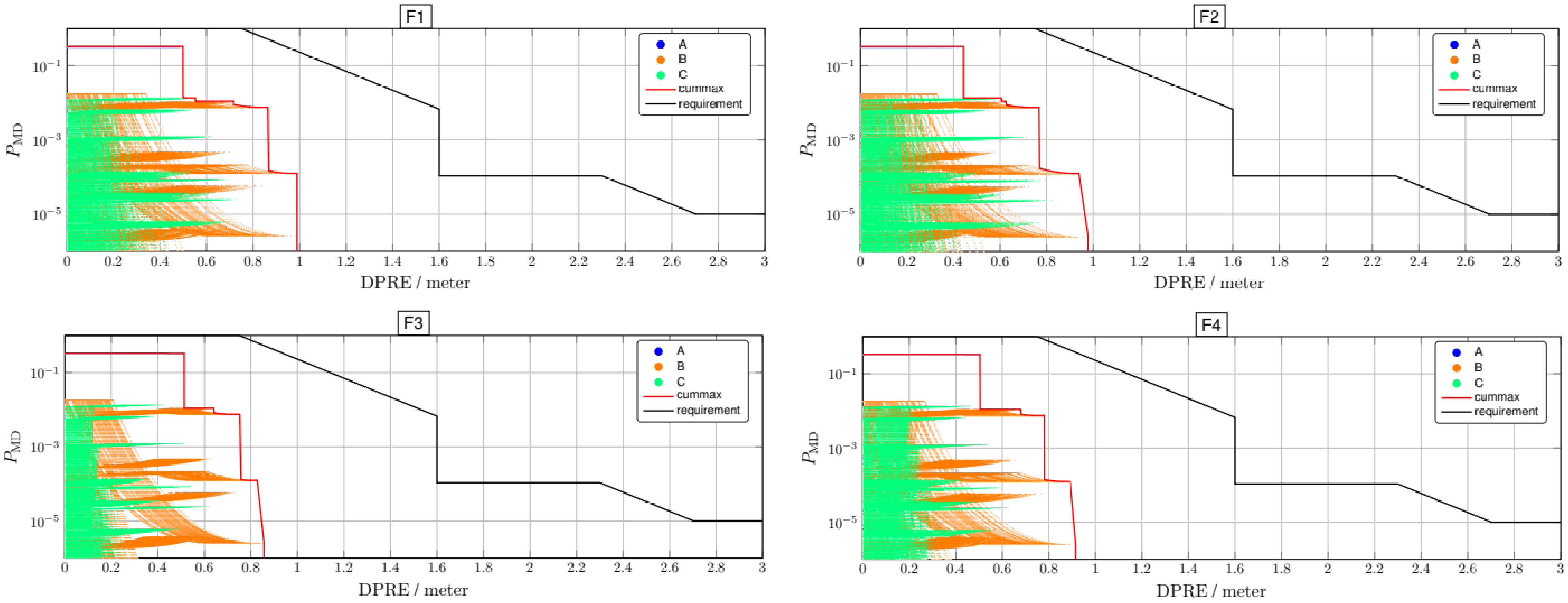






Results for Probability of Missed Detection

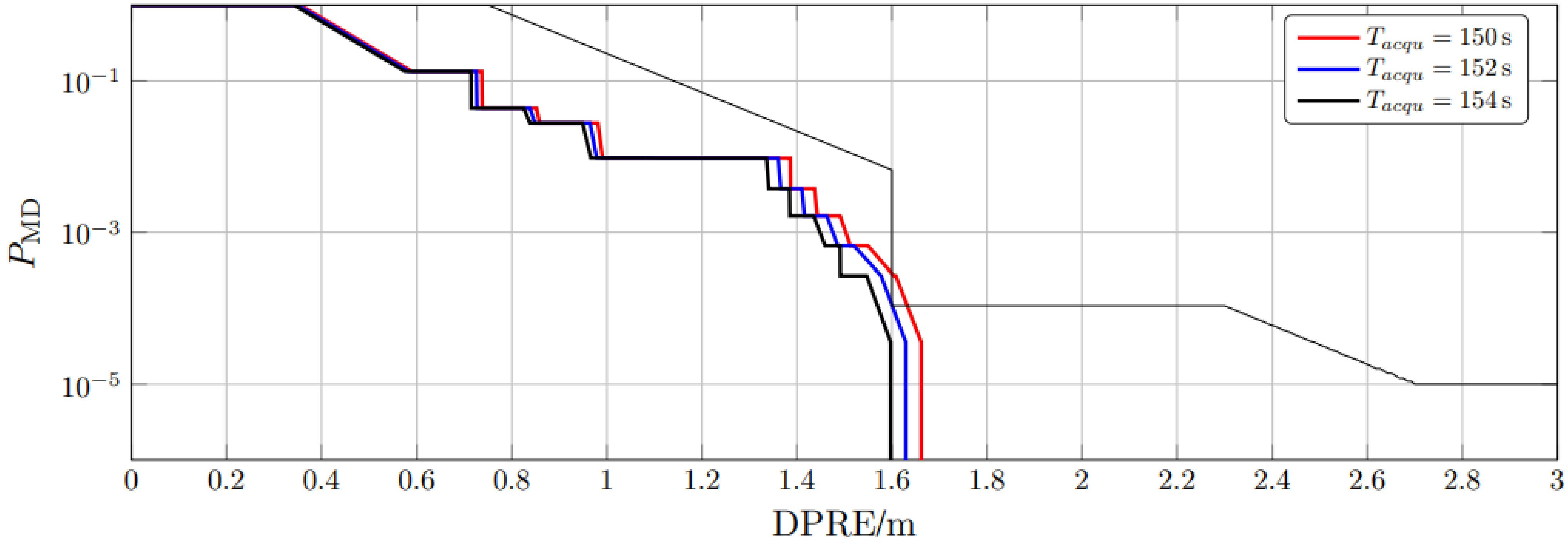
GAST D – Additional Integrity Requirement



Results for Probability of Missed Detection

DFMC

- G-III receiver, L1CA signal, filter F1, 25 mHz low pass filter
- GAST E with long time constant (600 s)
- The long time constant increases the period of filter mismatch between air and ground. This is mitigated by a longer waiting time compared to GAST D before outputting a position solution (152 s vs 50 s).



04

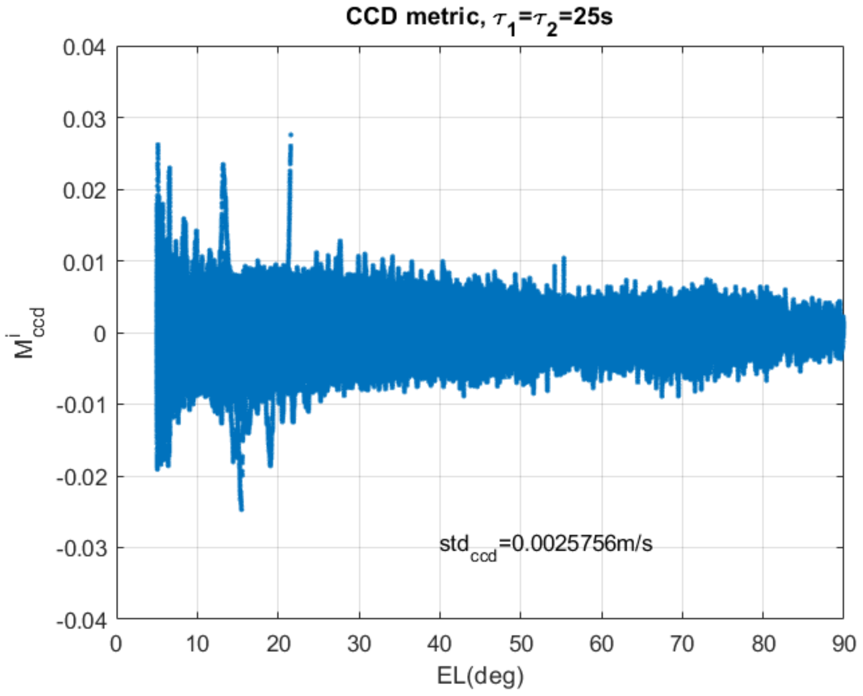
Code-Carrier Divergence Monitoring

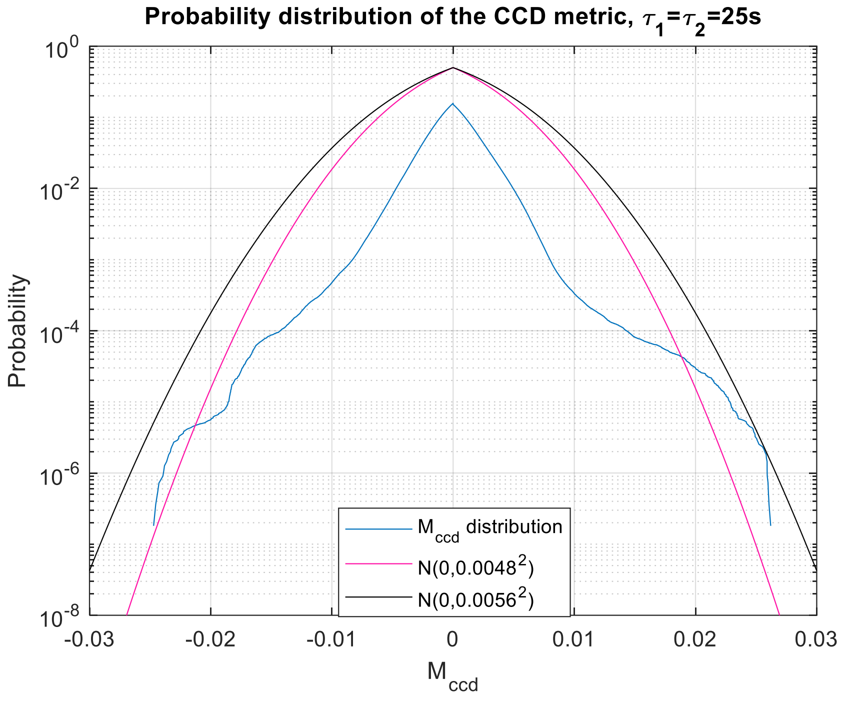
CCD Fault & Threat space

- Any divergence between the Code phase and carrier phase.
- Meant for divergence due to a faulted satellite, but it can also detect Ionospheric activity because it creates the same effect.
- This fault has two models:
  - A. Drift fault: grows **linearly** with time.
  - B. Jump fault: sudden jump on the PR to a constant value
- The fault can occur on both phases or on one of them only.
- The threat space of the fault has two dimensions (two variables):
  1. Magnitude of the fault
  2. Initialization time of the smoothing filter in the avionics
- Regarding initialization time, the worst cases occur when the smoothing filters in the GS and avionics are not matched, i.e.:
  - I. Filter coefficients are different (variant and invariant)
  - II. Fault starts after the GS filter reaches the steady state, and
  - III. Airborne filter is initialized around the time of the onset of the fault

CCD Monitor Parameters

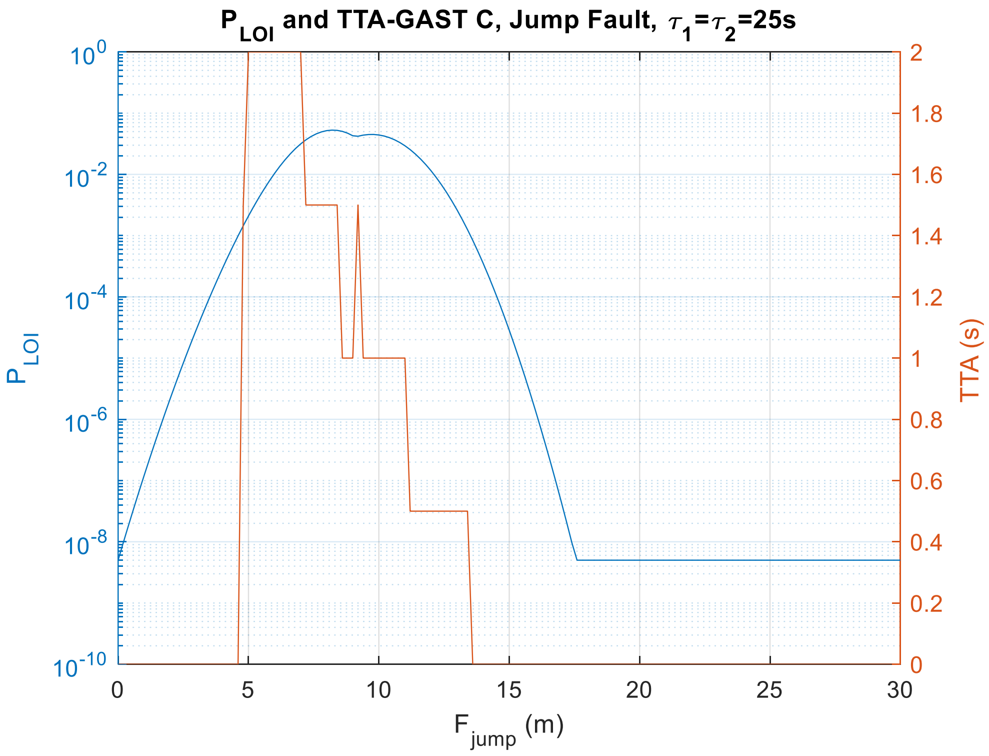
- Regular CCD filter
- 25s time constant
- The noise level obtained from three sites (OSL, FRA, TFN). The worst is from TFN:

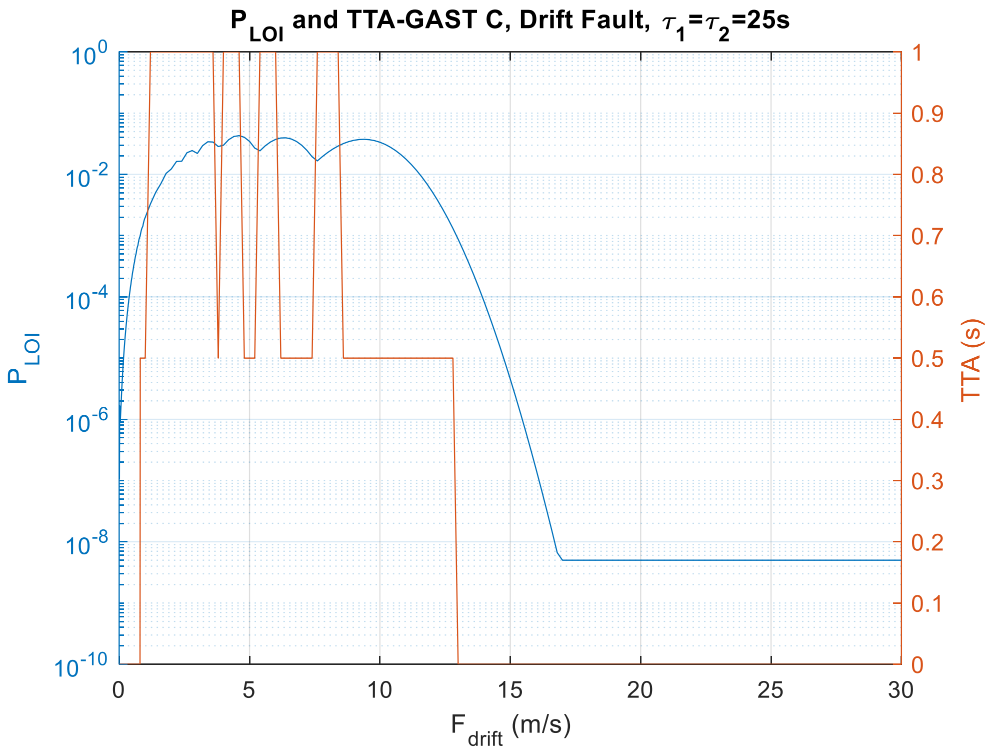




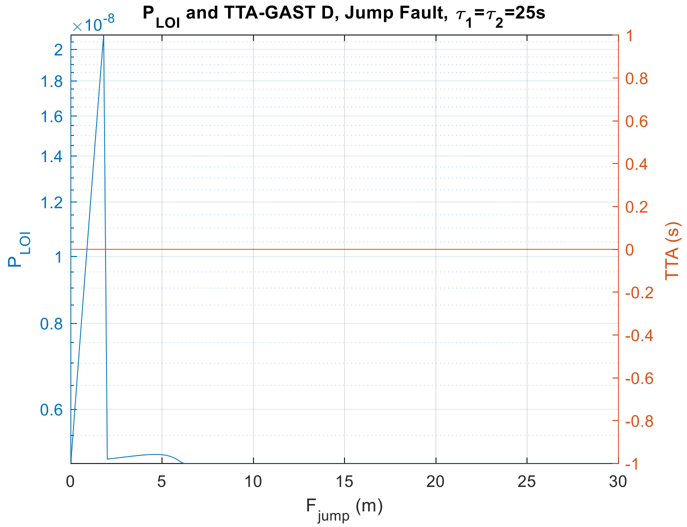
- For the threshold, a PFA of 1×10^{-8} was chosen

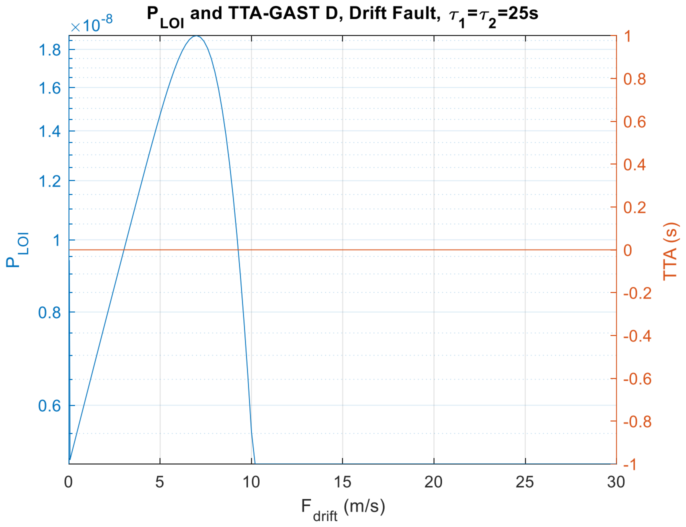
Integrity Results-GAST C

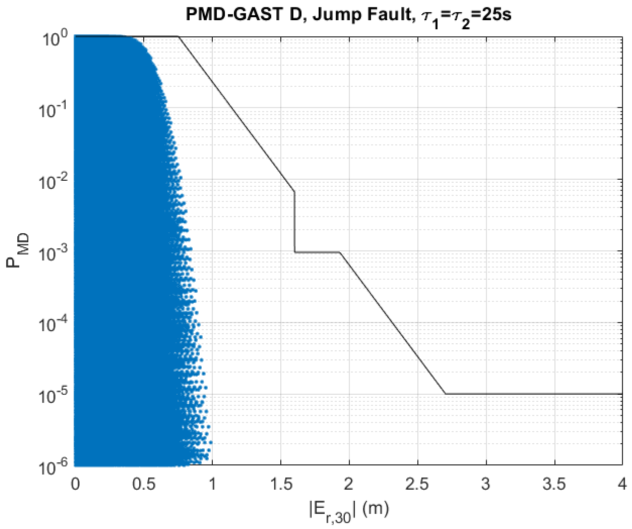


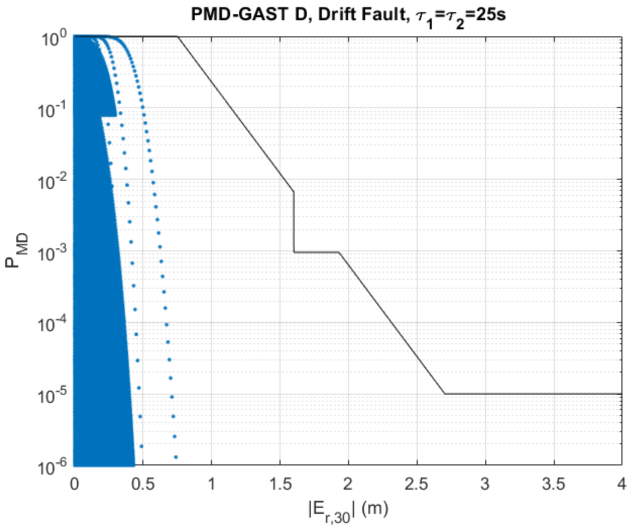


Integrity Results-GAST D



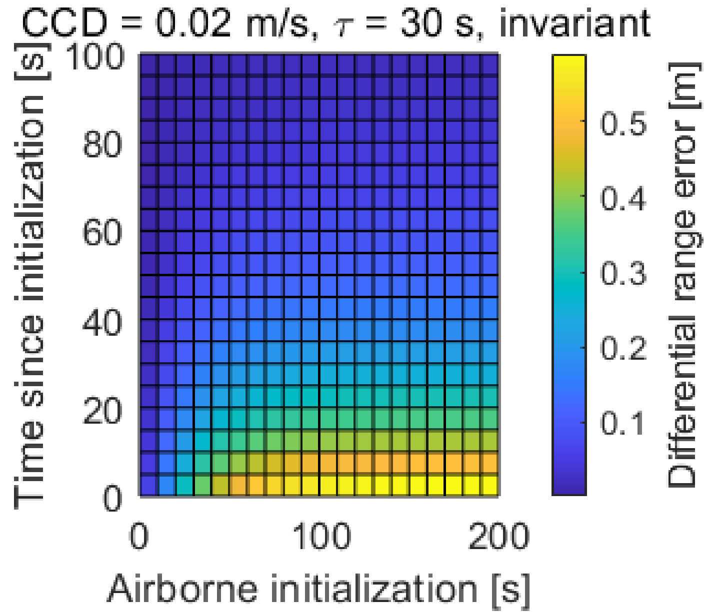


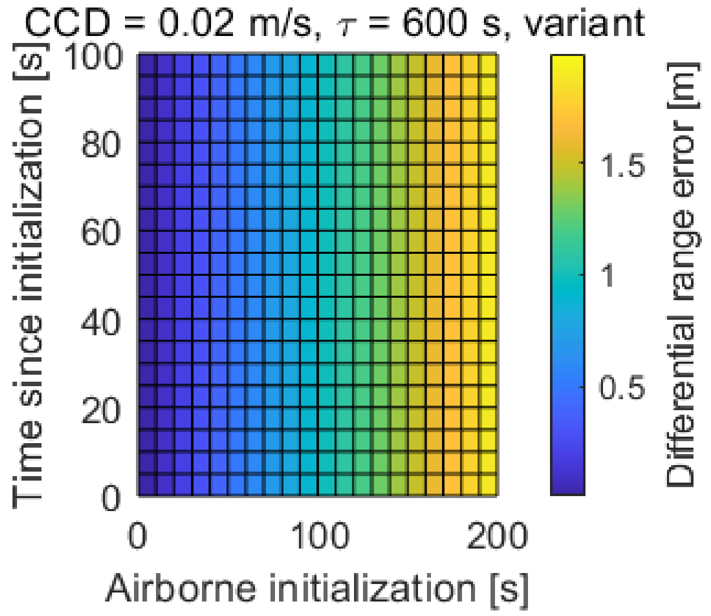




CCD for DFMC

- The CCD threat is sensitive to timing of the airborne and ground smoothing filters and the time constants used.
- For short time constants small CCD drift rates accumulate to smaller errors (e.g. GAST D), but longer time constants up to 600s lead to small divergence rates accumulating to larger errors.
- Whether the smoothing filters are invariant or variant also plays a role. Variant filters are used for GAST E.
- Since all smoothing filters are running on the airborne side in GAST E, we can control the timing of both air and ground filters. They can be matched to some degree during the transient phase to reduce the differential error.
- Since a CCD satellite fault can be separated from ionospheric activity with a dual frequency monitor, it may be possible to move the responsibility for the CCD threat to the airborne subsystem.
- Use of two frequencies can improve the ground CCD monitor performance.



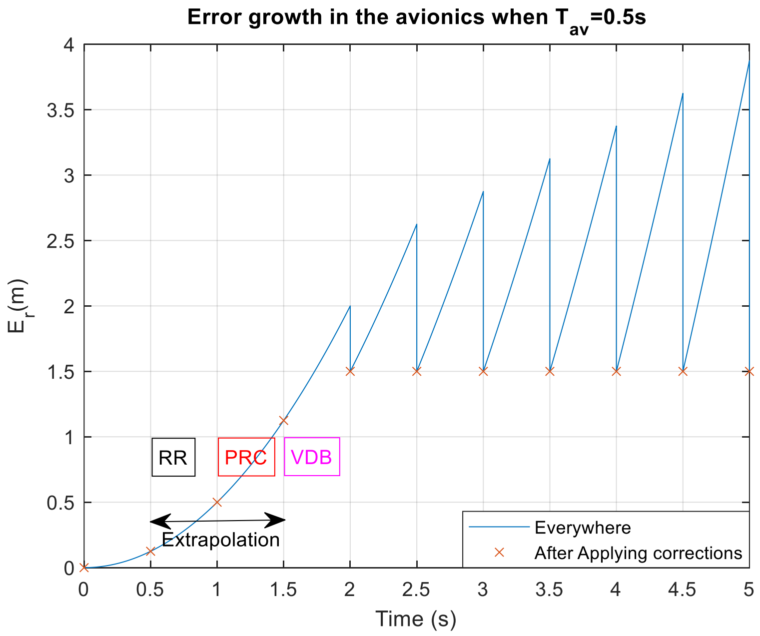


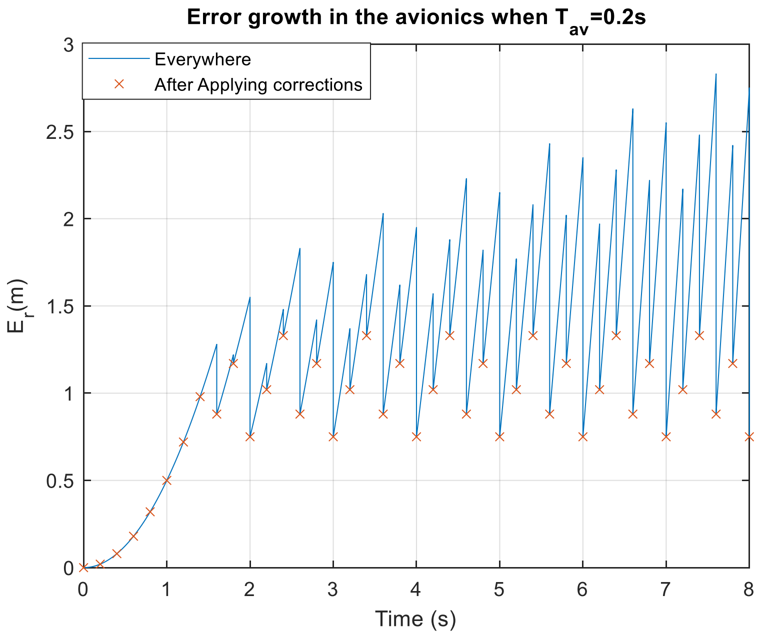
05

Excessive Pseudorange Acceleration

EA Fault & Threat space

- Excessive acceleration of both code phase and carrier phase (in unison) , usually due to satellite clock.
- The fault grows quadratically with time.
- The threat space of the fault has one dimension only, the magnitude of the fault.
- Difference of initialization time of filters (GS and avionics) is irrelevant, however the sampling time is important.
- Worst cases occur when the avionics sampling time is large (0.5s):





EA Monitor Parameters

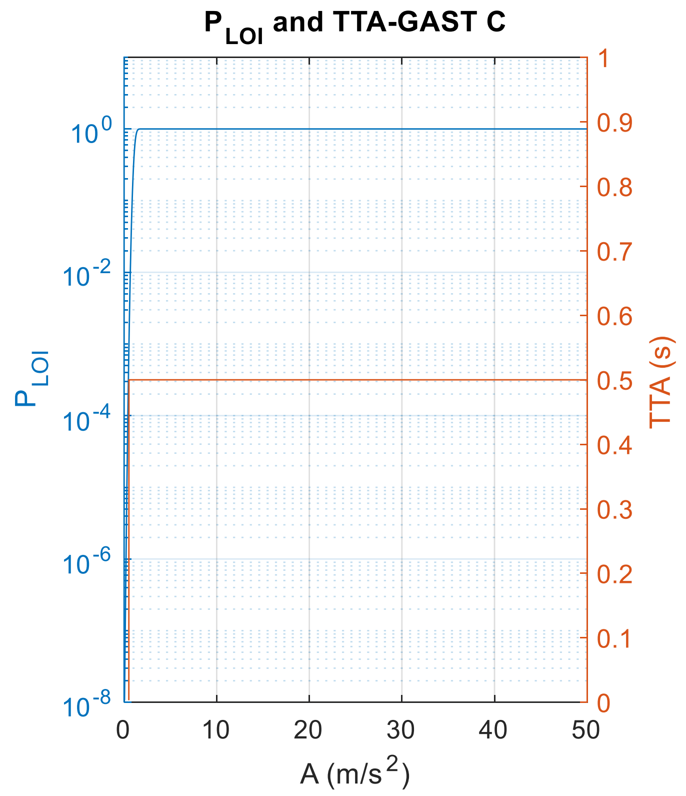
- Our monitor uses both the acceleration and velocity of the carrier phase.

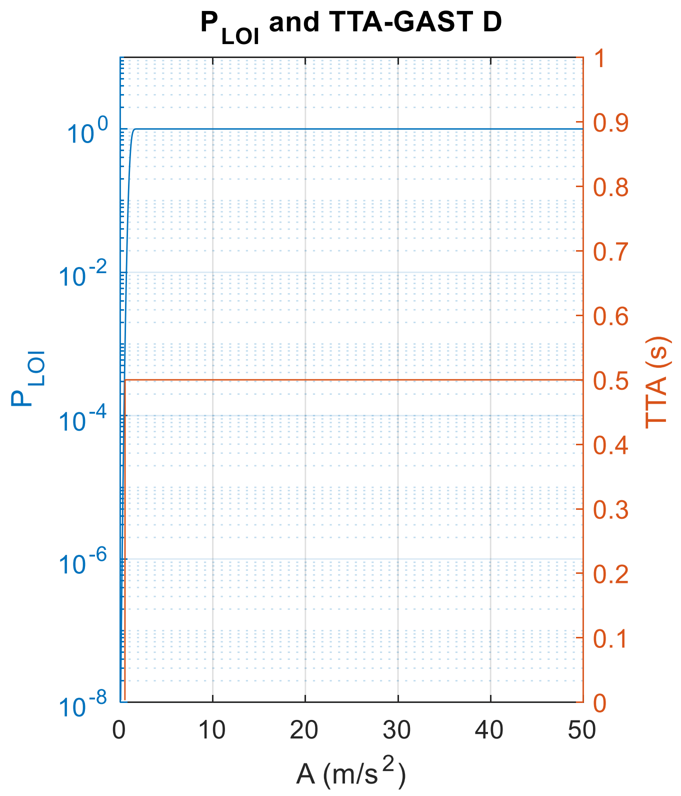
- The noise level on carrier phase is conservatively assumed 5mm.

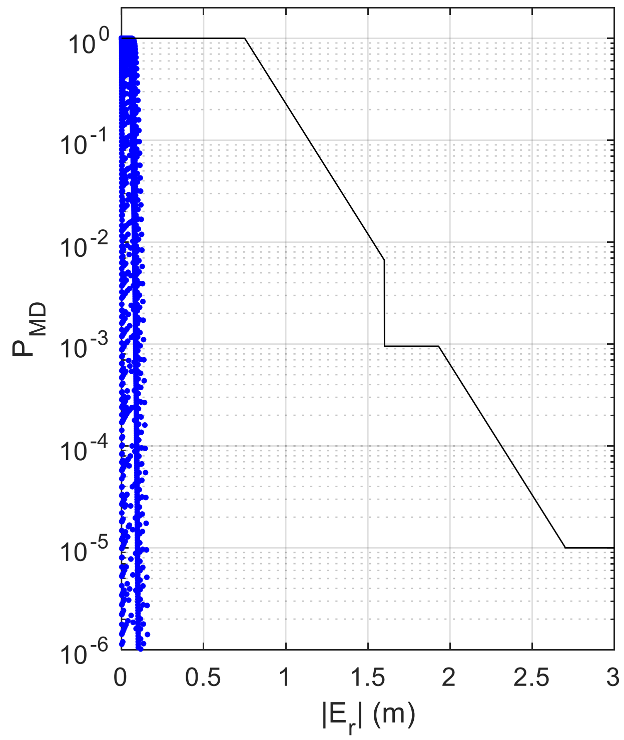
- We differentiate the EA event from cycle slips by using the following logic:
  - If there is a hit on all several RRs from one satellite, it is an EA event
  - If there is a hit on one RR from all satellite, it is a RR fault (possibly RFI)
  - If there is a hit on one RR from a satellite, it is a cycle slip.

- Based on this logic, the effective PFA will be very low.

Integrity Results-GAST C & D

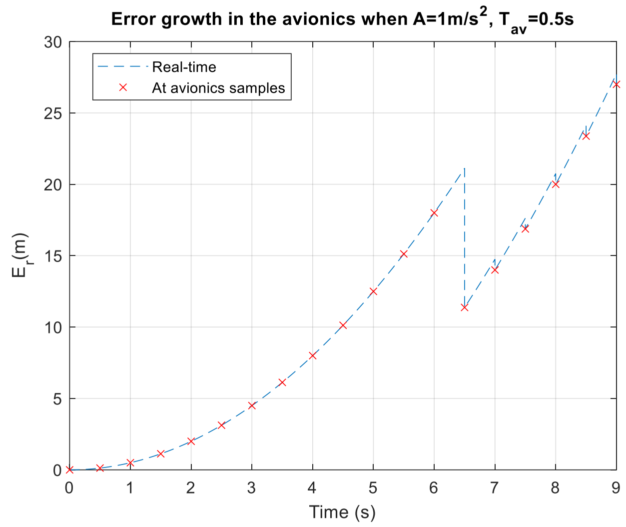


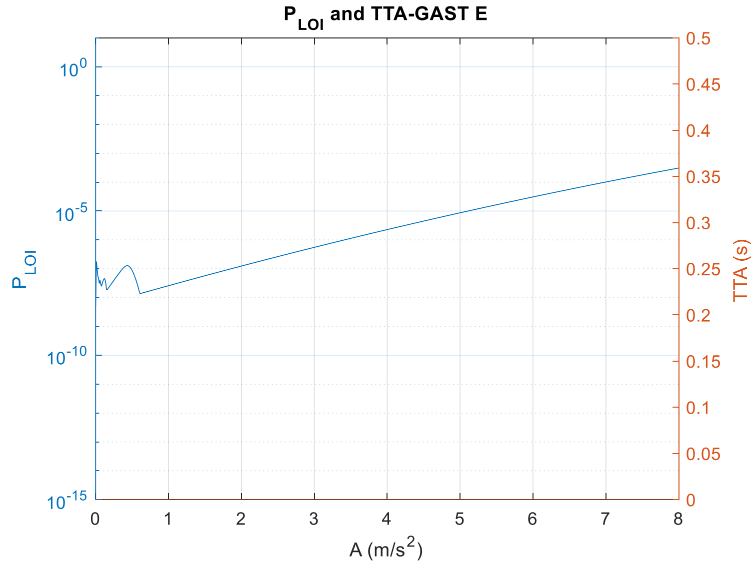


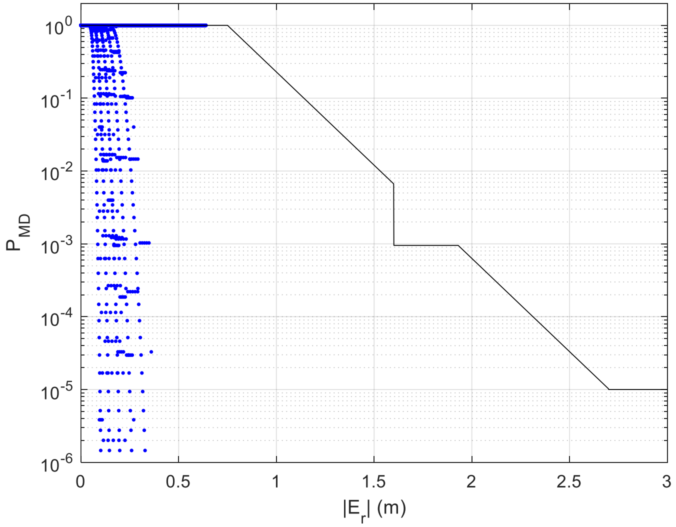


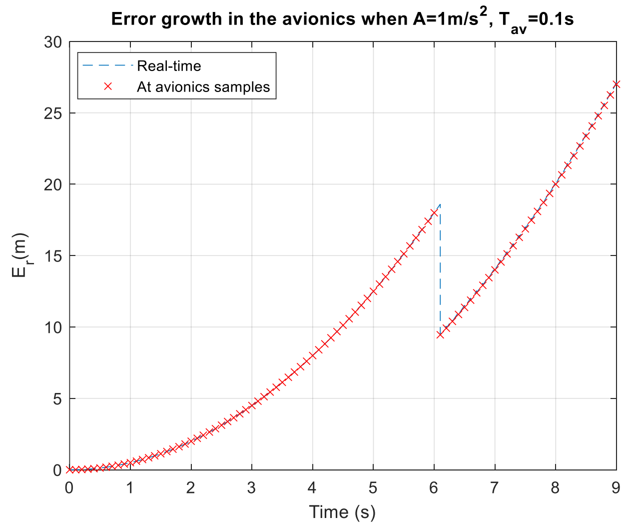
EA for DFMC

- ➢ The monitor will be applied to each frequency separately.
- ➢ Low update rate of MT23 is not a problem since the alert is sent in the more frequent MT50.
- ➢ Plots assuming: 3s update MT23.







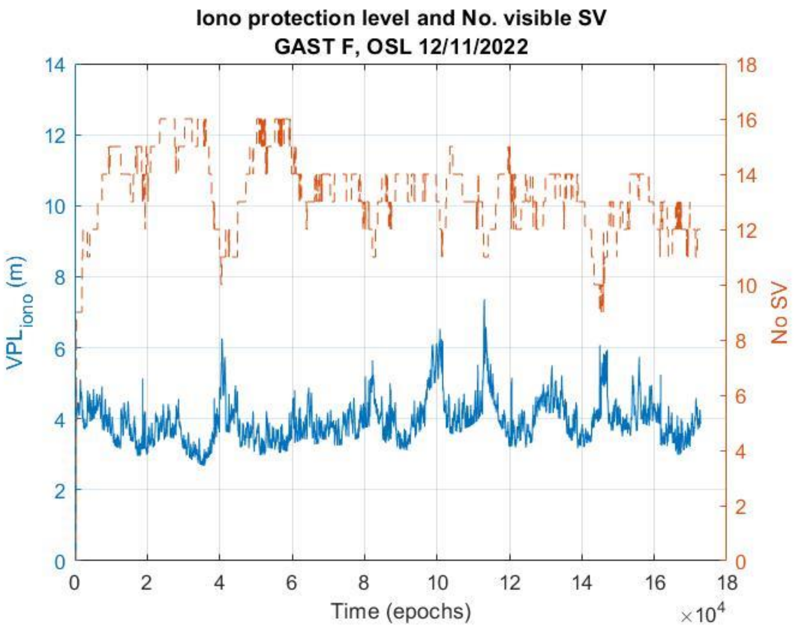


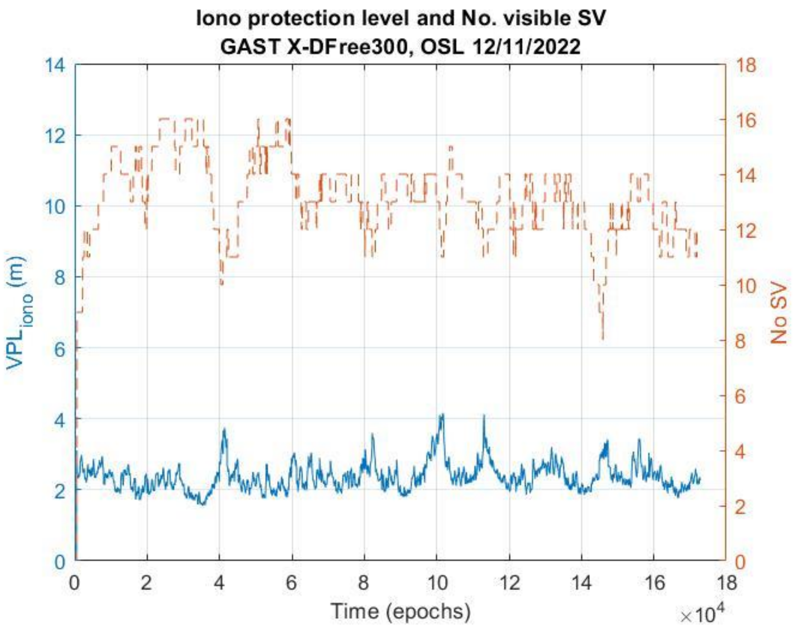
06

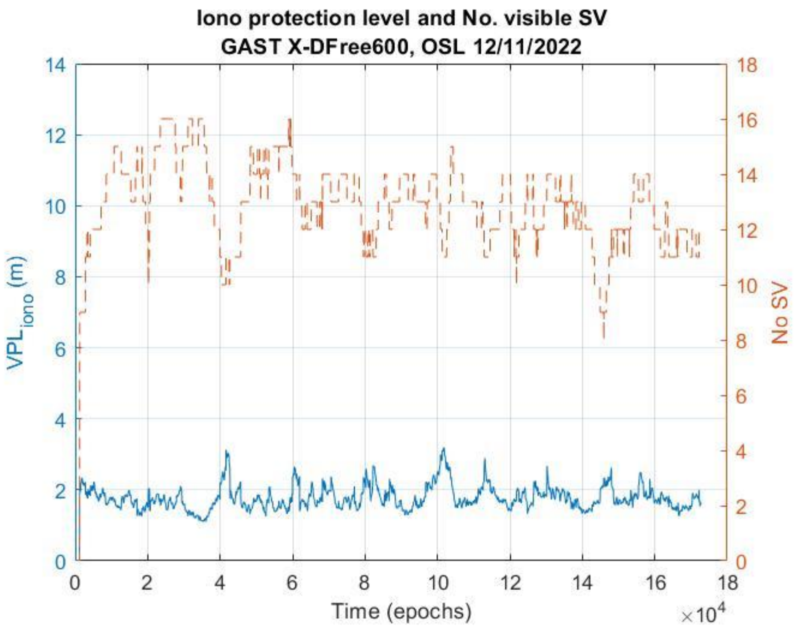
Evolution towards DFMC GBAS

Availability Analysis of DFMC Processing Modes

- During the project, nominal processing modes for DFMC GBAS were discussed at ICAO level.
- Indra contributed with availability simulations to compare the modes.
- Reliability parameters for GPS and Galileo were assumed equal.
- DFMC GBAS airborne ionospheric gradient monitor included – may trigger for poor satellite geometries, impacting availability.



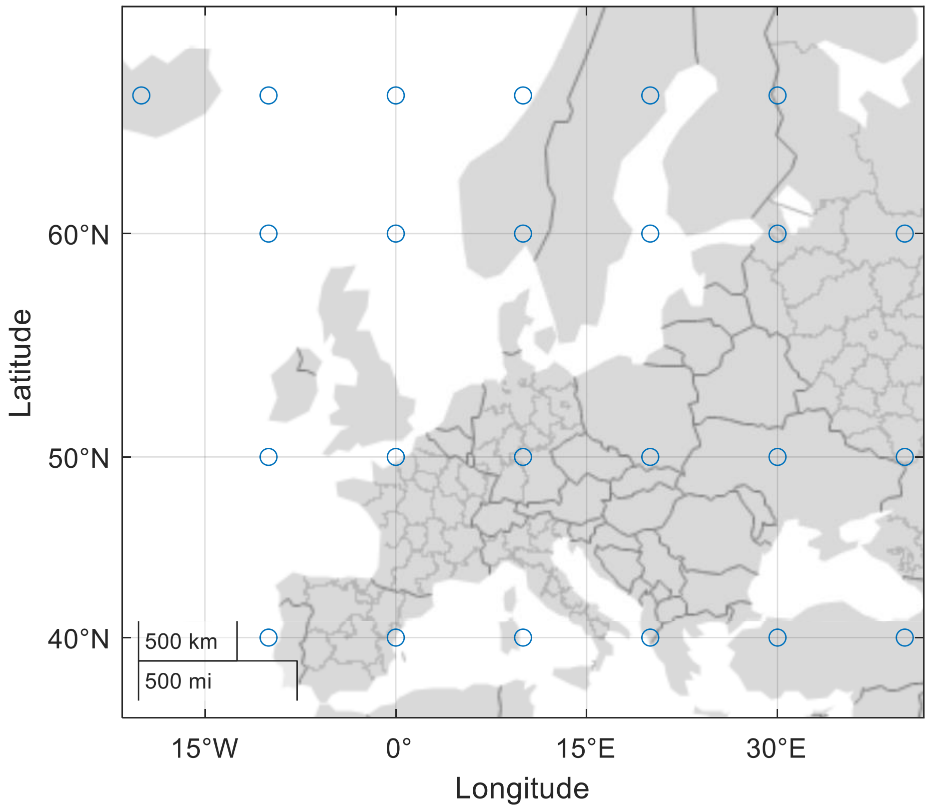




Availability Results of DFMC Processing Modes

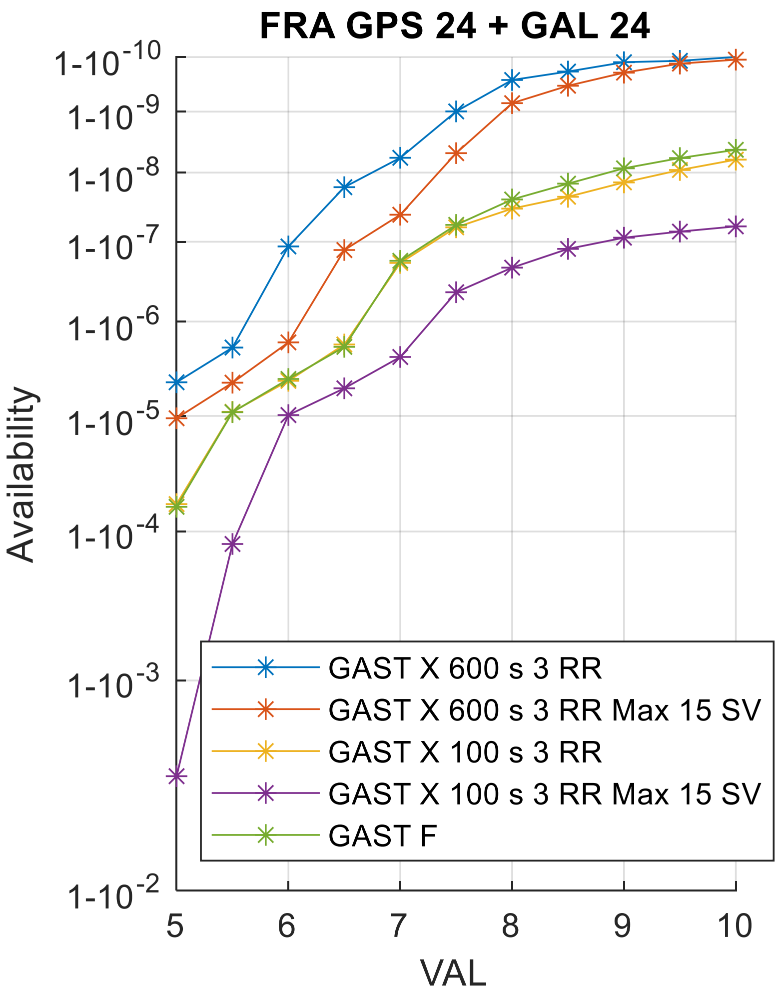
- ❑Availability results were computed for
  - ❑different geographic locations
  - ❑different smoothing time constants
  - ❑dual and single constellation, with restriction on number of satellites for dual constellation

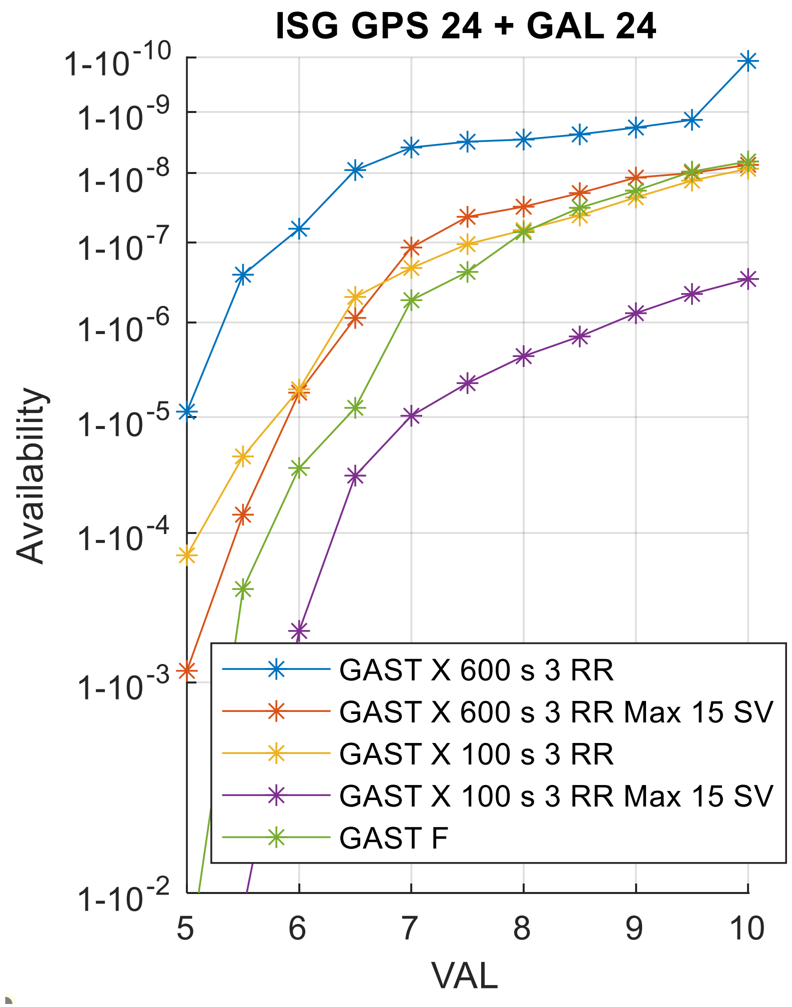
	ECAC	FRA	ISG
σ_{vig} [mm/km]	4	2	9.5
σ_n	18.3	18.3	27
h_0 [m]	8100	8100	15200



Dual Constellation Availability Results

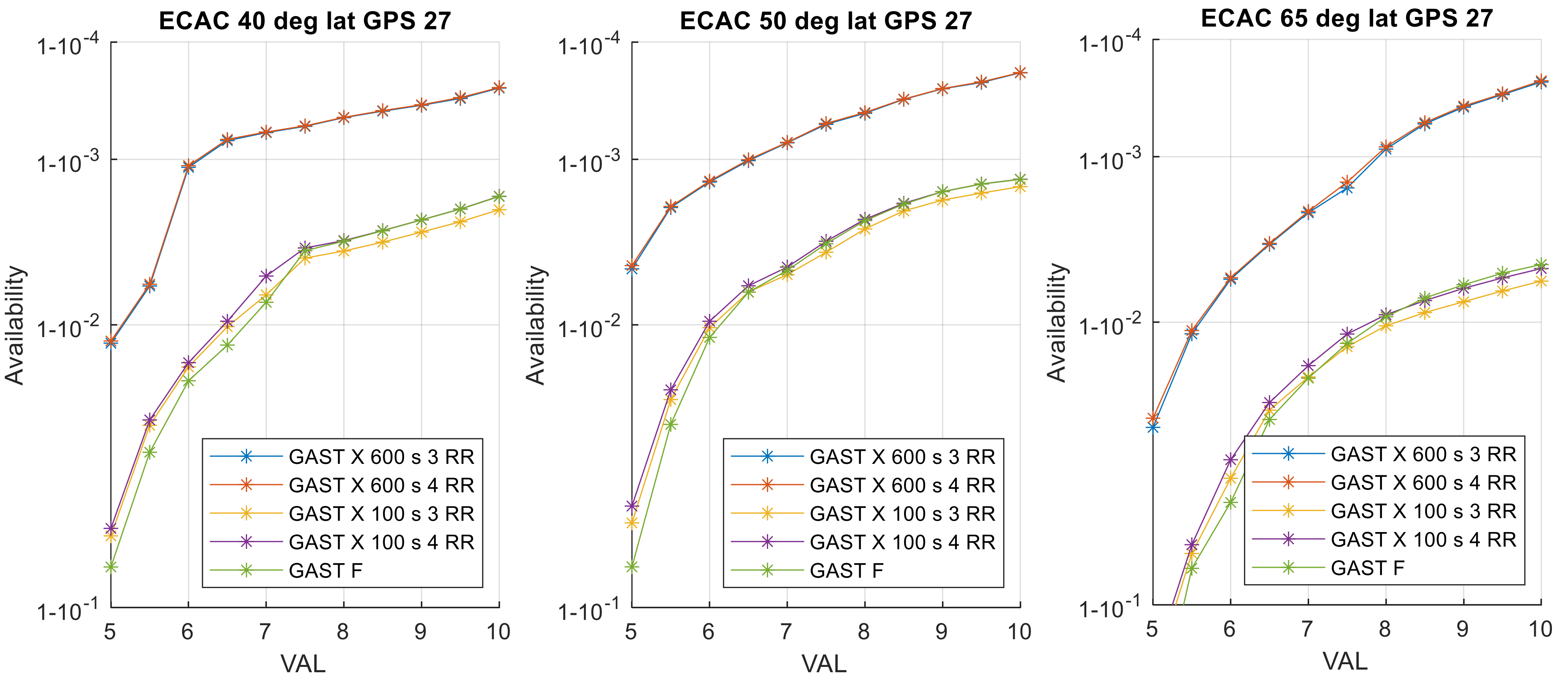
- Dual constellation is clearly beneficial as all processing modes perform well.
- Longer time constant improves the results.
- The nominal local ionosphere model has an impact. FRA ionosphere is benign compared to ISG.





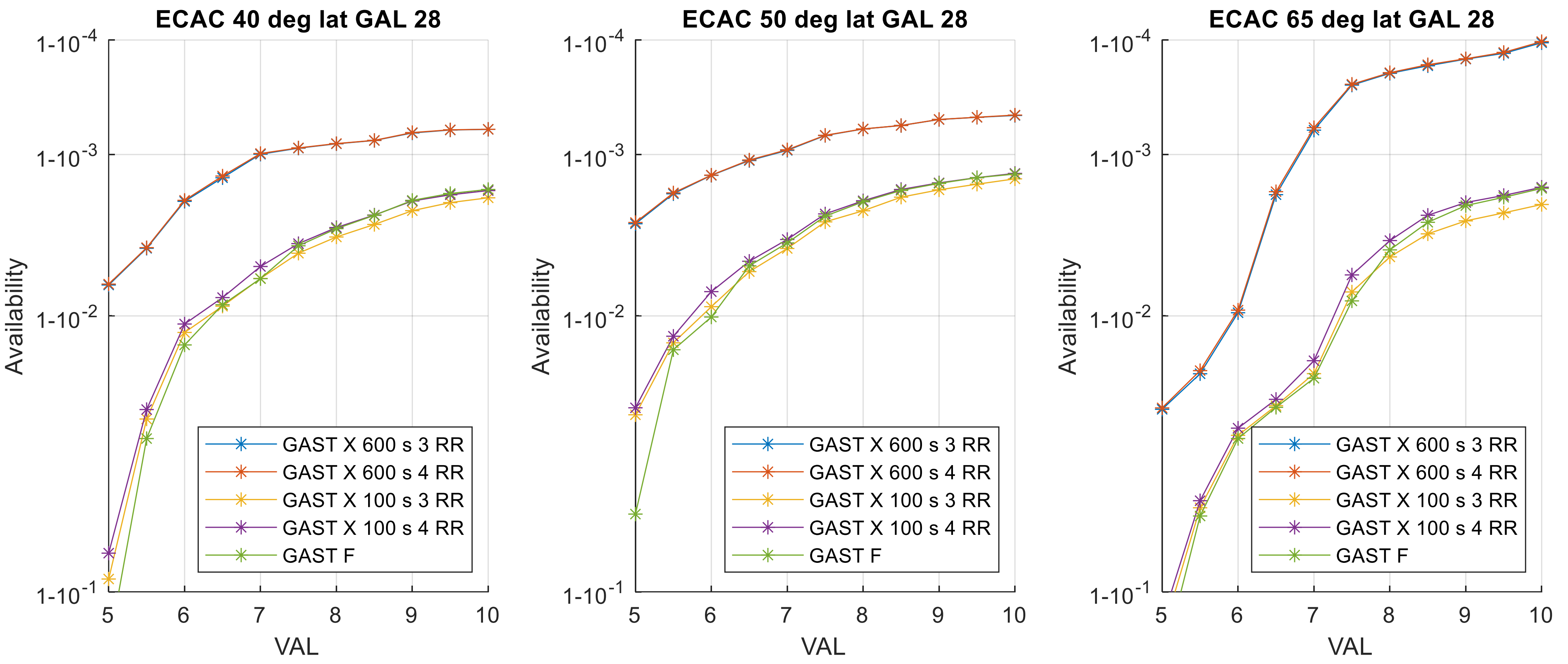
GPS Availability Results

- Need for good performance if a constellation is lost.
- It could be possible that an airborne user and a ground station only has one constellation in common.



Galileo Availability Results

- Galileo performance is slightly better in the North.
- The longer time constant improves performance significantly.



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07

Conclusion

DFMC GBAS Ground Station Integrity Monitors

To successfully operate a Dual Frequency Multi-Constellation DFMC GBAS ground station supporting GBAS Approach Service Type E (GAST E) the following integrity monitors have been identified:

1. Signal Deformation Monitor for each signal, i.e. GPS L1/L5 and GAL E1/E5a
2. Code-Carrier Divergence Monitor for each signal
3. Excessive Acceleration Monitor for each signal
4. Ephemeris Monitor for each signal
    a. Need to include mitigation of wide fault for Galileo.
5. Ionospheric Gradient Monitor is needed for each signal to support GAST D fallback modes, but not for the new GAST E processing modes.

Main Results and Product Viability

- Standardisation of DFMC GBAS at ICAO has been supported by this project, and ICAO paper references are included herein.
- Integrity threat mitigation was verified for the presented satellite faults for GAST C and D.
- Indra Navia is now in a position to pursue certification of the GBAS GAST D ground station (NORMARC 8100) when the market is ready.
- Indra Navia will benefit from the development of the GBAS ground station product to provide our customers with a complete navaids product portfolio and meet new needs of major customers (GBAS).
- In Europe there is an increasing concern over GNSS vulnerability to radio frequency interference and spoofing. The GBAS community is moving towards DFMC for increased robustness.

Published ICAO papers

- NSP/7-WP/24 DFMC GBAS AVAILABILITY CONSIDERATIONS, Montreal, Canada, January 2023
- JWGs/10-WP/18 DFMC GBAS NOMINAL IONOSPHERIC GRADIENT MITIGATION RESULTS USING GROUND COLLECTED FIELD DATA, Montreal, Canada, May 2023
- JWGs/11-IP/7 CARRIER-PHASE BASED IONOSPHERIC GRADIENT MONITORING FOR DFMC GBAS USING GROUND DATA, Montreal, Canada, November 2023
- JWGs/11-WP/13 COMPENSATING FOR CLOCK OFFSETS IN GROUND RECEIVERS FOR GAST E, Montreal, Canada, November 2023
- JWGs/11-WP/14 CONSTELLATION PROBABILITIES FOR DFMC GBAS AVAILABILITY CALCULATIONS, Montreal, Canada, November 2023
- JWGs/12-WP/21 GAST E INTEGRITY ALLOCATION, Montreal, Canada, May 2024
- JWGs/13-WP/15 CCD INTEGRITY THREAT ALLOCATION FOR GAST E, Montreal, Canada, November 2024

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