Ionospheric Effects on the Performance of GAGAN Satellites for Aircraft Precision Approach

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Narayan Dhital
Lead Space Application WG
Nepal Astronomical Society (NASO)
na.dhital@gmail.com
Professional Employee: GNSS Expert
Galileo Control Center, DLR GfR mbH
narayan.dhital@dlr-gfr.de

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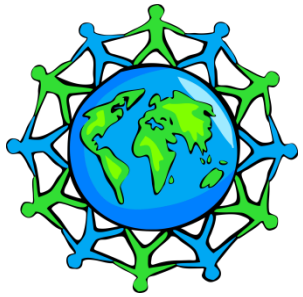
Innovation and Technology Transfer in International Cooperation

NASO strives for capacity building in science & technology and also for technology transfer



United Nations, OOSA has been one of the key stakeholders in the ecosystem

ICG Experts Meeting, Vienna, 2015: DLR GfR mbH (Galileo Control Center) highlighted the innovation in GNSS for airspace modernization. Dialogues with Civil Aviation Authority of Nepal.

UN/Nepal Workshop in GNSS, 2016: DLR GfR mbH as one of the sponsors contributed to create a ecosystem for innovation

UNOOSA/Dream Chaser Orbital Space Mission Technical Breifing, Vienna, 2019: DLR GfR mbH and NASO joint interest to the call

10 years strategic roadmap for technology discovery, feasibility assessment, market analysis, and implementation

Current Product/Service Discovery → **Product/Service Delivery**

Integrated Satellite Communication, Navigation and Surveillance Technologies

GAGAN Performance Analysis for Aircraft Precision Approach

Airspace Modernization through the implementation of GNSS technologies

Impact monitoring of Space Weather and Ionospheric Events on the Technologies

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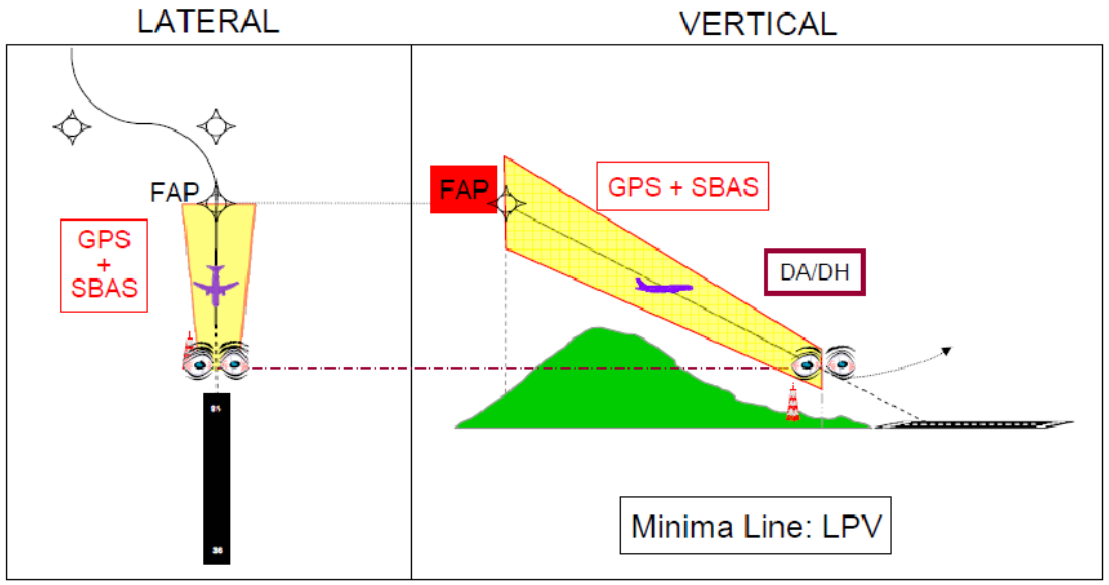
Ionospheric Impacts on Aircraft Approach Procedures



Aircraft Phase of Flight	Accuracy		Integrity			Maximum Probabilities of Failure	
	(2 σ or 95%)		Alert Limits (4-5 σ)		Time to Alert		
	Vertical	Horizontal	Vertical	Horizontal		Integrity	Continuity
NPA, Initial Approach, Departure	N/A	0.22 - 0.74 km	N/A	1.95 - 3.7 km	10-15 s	10^{-7}/hr	10^{-4}/hr
LNAV/VNAV	20 m	220 m	50 m	556 m	10 s	1.2×10^{-7} / 150 s	4.8×10^{-6} / 15 s
LPV		16 m		40 m			
APV I			35 m				
APV II	8 m		20 m		6 s		
LPV 200	4 m		35 m				
Precision Approach CAT I			10 m				
Precision Approach CAT II/III	< 2.9 m	< 6.9 m	5.3 m	< 17 m	< 2 s	$< 10^{-9}$ / 150 s	$< 4 \times 10^{-6}$ / 15 s

Safety bound of the aircraft position depends on the confidence of ionospheric corrections and irregularities monitoring!

Credit: ICAO

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Integrity Threat Model

- GNSS psuedorange errors assumed as Gaussian distribution, independent and uncorrelated

$$\sigma_i^2 = \sigma_{i,flt}^2 + \sigma_{i,UIRE}^2 + \sigma_{i,air}^2 + \sigma_{i,tropo}^2$$

- Integrity equation obtained by propagating covariance from psuedorange domain to position domain

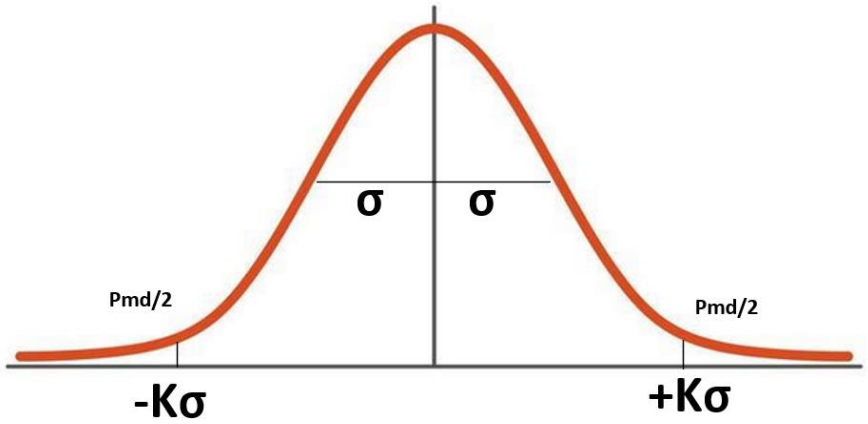
$$\Delta\hat{x} = (G^T W G)^{-1} G^T W \Delta\hat{y} \quad \text{and P} = (G^T W G)^{-1}$$

the psuedorange variance, σ_i^2, is inversed and placed on the diagonal term of the Weight matrix W, and G is the geometry matrix

- K value obtained from the CDF which bounds the error tail (contains errors not detected by the system)

- From the ionospheric grid Points, $\sigma_{i,UIRE}^2$ is derived using the obliquity factor and the GIVE

- During solar storms/ionospheric events, $\sigma_{i,UIRE}^2$ is elevated and as each element of the position covariance matrix is directly propoptional to σ_i^2, the protection levels are elevated as well, VPL even more so than the HPL



$$HPL = K_H\, d_{major}$$

$$VPL = K_V d_U$$

d_{major} and d_U given by elements of the covariance matrix,

$$\begin{bmatrix} d_E^2 & d_{EN} & d_{EU} & d_{ET} \\ d_{EN} & d_N^2 & d_{NU} & d_{NT} \\ d_{EU} & d_{NU} & d_U^2 & d_{UT} \\ d_{ET} & d_{NT} & d_{UT} & d_T^2 \end{bmatrix}$$

Credit: SBAS MOPS

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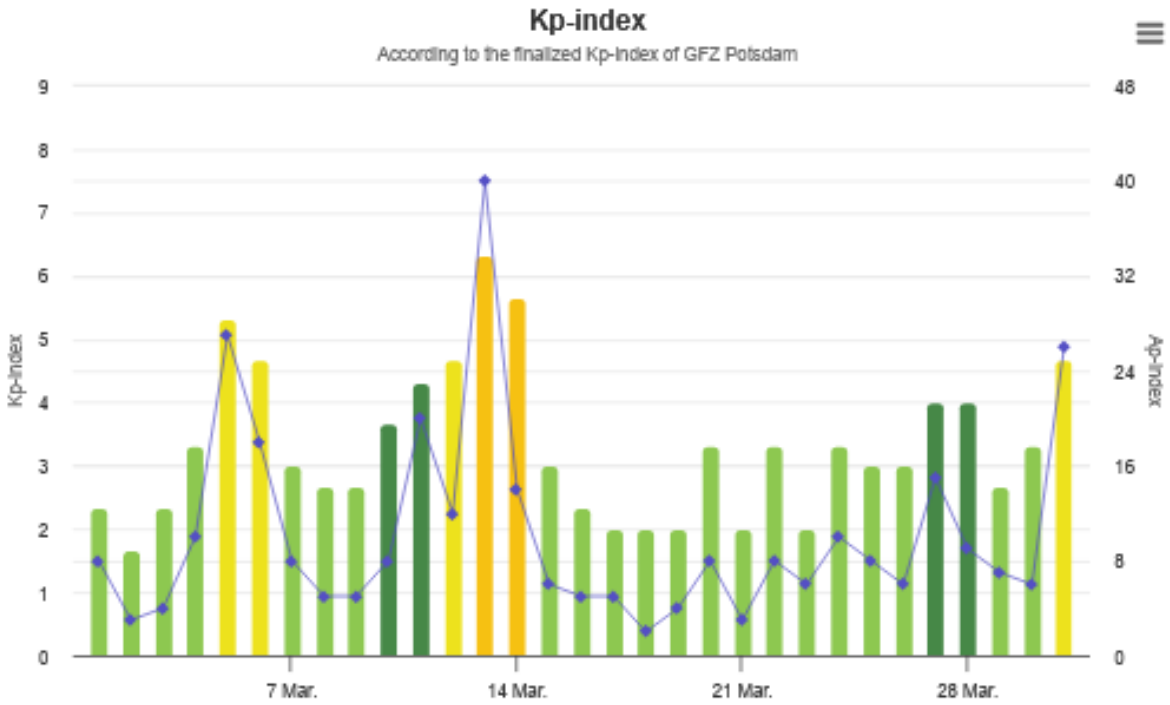
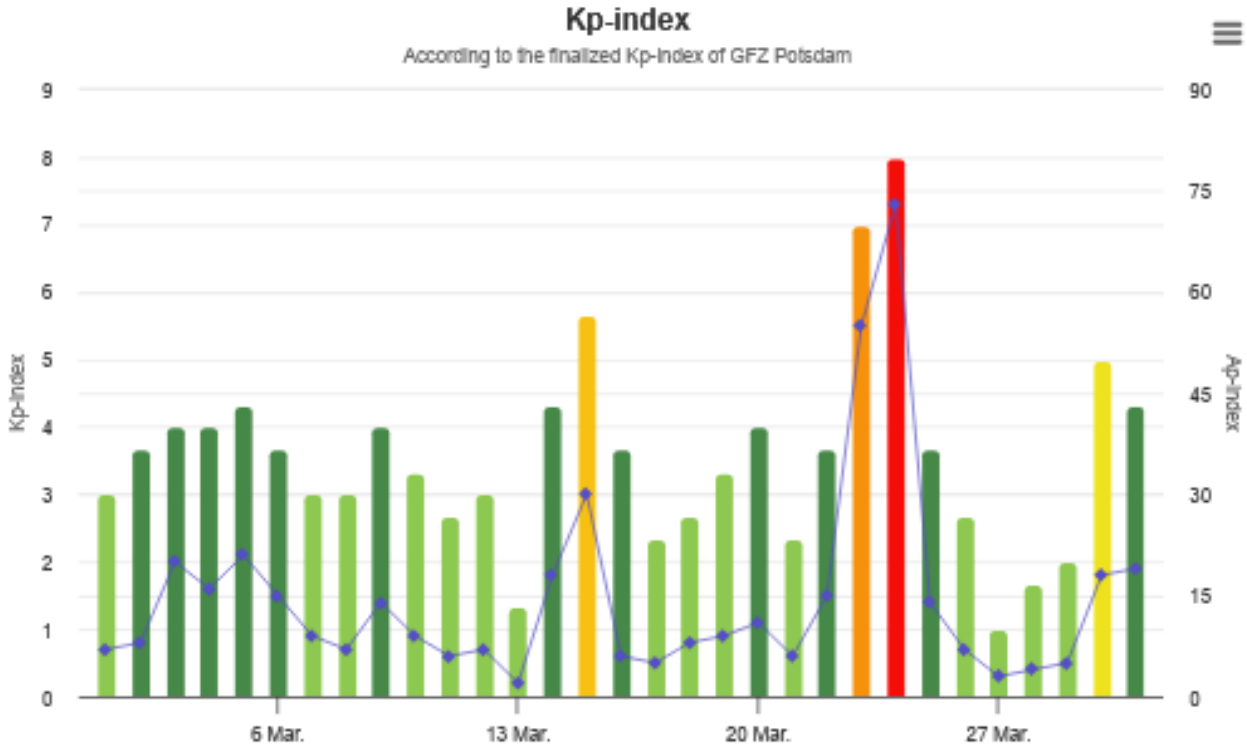
Ionospheric Events: Nominal and Non- Nominal Cases



2022



2023

Kp index tracks the geomagnetic storm and is one of a good indicators of impact on the GNSS performances

Credit: Space Weather Live

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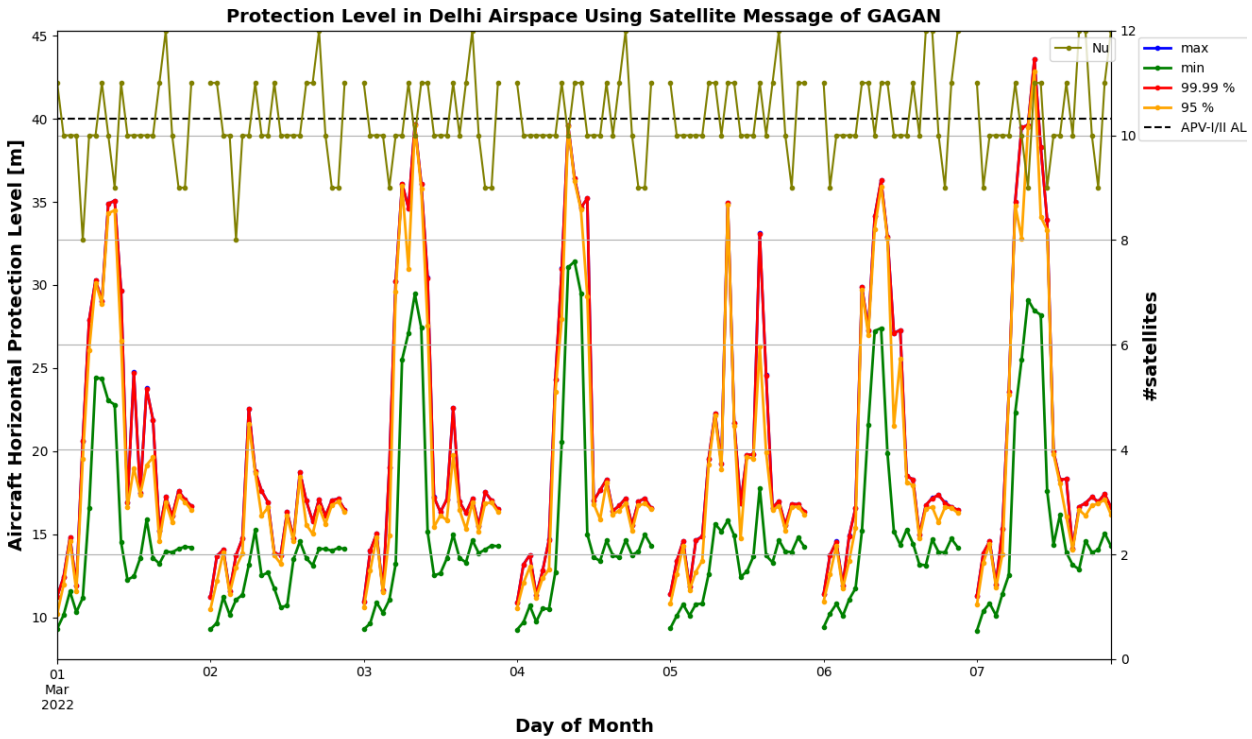
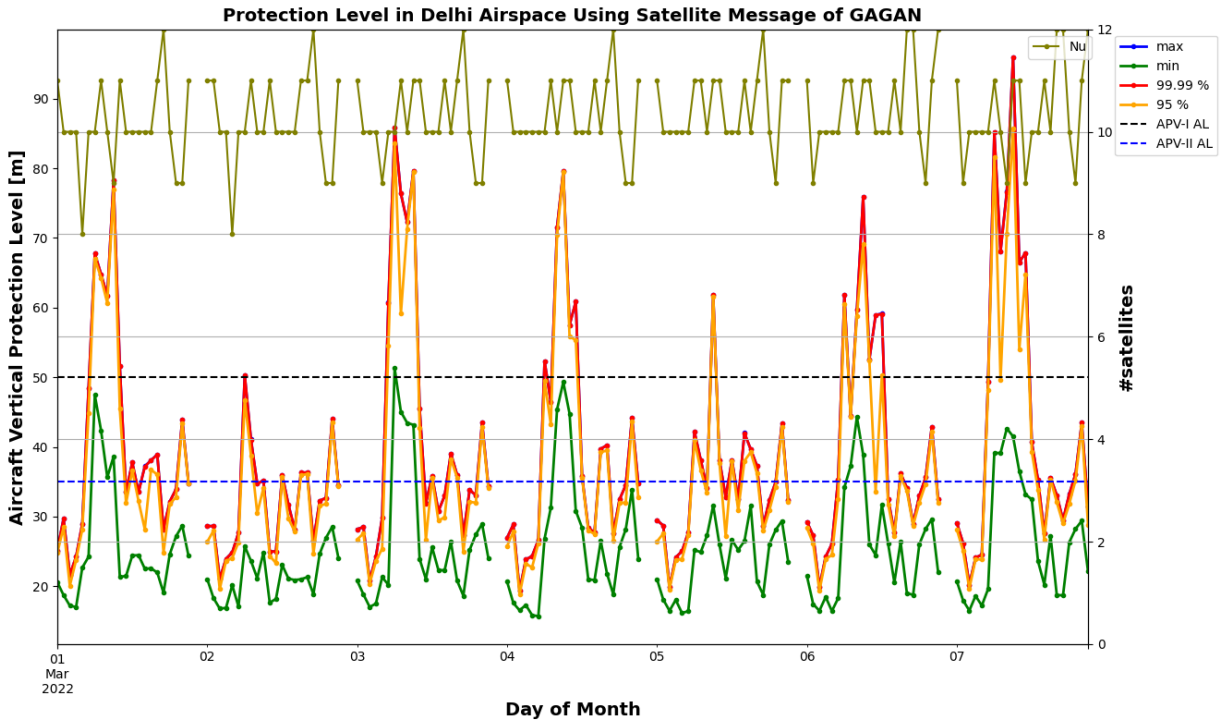
GAGAN Performance: Nominal Days (Kp Index < 5)





- In 2022, March 01 to March 07 provided nominal performance of GAGAN.
- Horizontal Protection Level below 40 m, except for a brief period on 07 March
- Vertical Protection Level fluctuates from one day to the next. The level is inflated in the mid-day, when TEC contents are higher
- APV-I approach is supported but not consistently; RNP 0.1 (i.e, HPL=186 m) is safely assured

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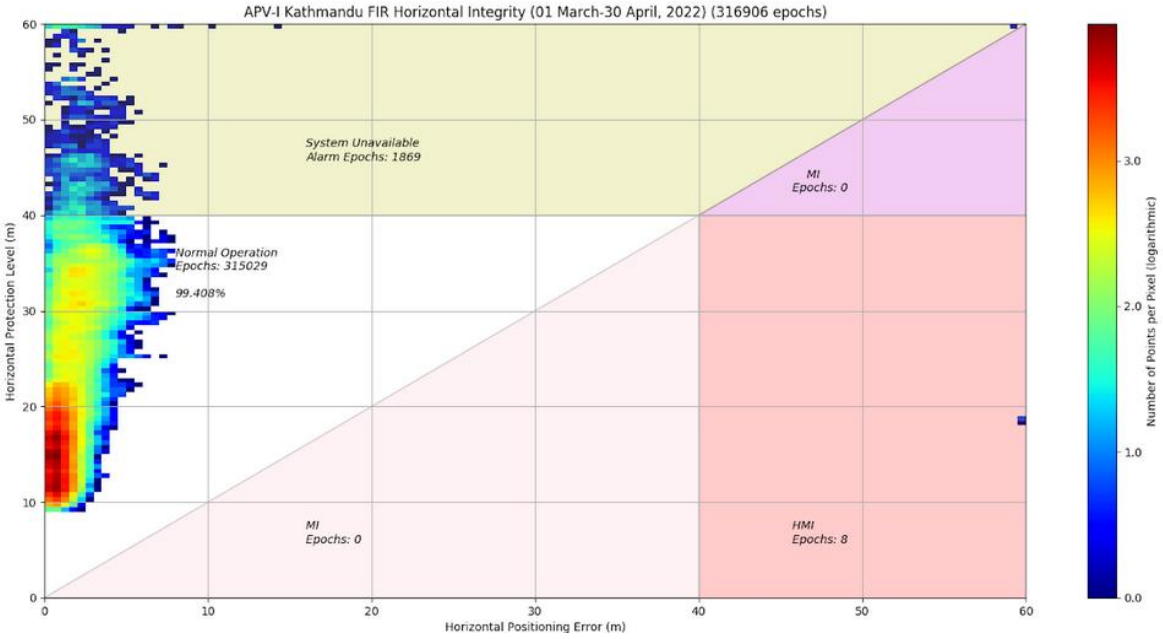
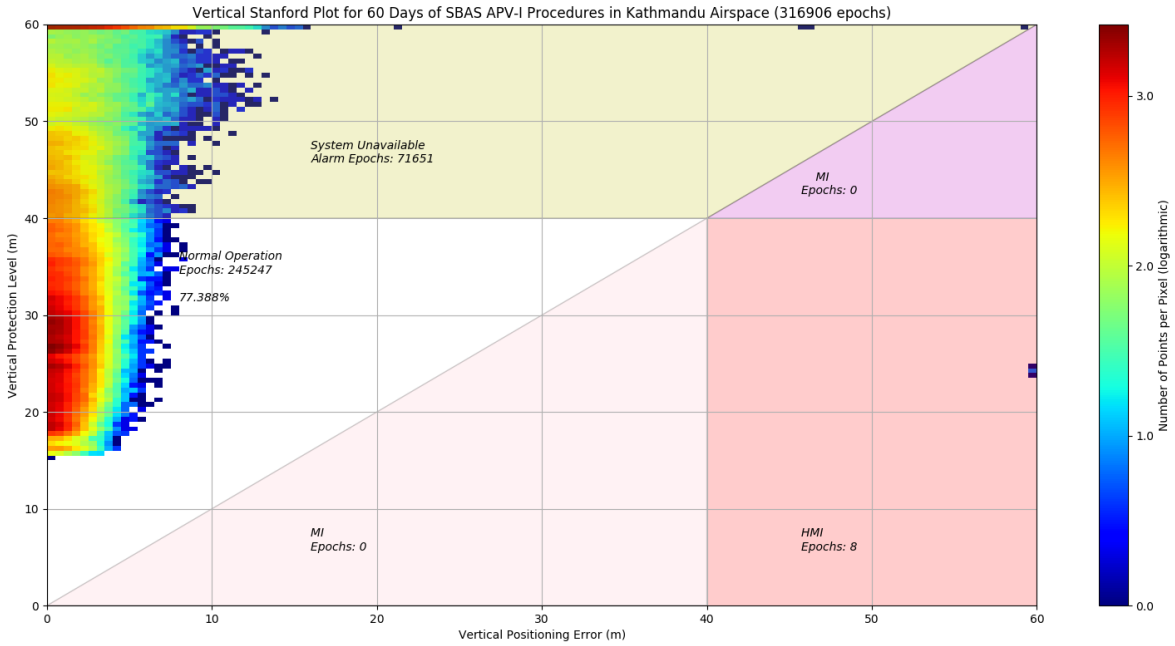
GAGAN Performance with Stanford Plots for Kathmandu Airspace





- APV-I procedure supported only for 77.38 % of the time
- Integrity monitoring reference stations not dense enough for a robust coverage of the observations
- Ionospheric threat model inflates the variance to protect the user, subsequently inflating the protection level
- RNP 0.1 and LNAV procedures are safely enabled

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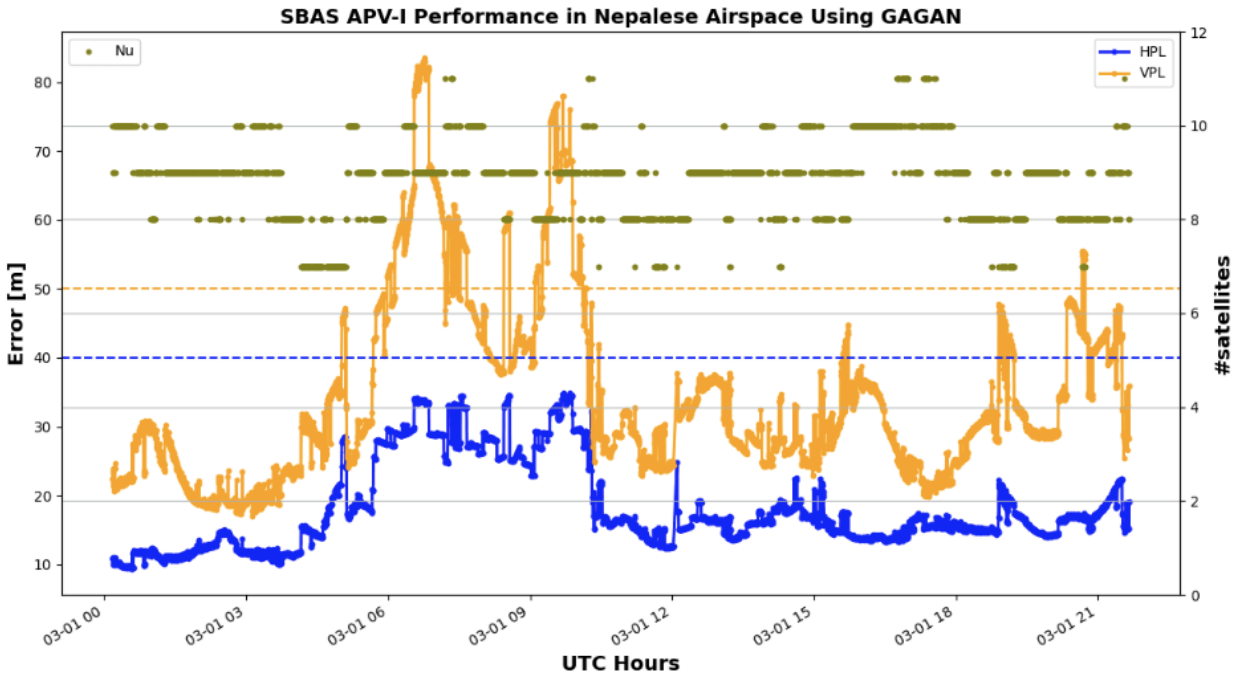
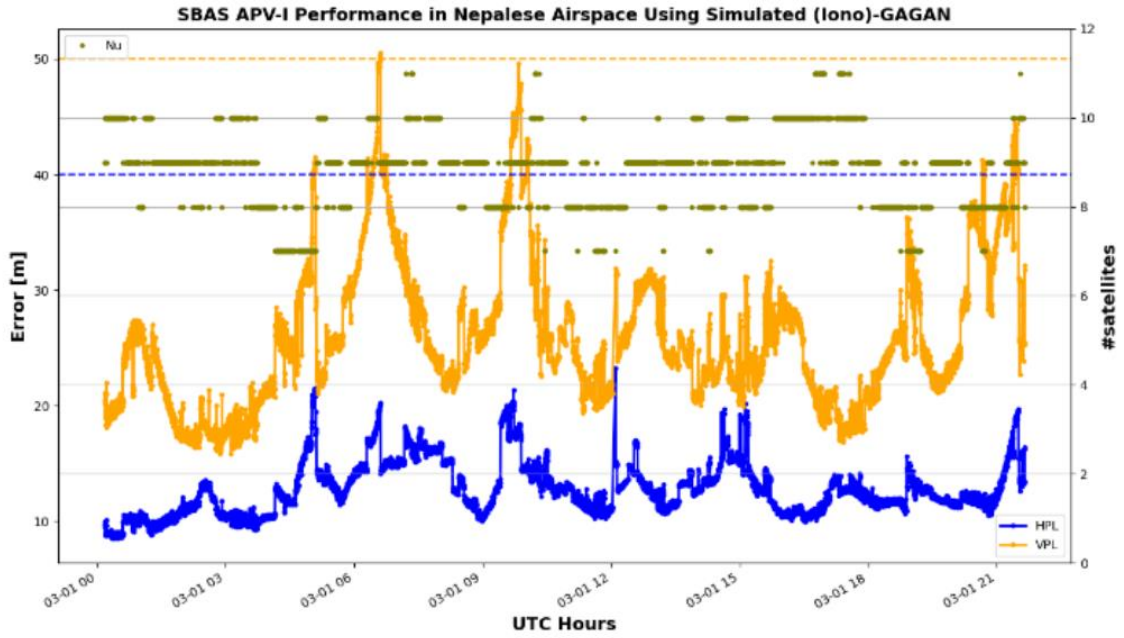
Ionospheric Protection Level with Simulated Variance





Real Data: APV-I Not Achieved **Simulated Data: APV-I Achieved**

- Zero-mean Gaussian distribution assumption allows an independent assessment on the impact of ionospheric on the protection level, all other error confidence terms being unchanged
- ESA SBAS MENTOR software used to simulate the GAGAN message with better iono variance (through GIVE index)

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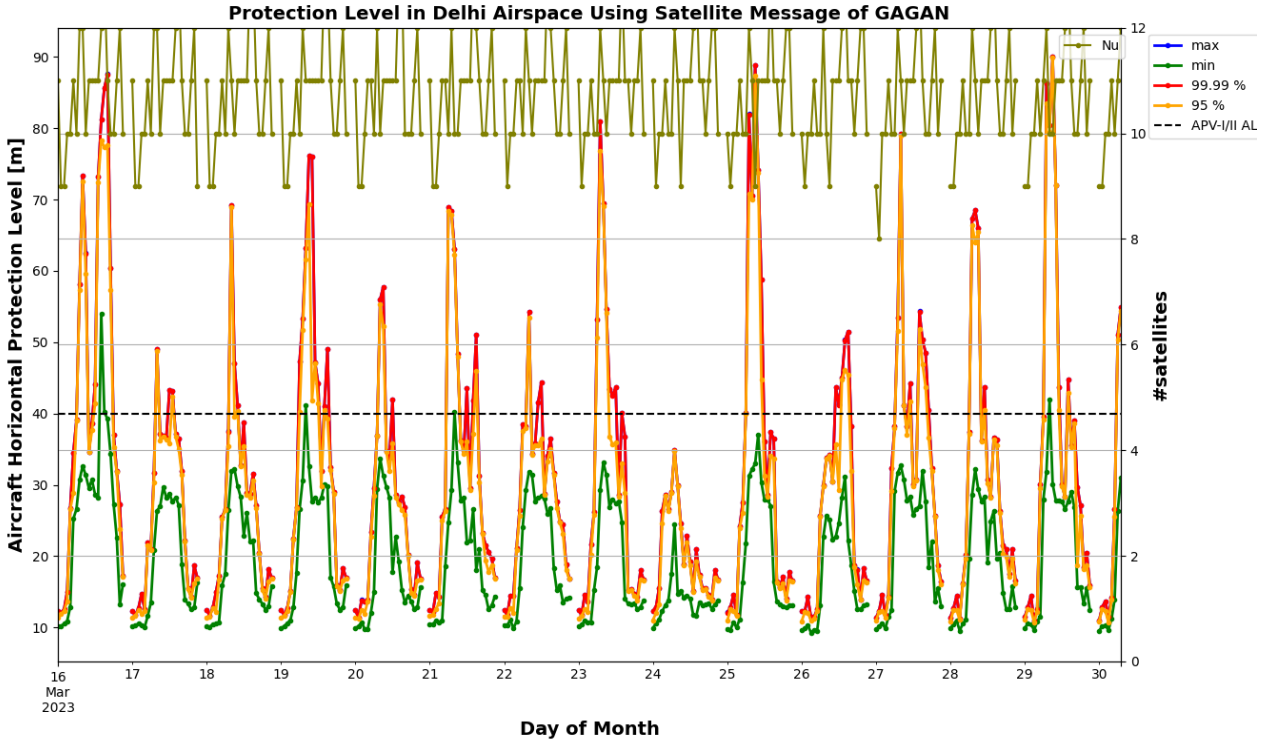
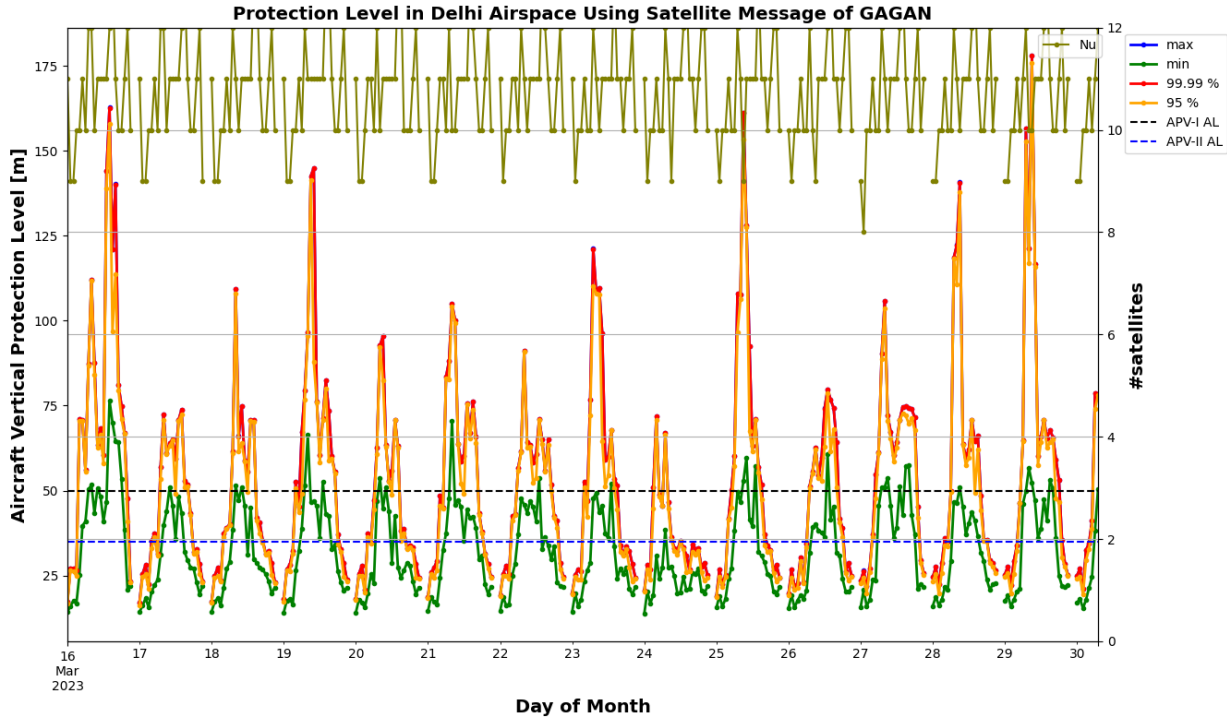
GAGAN Performance: High Geomagnetic Storm

- Higher ionospheric activities, Kp index > 7 (24 March, 2023)
- Both VPL and HPL elevated
- AVP-I not met for vast majority of the period





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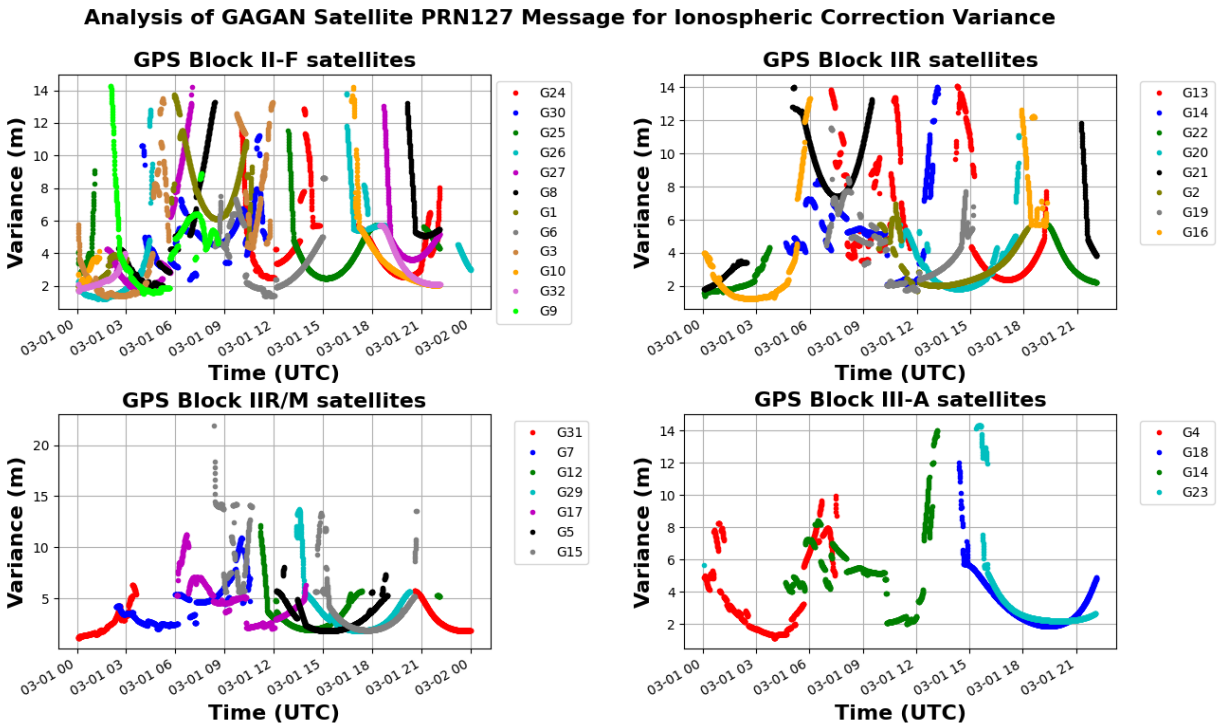
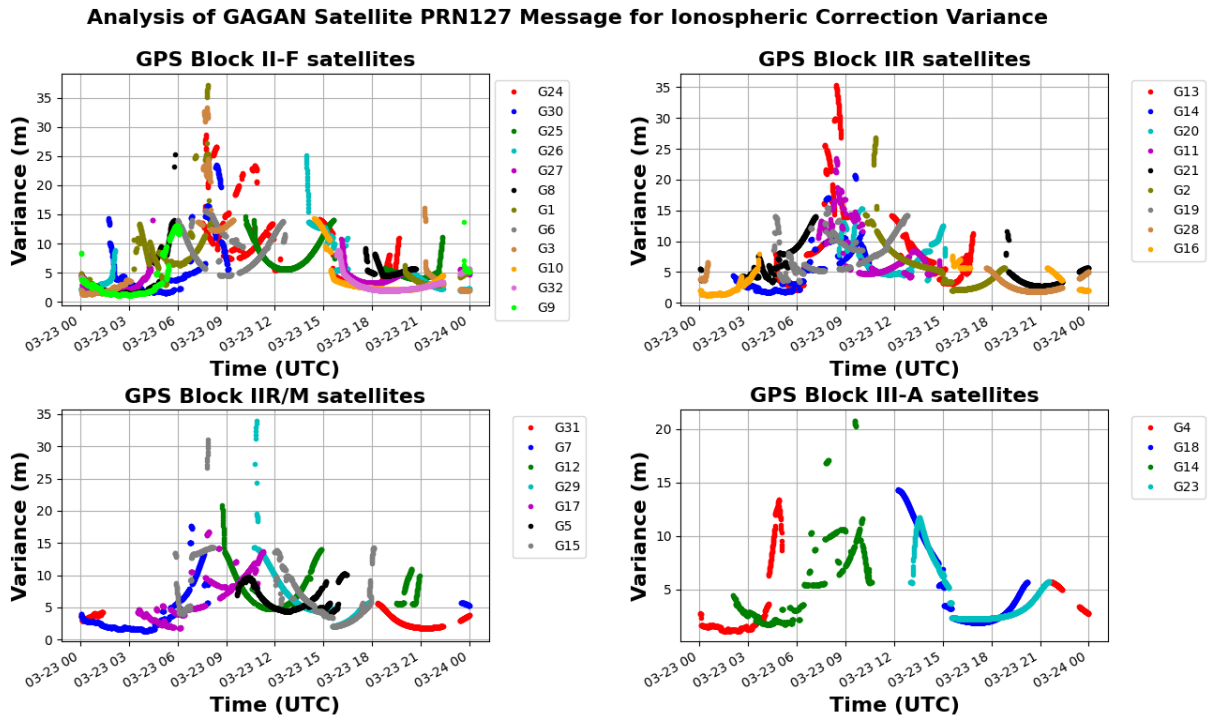
Ionospheric Variance from the GAGAN Threat Model



Nominal Kp Index < 5 (March 01, 2022)



Geomagnetic Storm Kp Index > 7 (March 23, 2023)

- The GAGAN ionospheric threat model inflated the Grid Ionospheric Variance Error during geomagnetic storm
- The confidence of the User Ionospheric Vertical Error also degraded as seen in the analysis plots
- Each satellite signal is impacted in comparison to the nominal day

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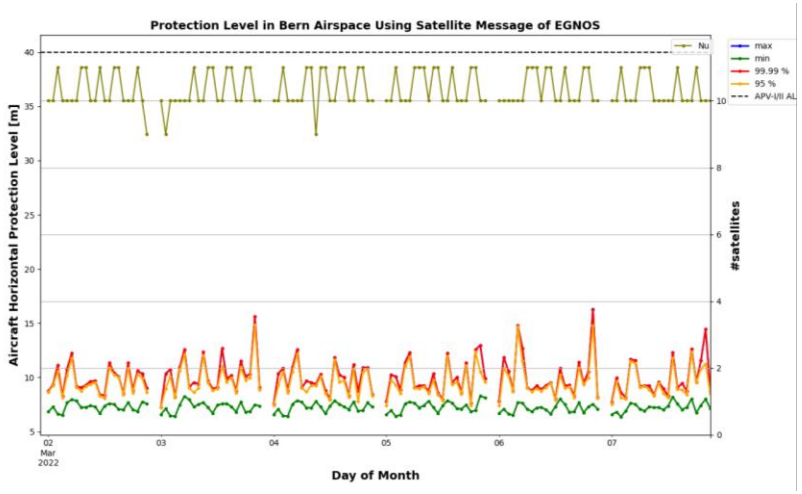
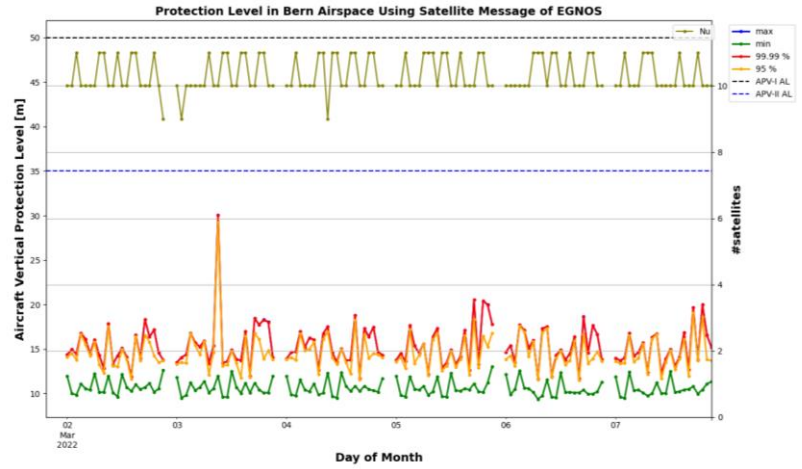
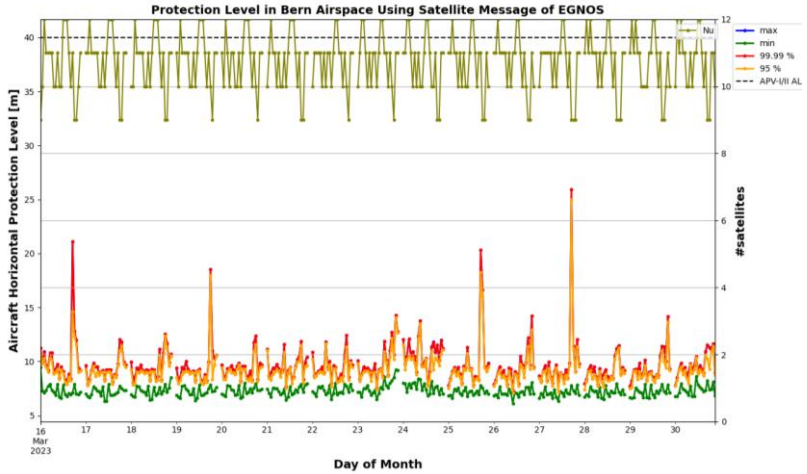
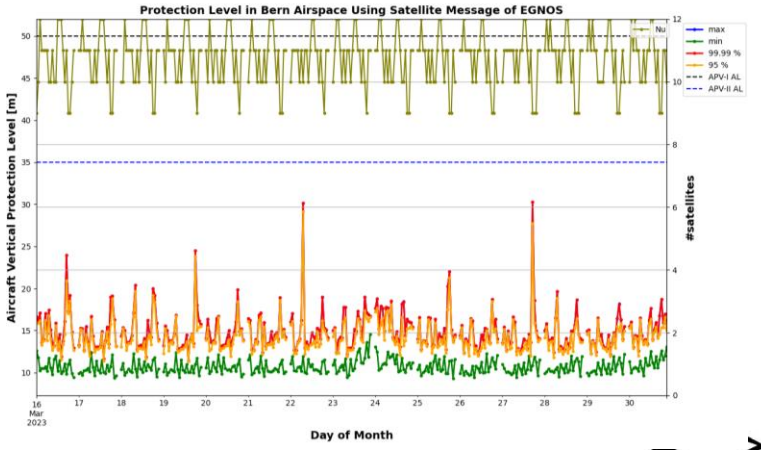
Comparsion with Global Systems: EGNOS Coverage Center

- Zimmerwald, near Bern, the performance for both nominal and non-nominal situations meet APV-I and II
- EGNOS central coverage is strong through last software updates
- Higher confidence in the ionospheric corrections
- Minor inflation is observed on 24 March, where Kp index > 7.4









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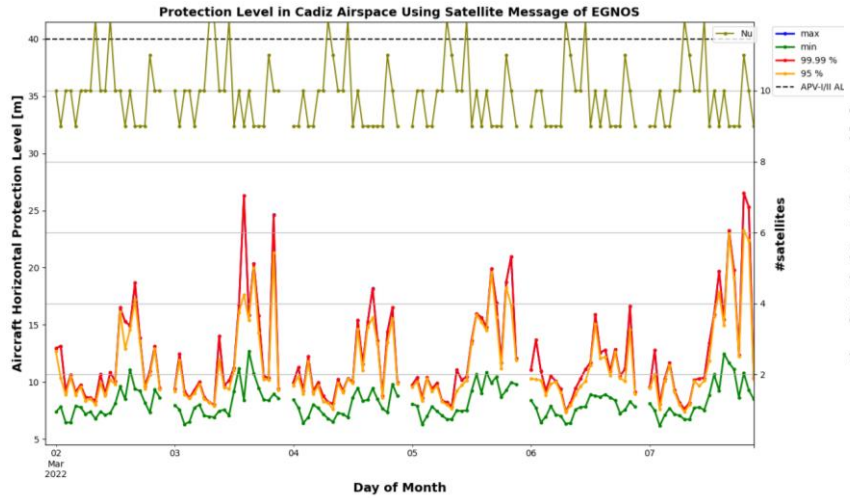
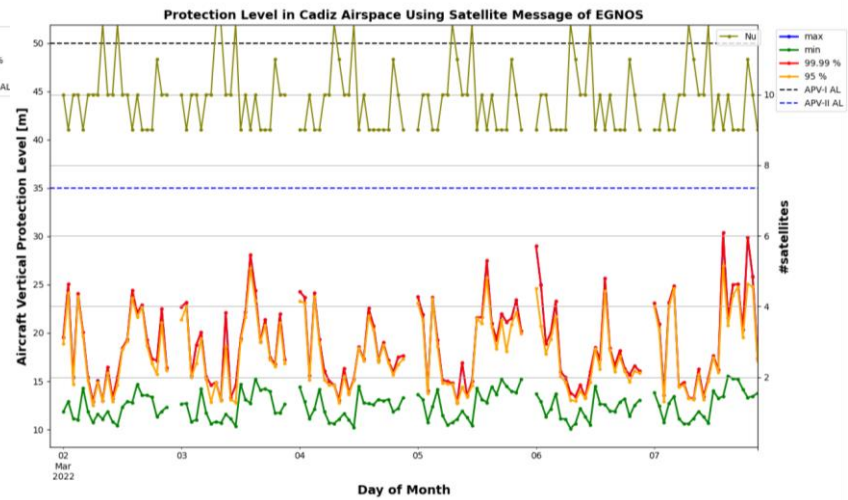
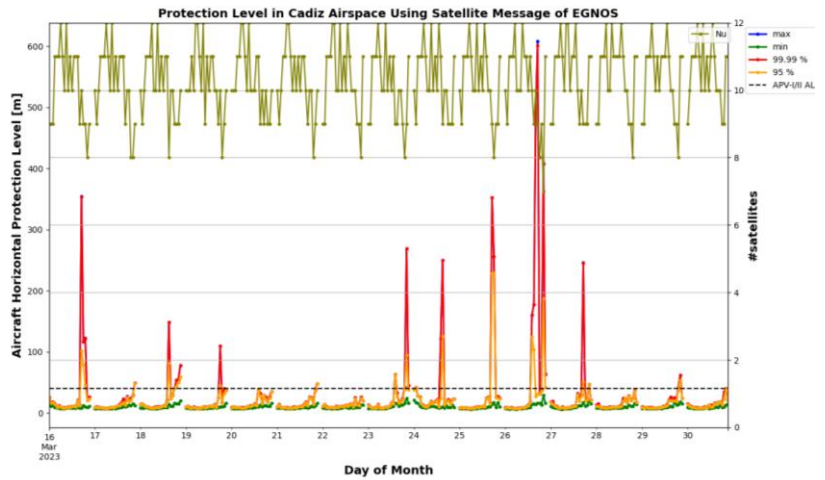
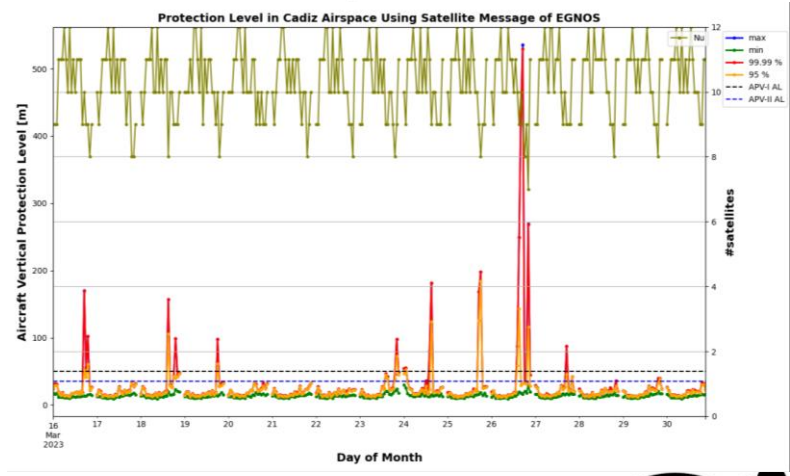
Comparsion with Global Systems: EGNOS Coverage Edge

- ROAG, near Cadiz, Spain, the performance for nominal days supports both APV-I and APV-II
- Protection levels are slightly elevated in comparison to Bern
- In geomagnetic storm, weak confidence in the ionospheric corrections
- Major inflation of protection level is observed several days in March, 2023
- The edge of EGNOS coverage has relatively poorer observation of ionospheric pierce points









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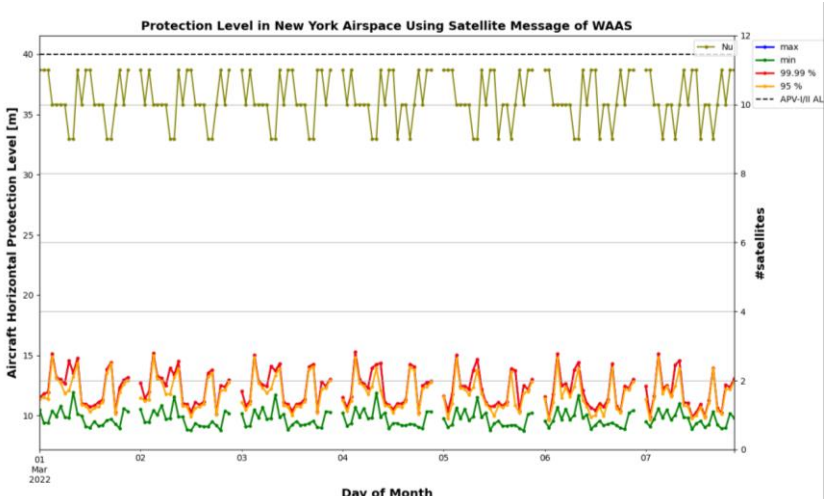
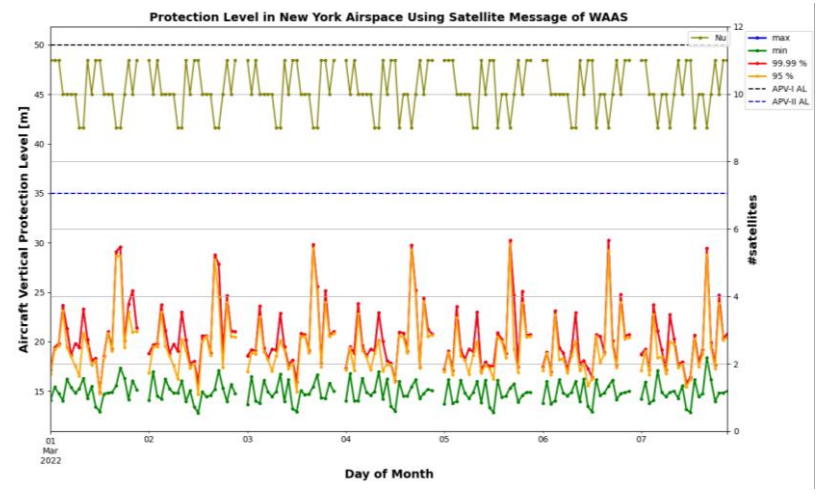
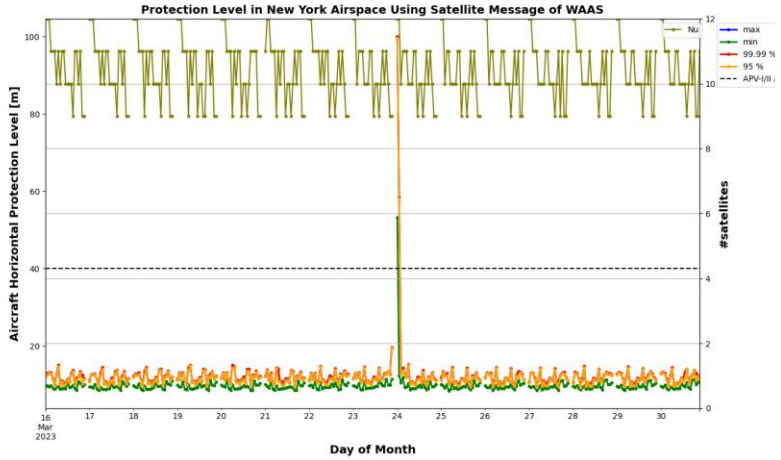
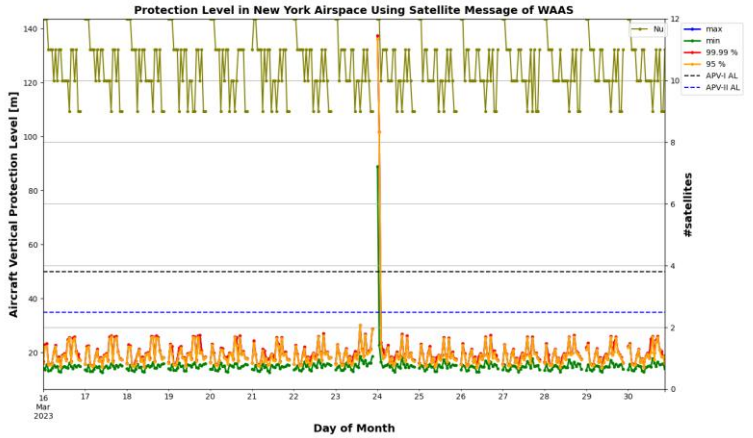
Comparsion with Global Systems: WAAS

- New York, the performance for nominal days supports both APV-I and APV-II
- In geomagnetic storm, Kp index > 7.4 triggered a big inflation in the protection level
- APV-I and APV-II availability impacted









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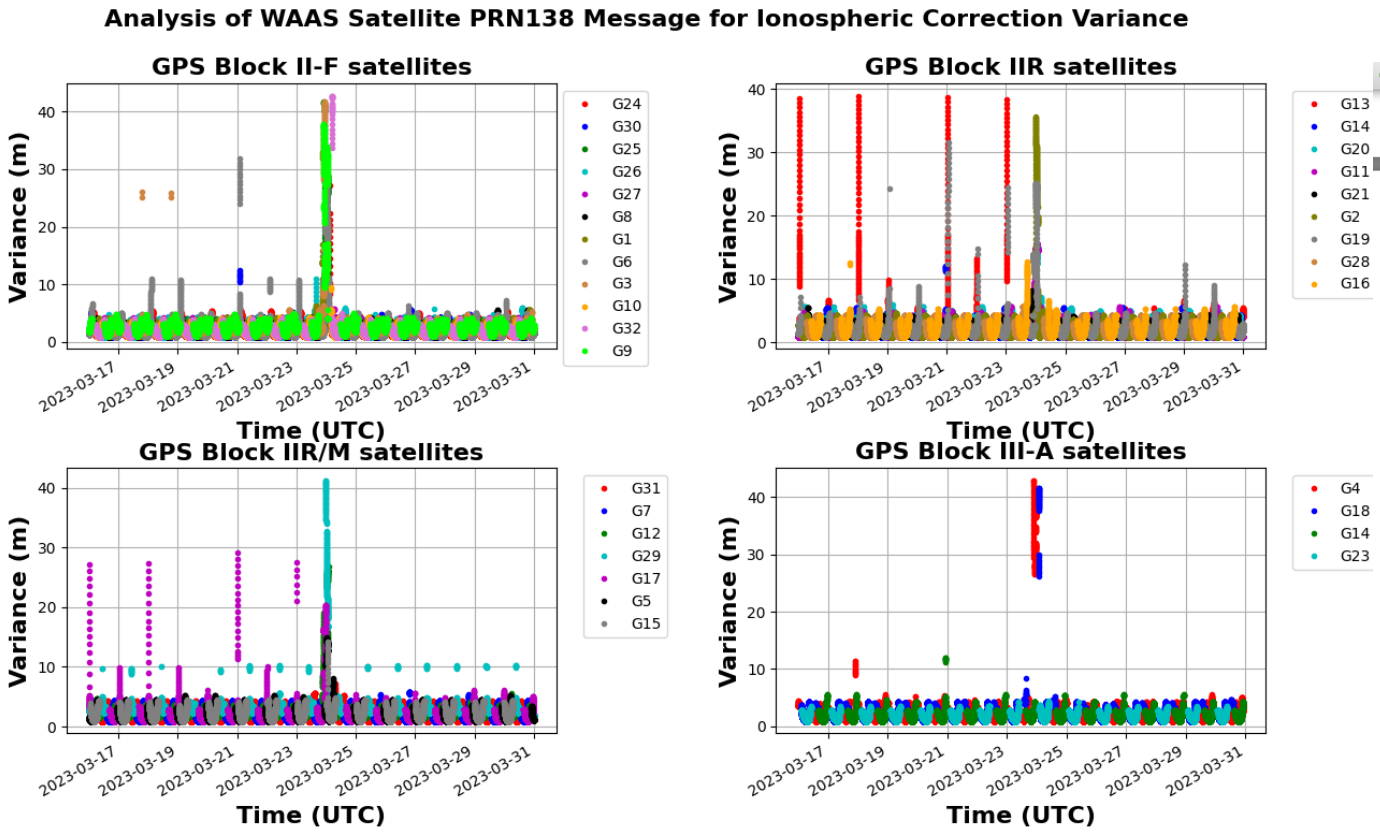
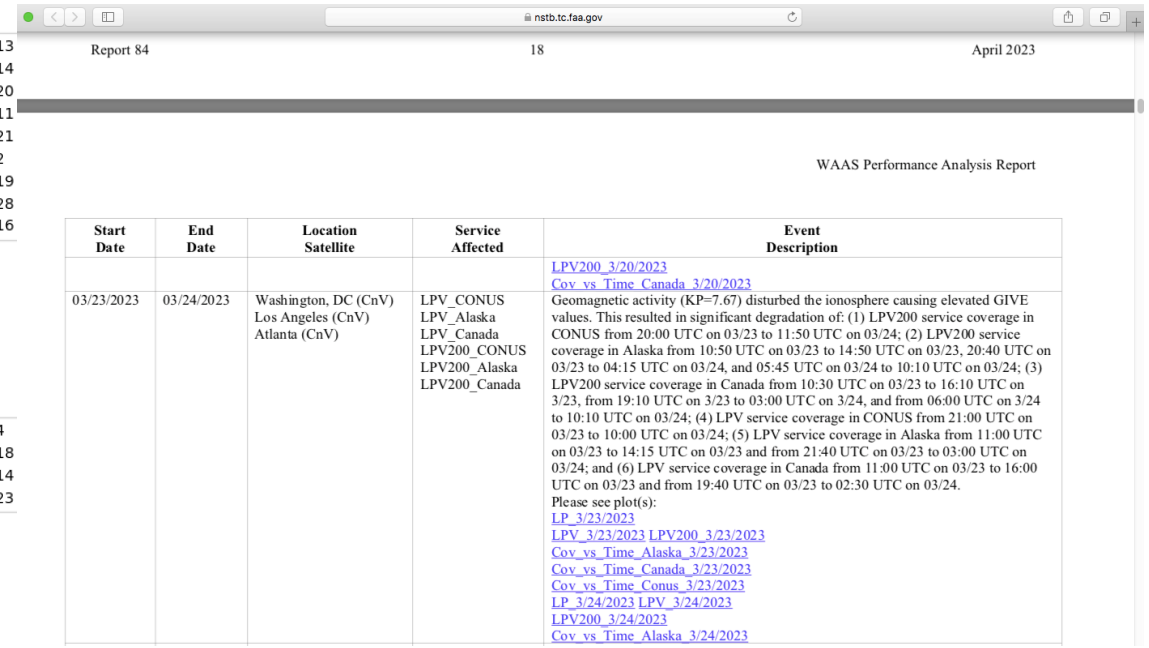
Ionospheric Variance from the WAAS Threat Model





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Report 84 18 April 2023

WAAS Performance Analysis Report

Start Date	End Date	Location Satellite	Service Affected	Event Description
				LPV200_3/20/2023 Cov_vs_Time_Canada_3/20/2023
03/23/2023	03/24/2023	Washington, DC (CnV) Los Angeles (CnV) Atlanta (CnV)	LPV_CONUS LPV_Alaska LPV_Canada LPV200_CONUS LPV200_Alaska LPV200_Canada	Geomagnetic activity (KP=7.67) disturbed the ionosphere causing elevated GIVE values. This resulted in significant degradation of: (1) LPV200 service coverage in CONUS from 20:00 UTC on 03/23 to 11:50 UTC on 03/24; (2) LPV200 service coverage in Alaska from 10:50 UTC on 03/23 to 14:50 UTC on 03/23, 20:40 UTC on 03/23 to 04:15 UTC on 03/24, and 05:45 UTC on 03/24 to 10:10 UTC on 03/24; (3) LPV200 service coverage in Canada from 10:30 UTC on 03/23 to 16:10 UTC on 3/23, from 19:10 UTC on 3/23 to 03:00 UTC on 3/24, and from 06:00 UTC on 3/24 to 10:10 UTC on 03/24; (4) LPV service coverage in CONUS from 21:00 UTC on 03/23 to 10:00 UTC on 03/24; (5) LPV service coverage in Alaska from 11:00 UTC on 03/23 to 14:15 UTC on 03/23 and from 21:40 UTC on 03/23 to 03:00 UTC on 03/24; and (6) LPV service coverage in Canada from 11:00 UTC on 03/23 to 16:00 UTC on 03/23 and from 19:40 UTC on 03/23 to 02:30 UTC on 03/24. Please see plot(s): LP_3/23/2023 LPV_3/23/2023 LPV200_3/23/2023 Cov_vs_Time_Alaska_3/23/2023 Cov_vs_Time_Canada_3/23/2023 Cov_vs_Time_Conus_3/23/2023 LP_3/24/2023 LPV_3/24/2023 LPV200_3/24/2023 Cov_vs_Time_Alaska_3/24/2023

Credit: FAA

- Geomagnetic storm on the 23 March impacted the WAAS Ionospheric Grid variance
- FAA WAAS quarterly report indicates impact in numerous flight regions in the US and Canada

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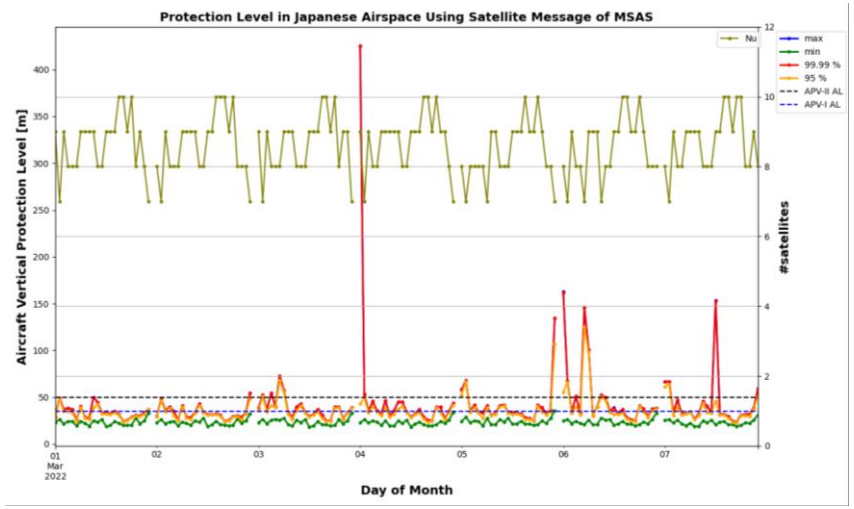
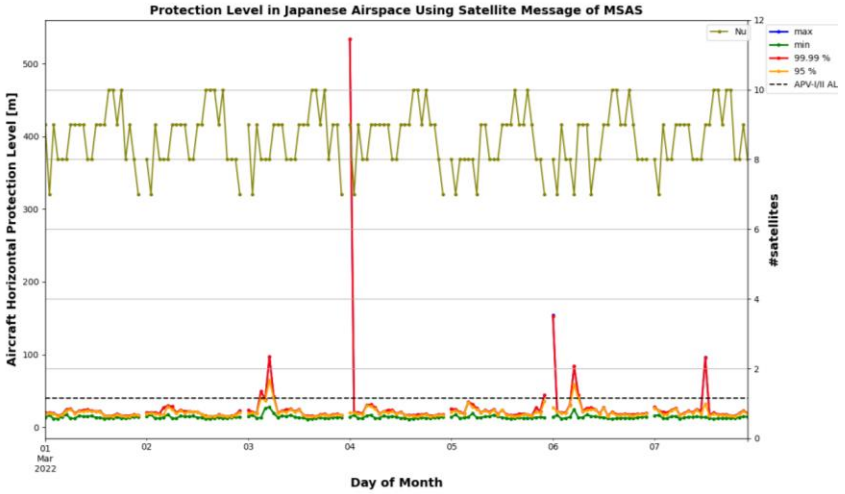
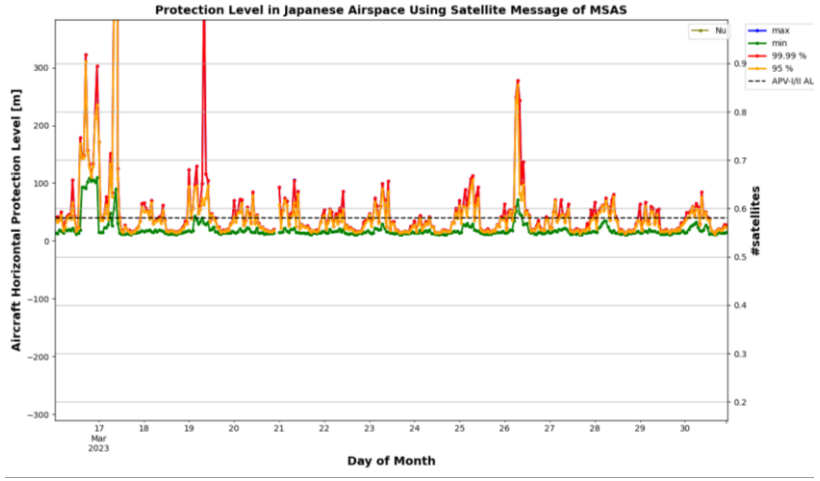
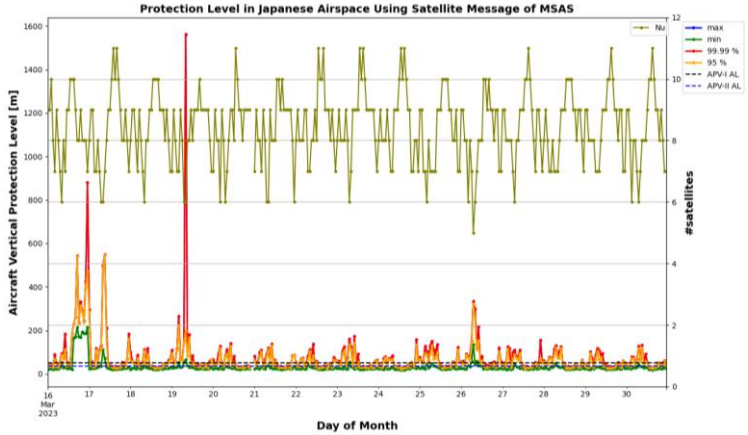
Comparsion with Global Systems: MAAS

- Japanese airspace, the performance for nominal days does not support either of APV-I and APV-II. RNP 0.1 supported.
- In high ionospheric activities, March 2023, big inflation in the protection level observed
- In some days, horizontal procedures (RNP 0.1,..) are also impacted
- In general, threat space is larger in Japanese system due to less integrity monitoring stations and severe ionospheric conditions









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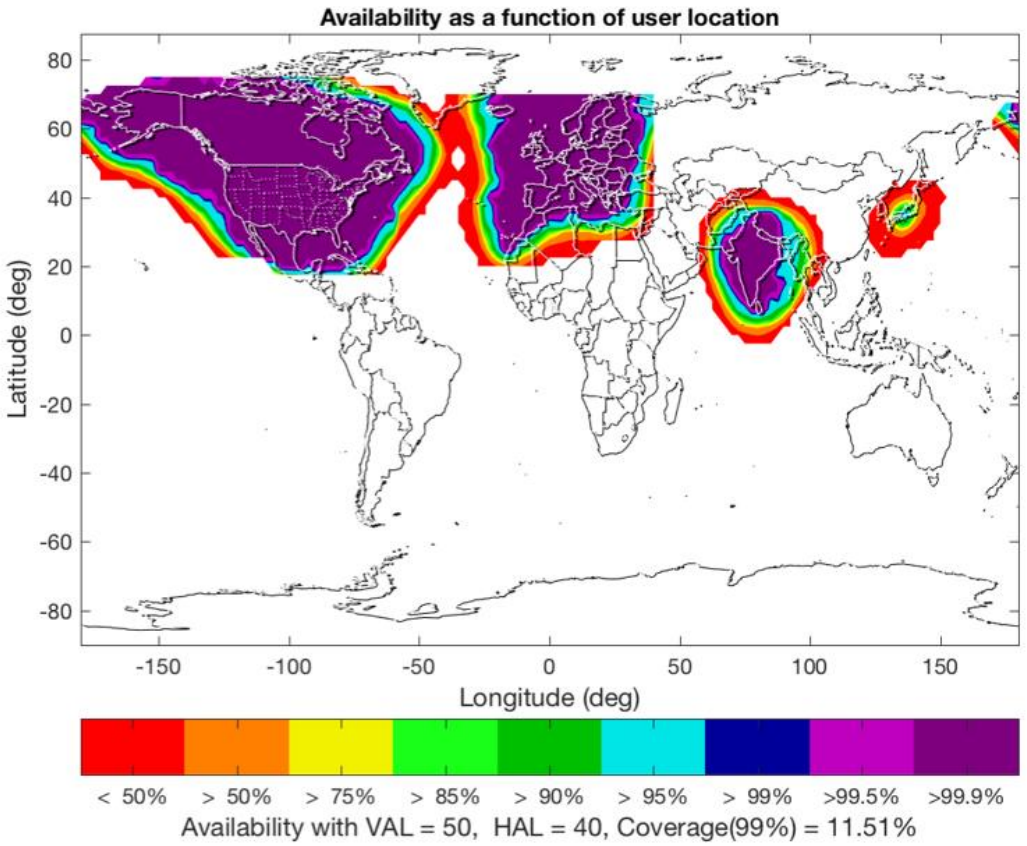
Summary

- The GAGAN performance in the nominal ionospheric days match availability indicators provided by service operators
- GAGAN APV-I is not consistently met in the coverage zone; even where it is met, the protection levels are just below the border line
- During enhanced ionospheric events, GAGAN APV-I requirement can be easily violated
- GAGAN integrity monitoring stations are planned to be increased which has potentials to support also the neighbouring countries
- Enhanced GAGAN ionospheric threat model will increase the availability
- GAGAN performs better than MSAS but lags behind WAAS and EGNOS
- 24 March, 2023, Kp >7 impacted all SBAS systems in a varying degree



Credit: FAA (2022)

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Special Thanks To

- SBAS Raw Messages Data (CNES Public ftp Server)
- GPS RINEX Data (UNAVCO)
- GPS Navigation Data (CDDIS)
- SBAS Message Analysis Tool (ESA SBAS Mentor)
- SBAS User Level Protection Analysis (PEGASUS and gLAB)

Thank You Very Much for Listening

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