Inclined Geosynchronous Satellite Augmentation to Maximize Availability of Integrity for Future SBAS and ARAIM Users

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ION ITM 2022 **Long Beach, CA**

27 January 2022

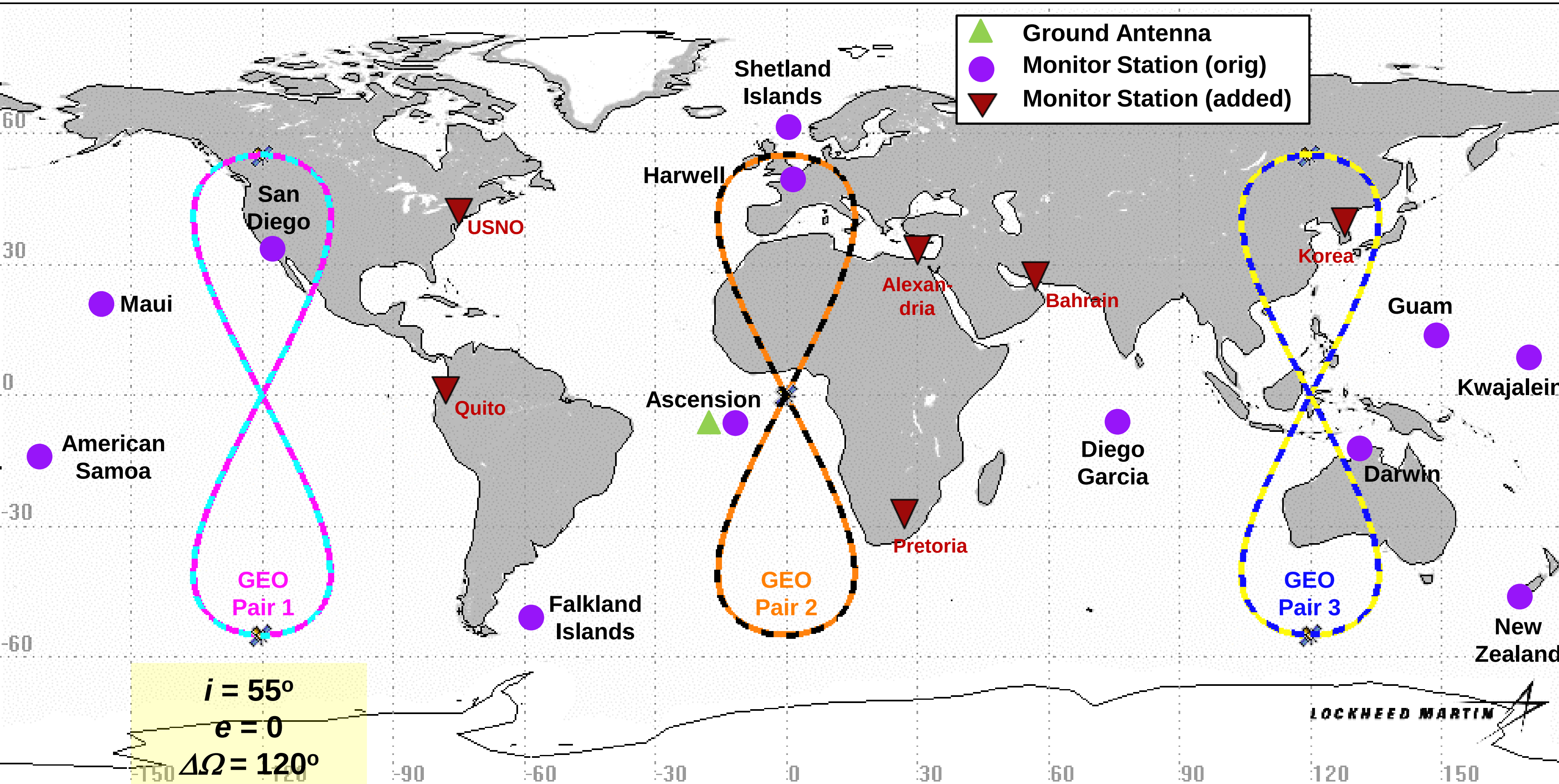
Outline

- Inclined geosynchronous satellite (I-GEO) concept
- SBAS and ARAIM integrity concepts
- Results before and after including I-GEOs
  - SBAS integrity application
  - ARAIM integrity application
- Summary and Ongoing Work

Motivation for Inclined GEO Satellites

- Inclined GEOs proposed by Lockheed Martin are satellites in roughly circular orbits at GEO altitude with 55 degrees inclination (similar to GPS satellites).
- In this concept, they carry navigation payloads and thus provide signal-in-space accuracy similar to that of Block III GPS satellites.
- They also broadcast SBAS-like messages to support SBAS-like accuracy and integrity.
- Thus, they support both SBAS and Advanced RAIM (ARAIM) approaches to integrity.
- One proposed configuration shown on next slide…

6 Inclined GEO SVs (in 3 Planes) and 19-RS Network



$i = 55^{o}$
$e = 0$
$\Delta\Omega = 120^{o}$
$\Delta M = 180^{o}$

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SBAS and ARAIM Integrity Differences

- **SBAS integrity is based on using broadcast error bounds to compute protection levels for measurements approved by SBAS [4].**

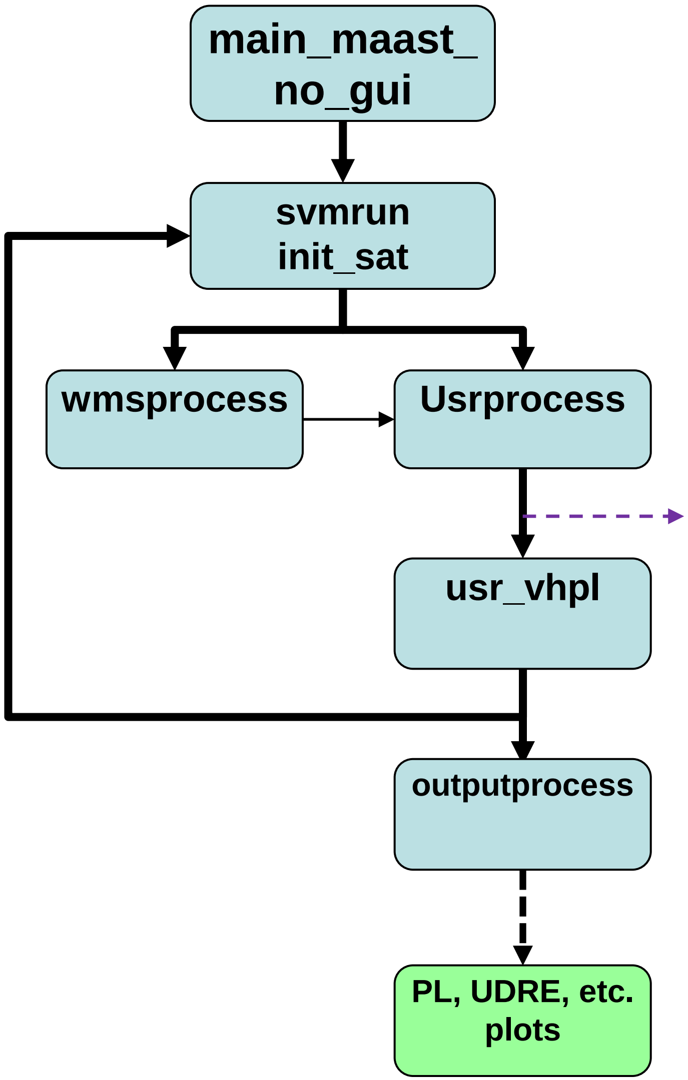
$$VPL_{SBAS\_PA} = K_{V\_PA}\,\mathbf{S}[3,3] \qquad \mathbf{S} = \left(\mathbf{G}^{\mathrm{T}}\,\mathbf{W}\,\mathbf{G}\right)^{-1}$$

- **ARAIM instead requires real-time confirmation of signal-in-space measurement integrity [5].**
  - **Protection levels based on real-time calculation of position differences between measurement subsets (hypothetical faults) and “all-in-view” solution.**
  - **External error bounds (provided less frequently) are also applied but are not confirmed in real time.**

$$2Q\left(\frac{VPL - b_3^{(0)}}{\sigma_3^{(0)}}\right) + \sum_{k=1}^{N_{fault\ mode}} p_{fault,k}\, Q\left(\frac{VPL - T_{k,3} - b_3^{(k)}}{\sigma_3^{(k)}}\right) =$$

$$PHMI_{VERT}\left(1 - \frac{P_{sat,not\ monitored} + P_{const,not\ monitored}}{PHMI_{VERT} + PHMI_{HOR}}\right)$$

SBAS Monitoring of Satellite Errors: MAAST Simulation ([1])



Main function: defines simulation parameters (e.g., SV almanac, SV and WRS errors, WRS and user locations, fault probabilities, etc.)

Get satellite parameters & run satellite simulation (determine SV positions for each epoch)

WAAS Master Station processing (SV errors only due to use of L1 and L2 for ionosphere removal)

User process calculates range integrity/accuracy error bounds (e.g., UDRE → DFRE)

Perform WAAS protection level calculations

Output results to Matlab data files (when time steps are complete)

Load Matlab data files and plot results (for dual frequency, UDRE = DFRE)

Constellation Integrity Support Parameter Commitments for ARAIM (see [1])

DF = dual-frequency | SF = single-frequency

Parameter	GPS	GPS and LM I-GEOs (with ground monitoring)		
URA	in Nav Data (ICD table)	URA = 1.0 m; URE = 0.63 m; bias = 0.35 m		
URA Threshold	4.42 × URA	URA Threshold based on P_{sat}		
R_{sat}	10^{-5} / hour	$R_{sat} = 5 \times 10^{-7}$ / hour		
P_{sat}	10^{-5}	$P_{sat} = 5 \times 10^{-7}$		
P_{const}	10^{-8} (†)	$P_{const} = 2.5 \times 10^{-9}$		
MFD	1 hour	MFD = 1 hour		
TTA	10 seconds	TTA = 10 seconds		
Sources	SPS PS and NSP6_wp2	NSP6_wp4	NSP6_wp3	NSP6_wp5

(†) Recently proposed $R_{const} = 10^{-9}$ / hour and MFD_{const} = 10 hours

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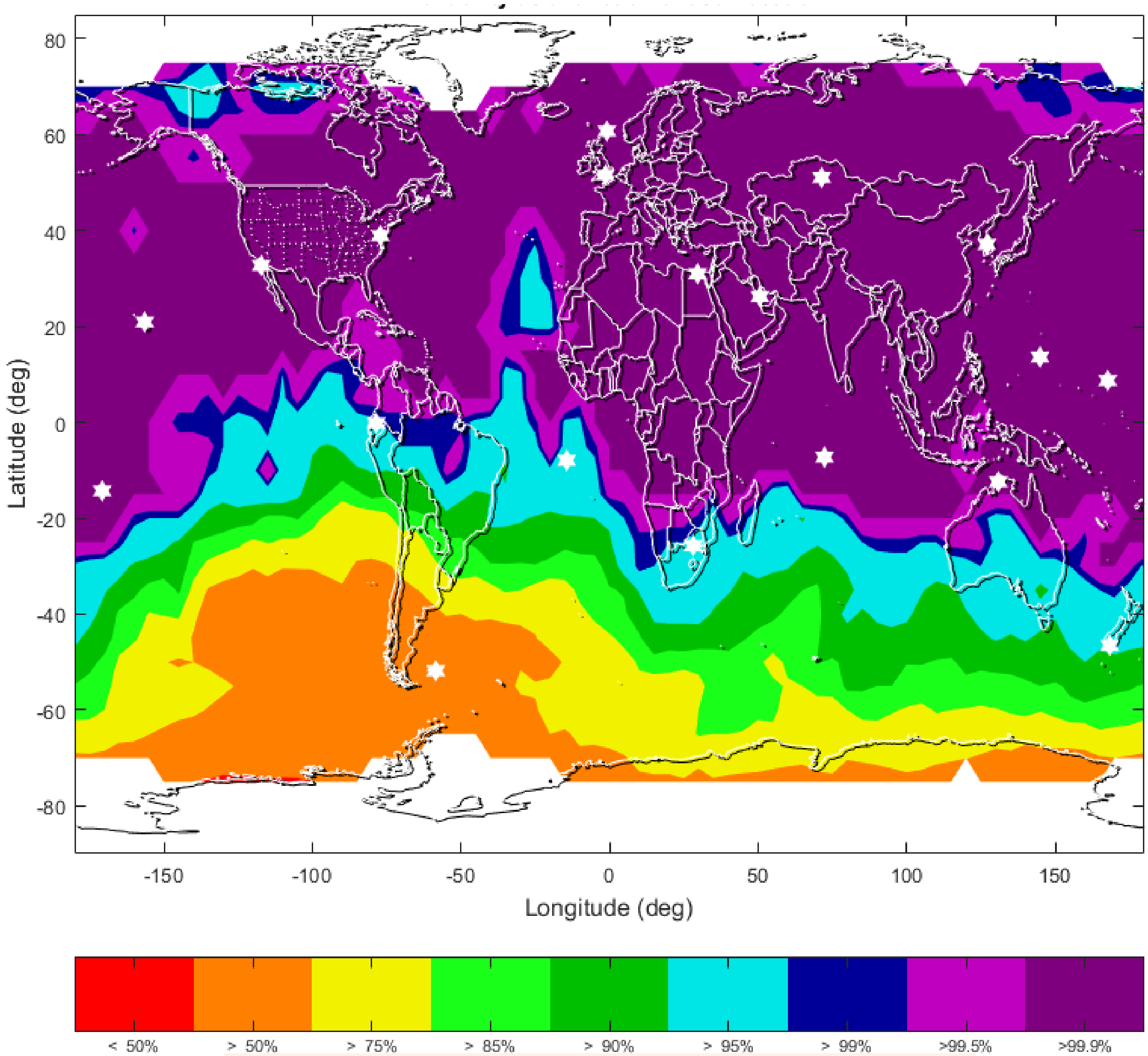
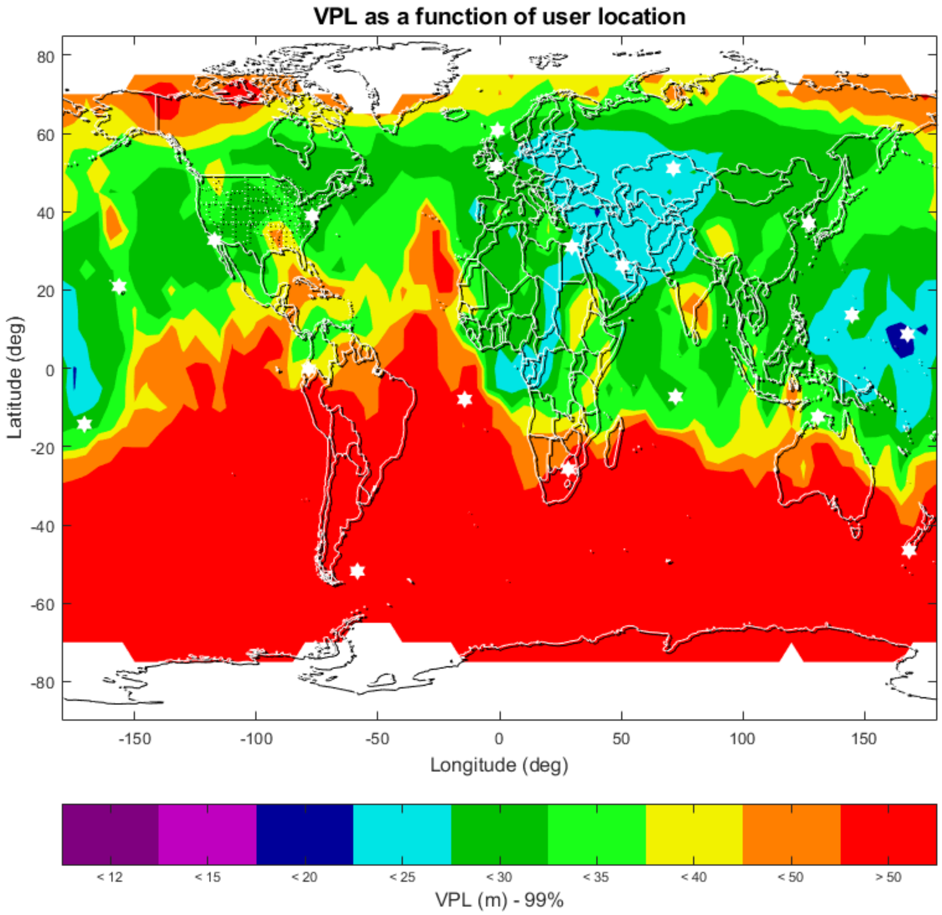
SBAS LPV Approach Availability (24-SV GPS Const., 19 RS, no I-GEOs)



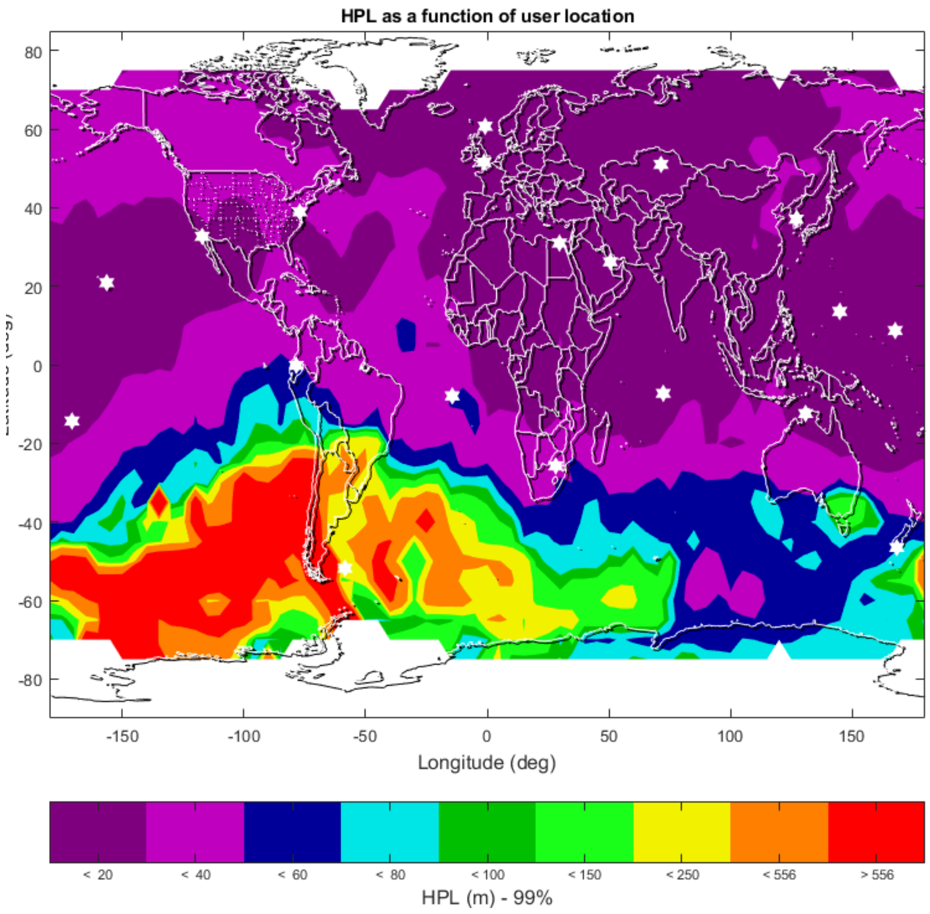
Availability with VAL = 50, HAL = 40, Coverage(99%) = 61.28%

SBAS Protection Level Results (24-SV GPS Const., 19 RS, no I-GEOs)

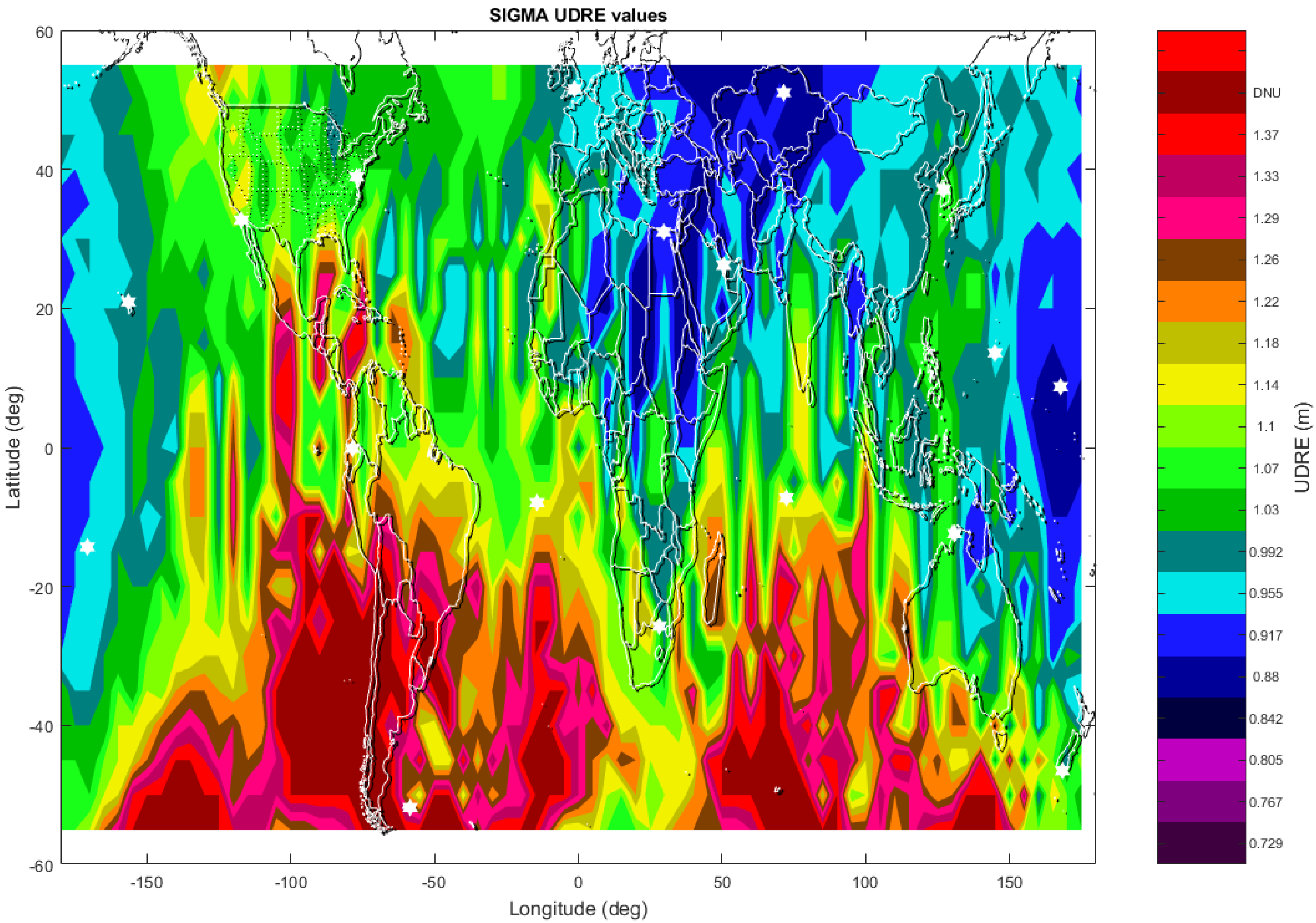
VPL



HPL



SBAS σ_{UDRE} (σ_{DFRE}) Results (24-SV GPS Const., 19 RS, no I-GEOs)

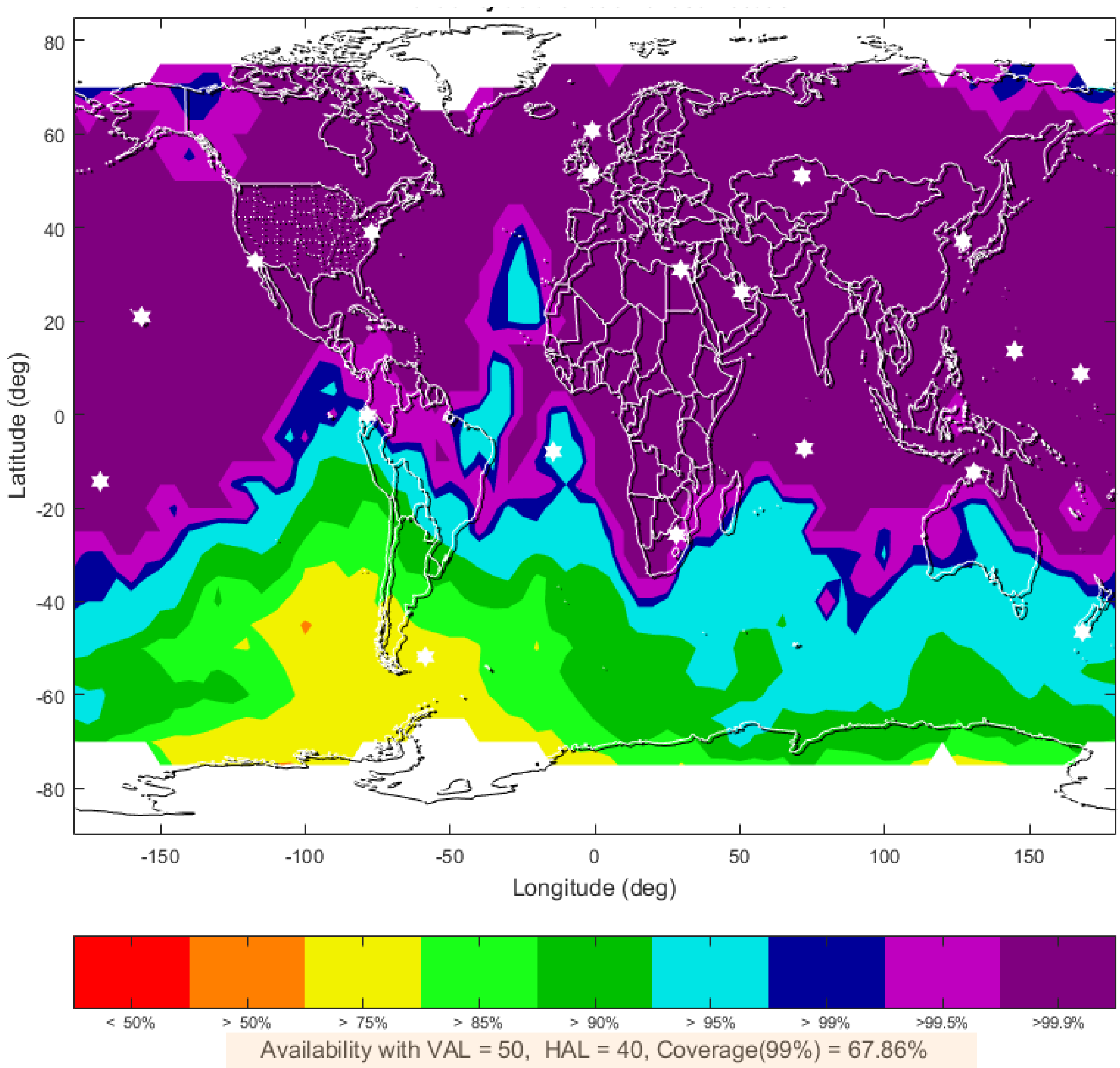


σ_{UDRE} = UDRE / 3.29

99th-percentile σ_{UDRE} discretized from 0.75 to 1.40 in 20 bins

σ_{UDRE} contours discretized into 20 colors

SBAS LPV Approach Availability (24-SV GPS Const., 19 RS, *6 I-GEOs*)



SBAS Protection Level Results (24-SV GPS Const., 19 RS, *6 I-GEOs*)

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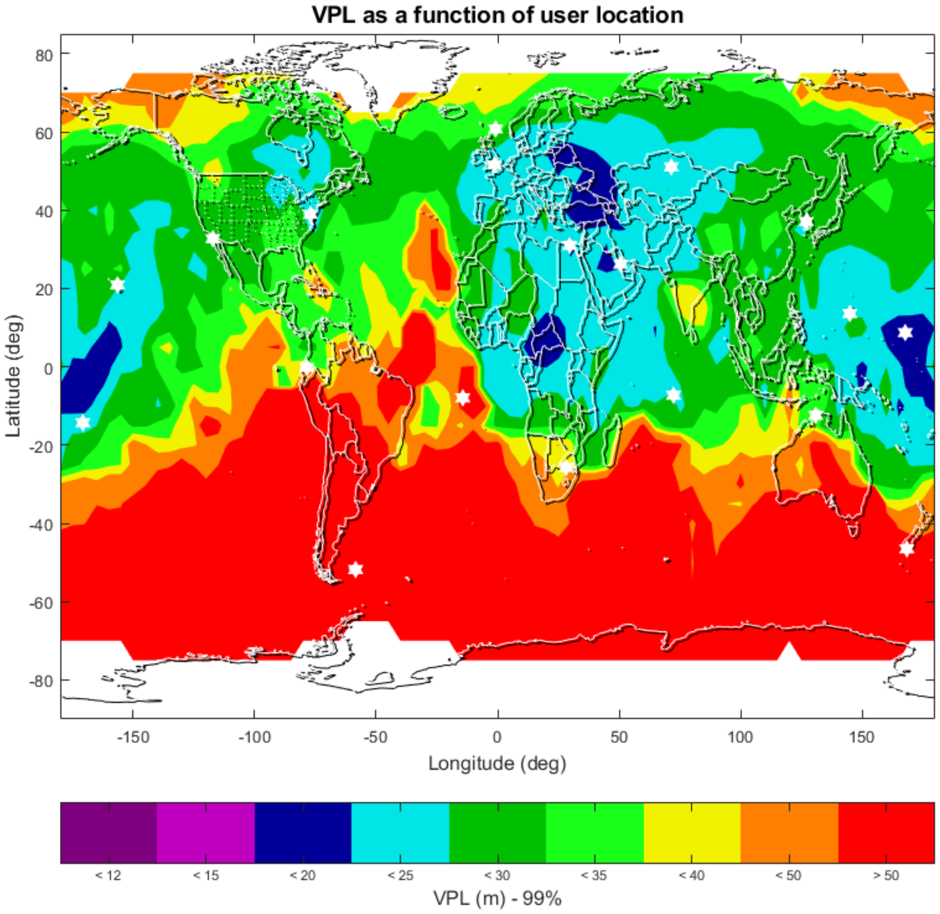
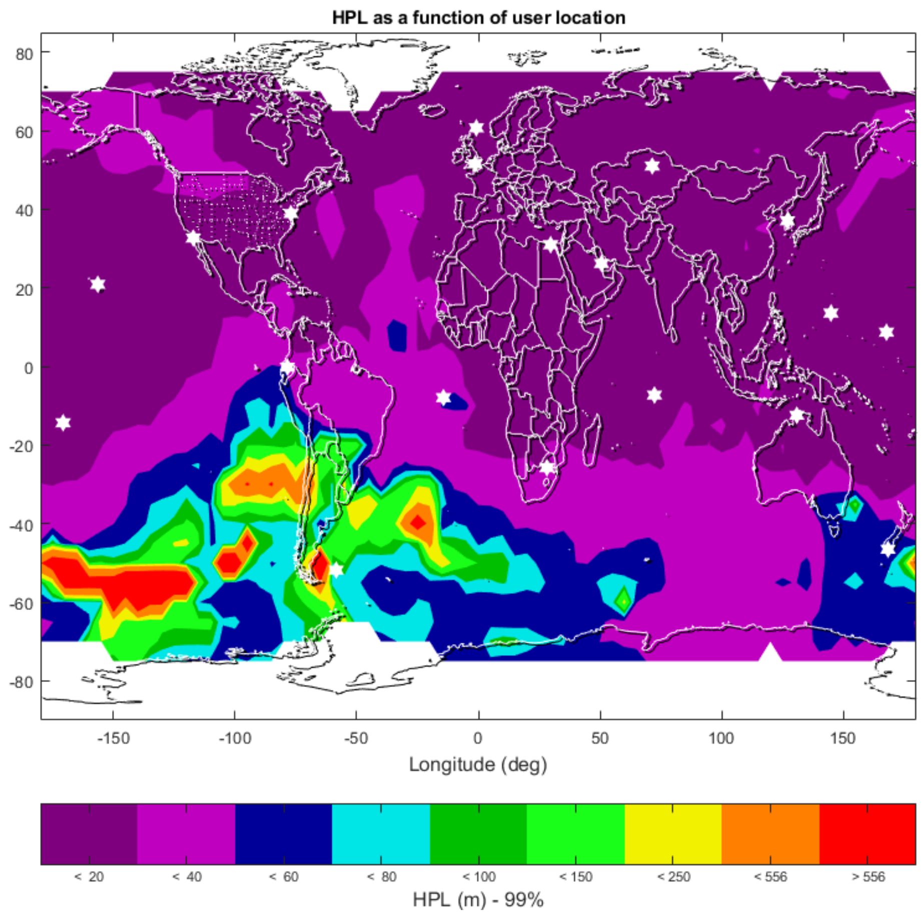
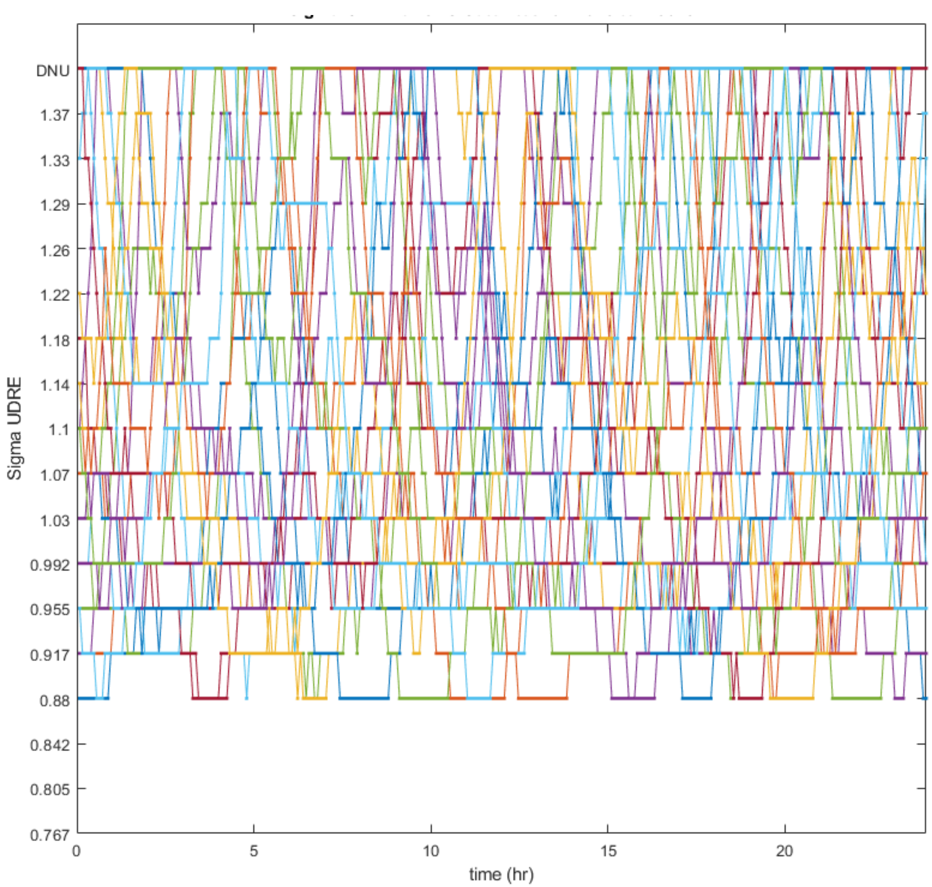


HPL

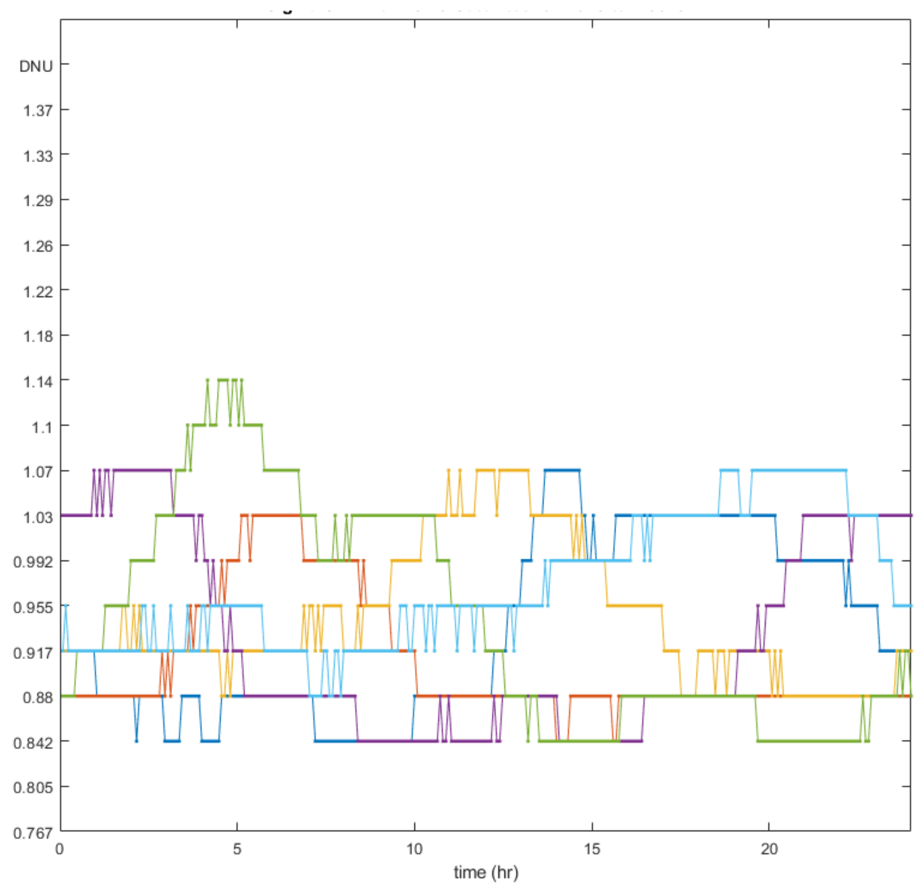


SBAS Sigma UDRE vs Time (19 RS): *Comparison of GPS and I-GEO SVs*

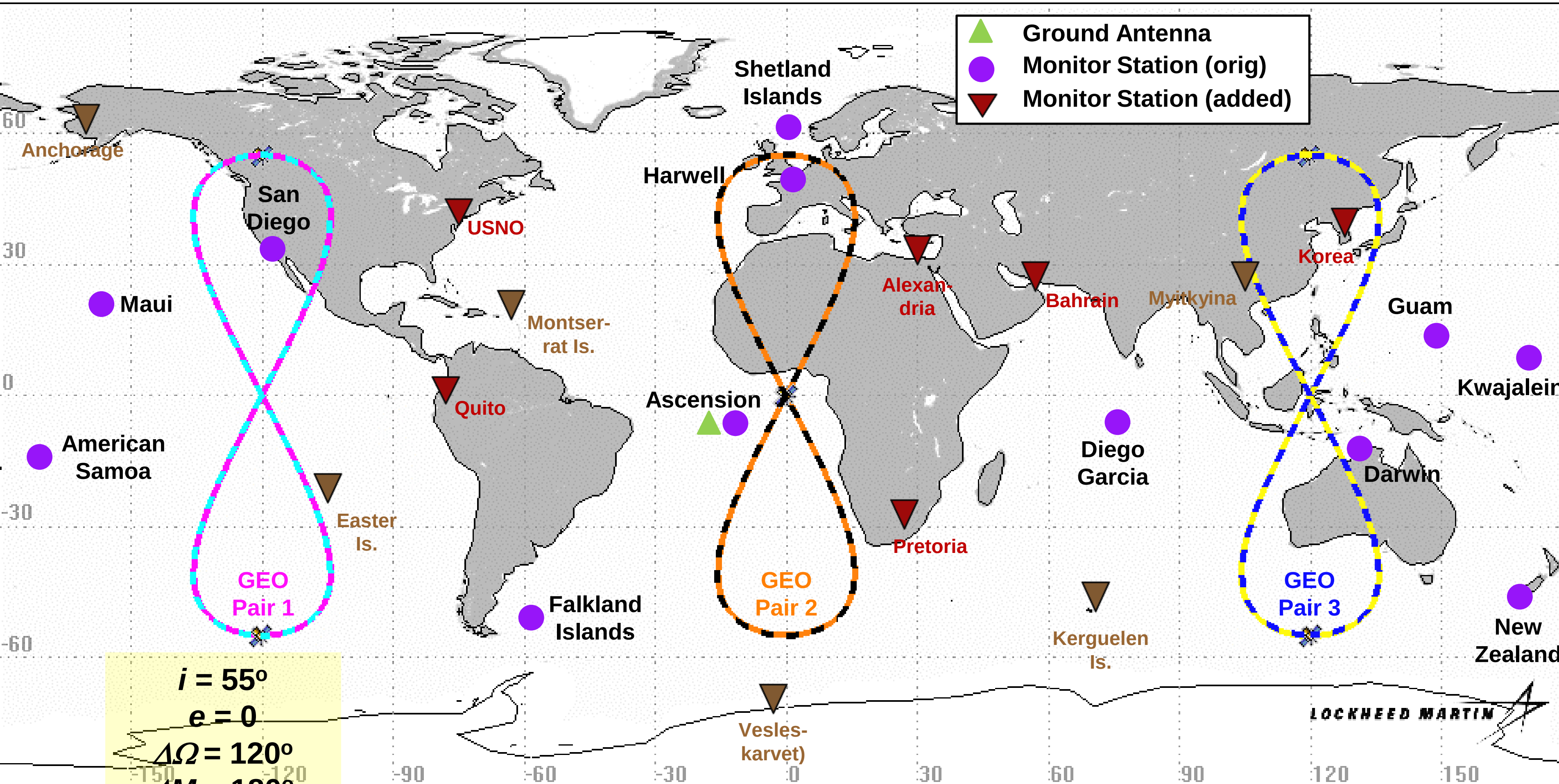
24 GPS SVs



6 I-GEO SVs

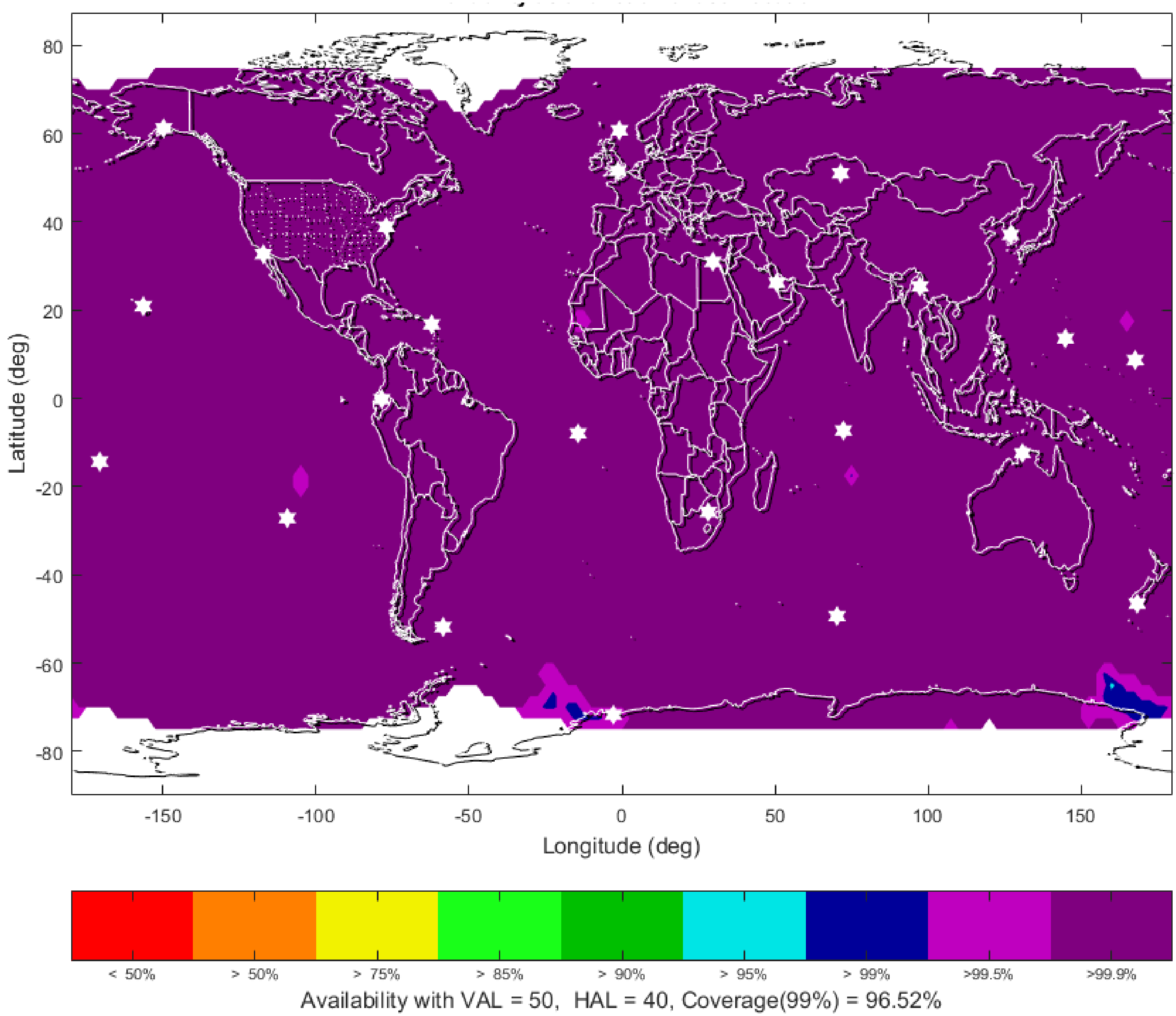


6 Inclined GEO SVs (in 3 Planes) and 25-RS Network



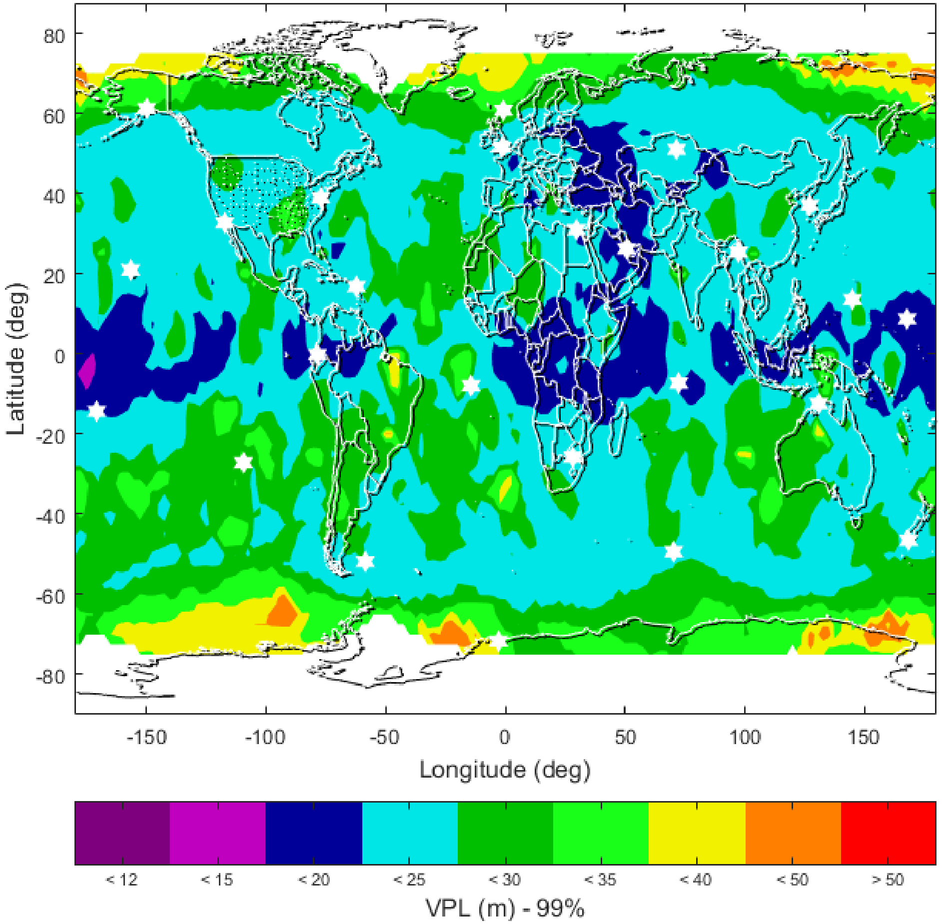
$i = 55^o$
$e = 0$
$\Delta\Omega = 120^o$
$\Delta M = 180^o$

SBAS LPV Approach Availability
(24-SV GPS Const., 25 RS, *6 I-GEOs*)

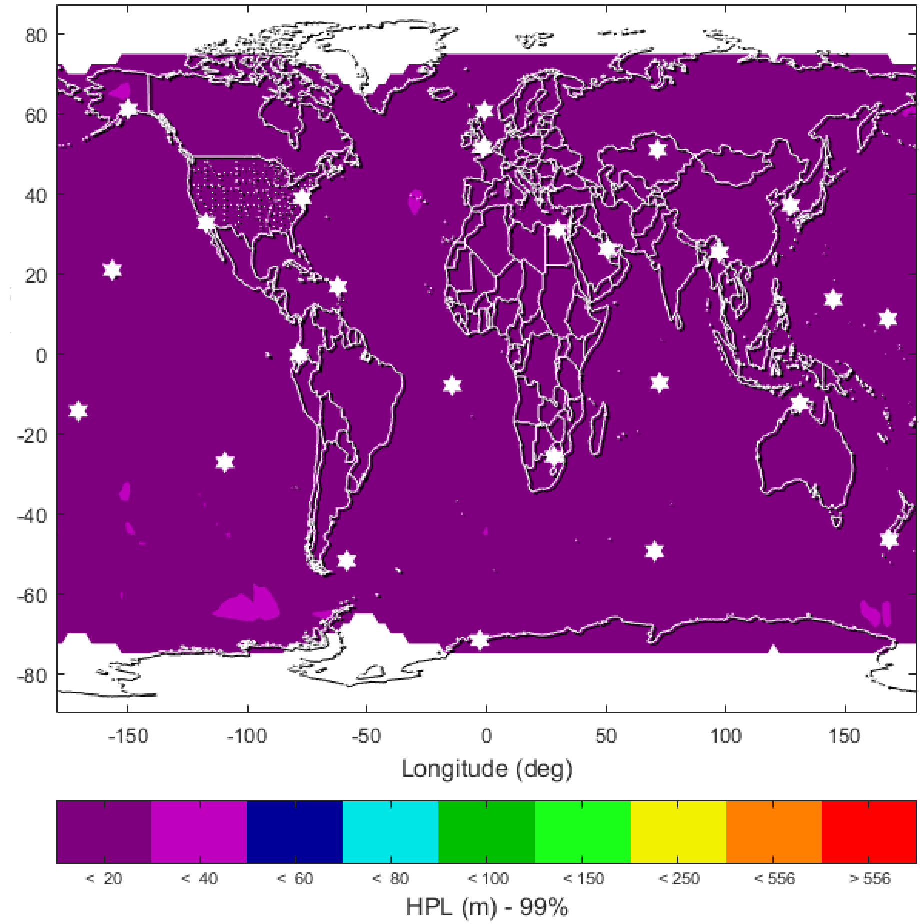


SBAS Protection Level Results
(24-SV GPS Const., 25 RS, *6 I-GEOs*)

VPL

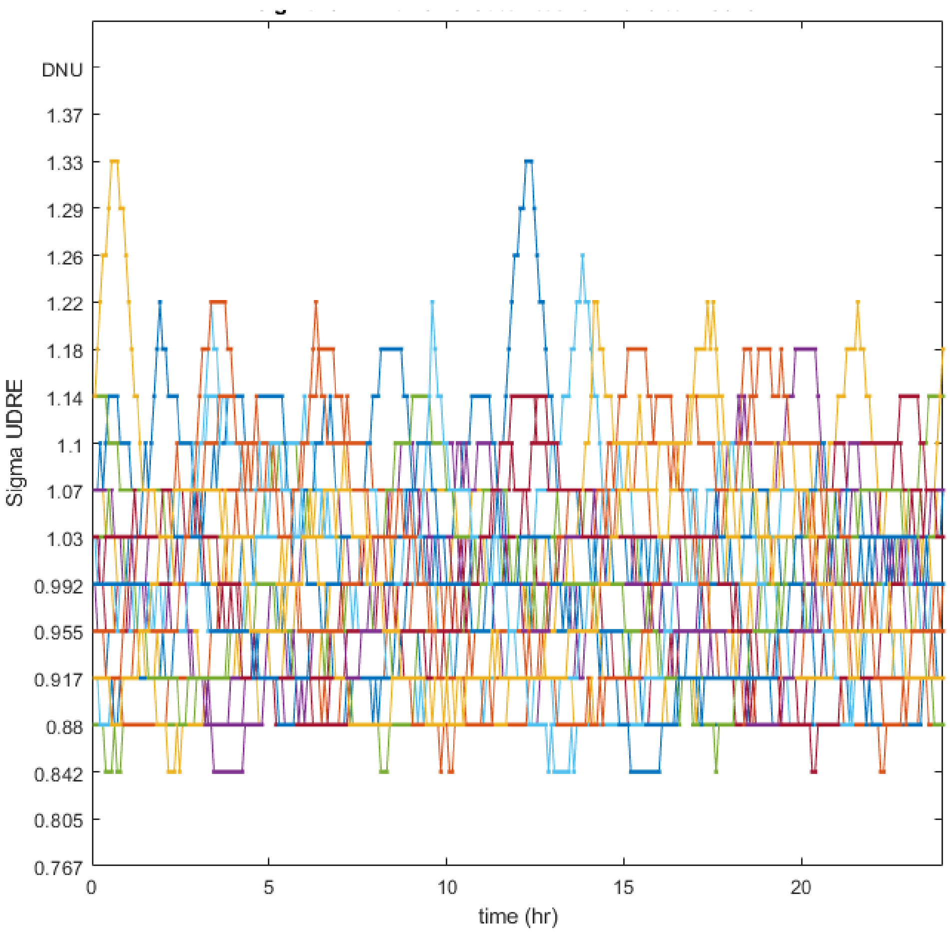


HPL

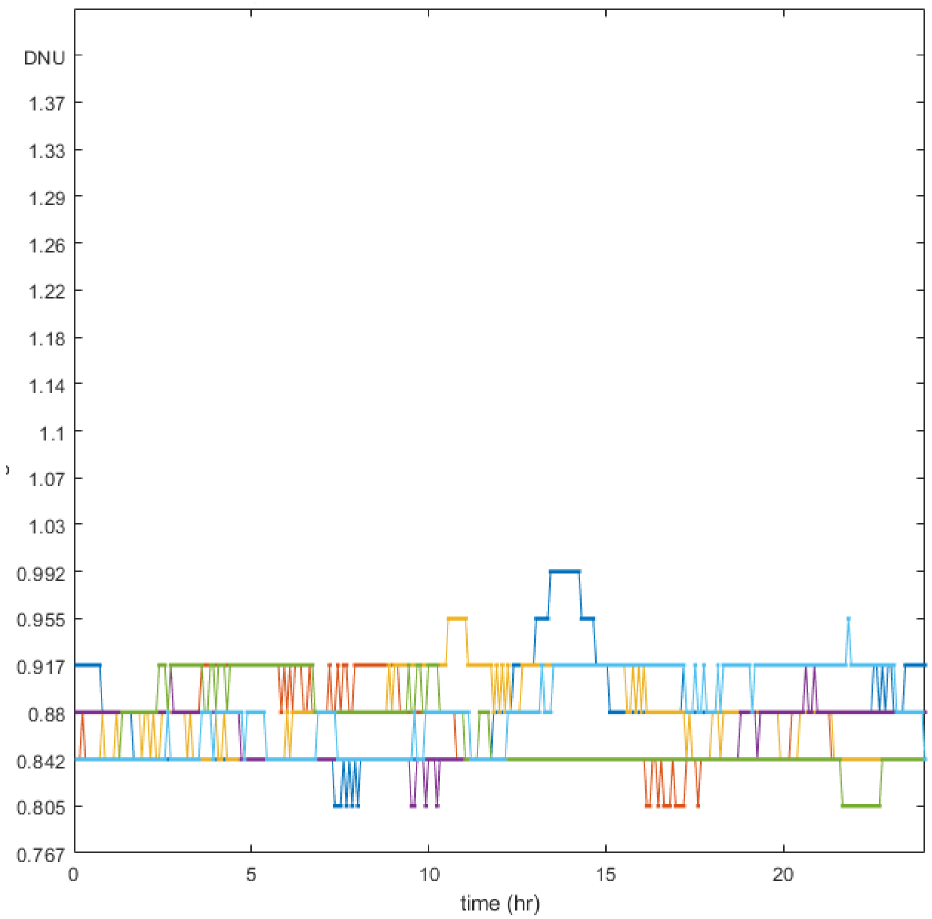


SBAS Sigma UDRE vs Time (25 RS): *Comparison of GPS and I-GEO SVs*

24 GPS SVs



6 I-GEO SVs



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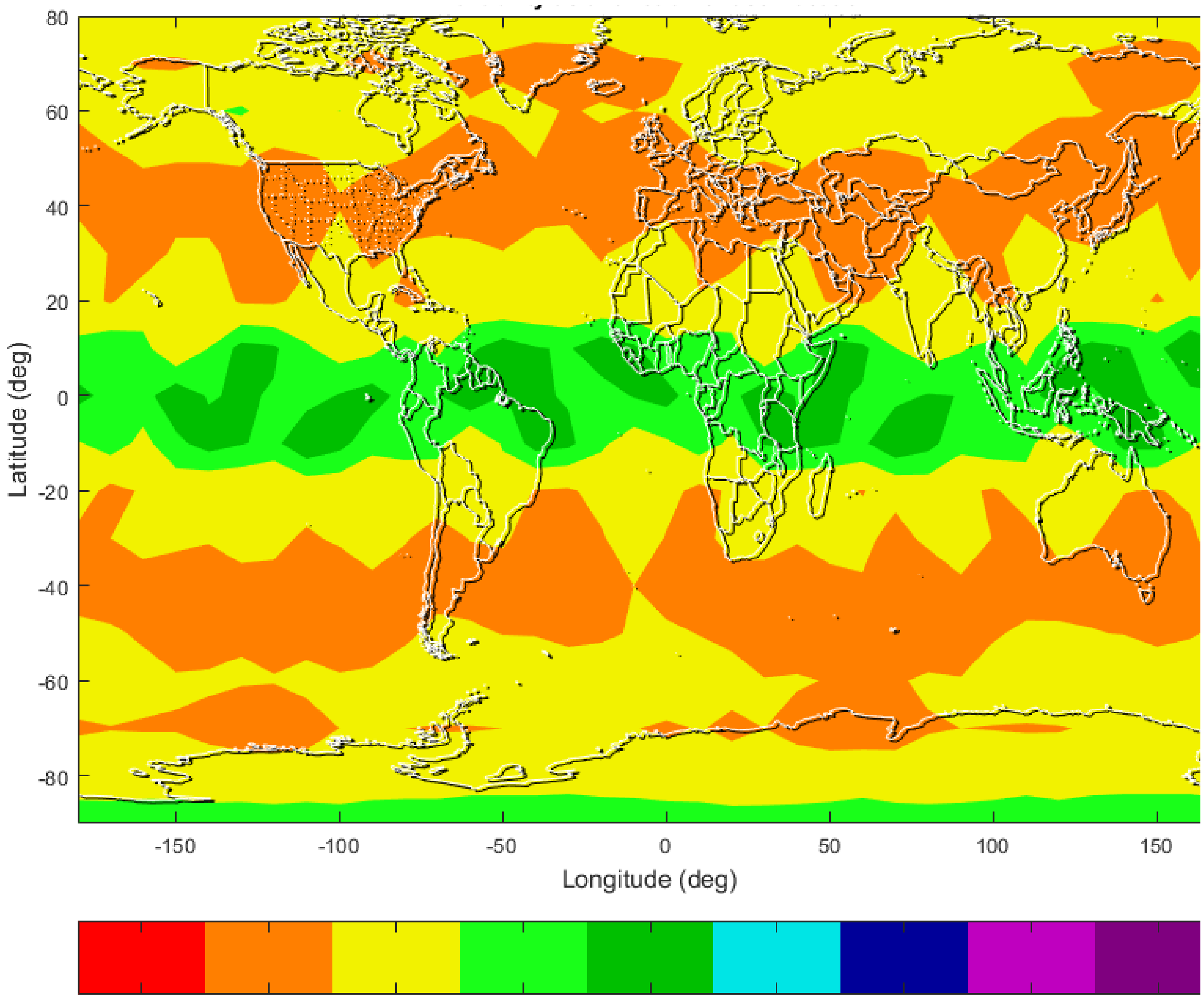
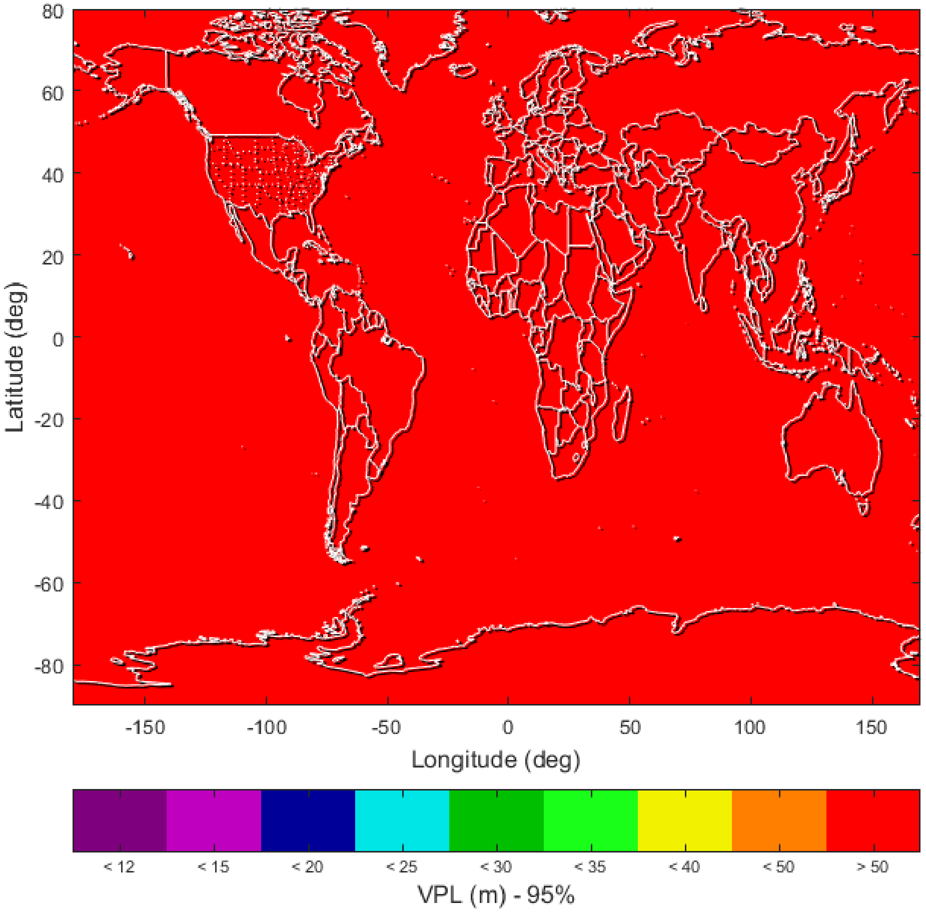
ARAIM LPV Approach Availability (24-SV Standard GPS Const, no I-GEOs)



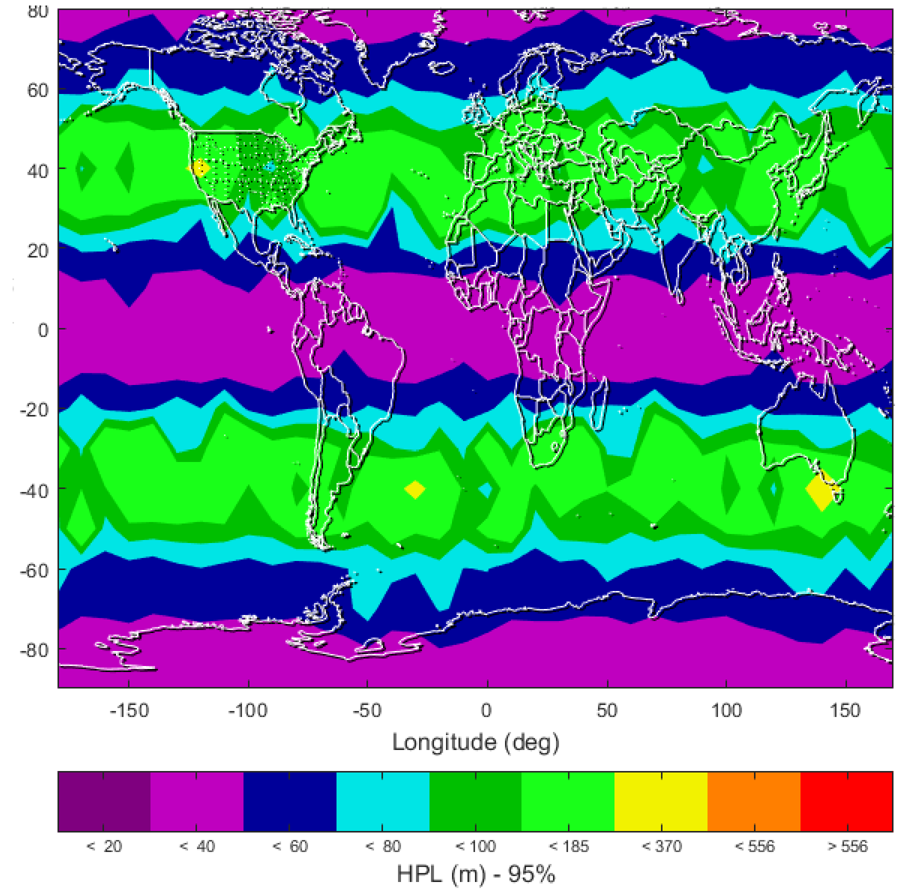
VAL = 50, HAL = 40, EMT_{th} = 100000, σ_{acc} = 10000, Coverage(95%) = 0%

ARAIM Protection Level Results (24-SV Standard GPS Const, no I-GEOs)

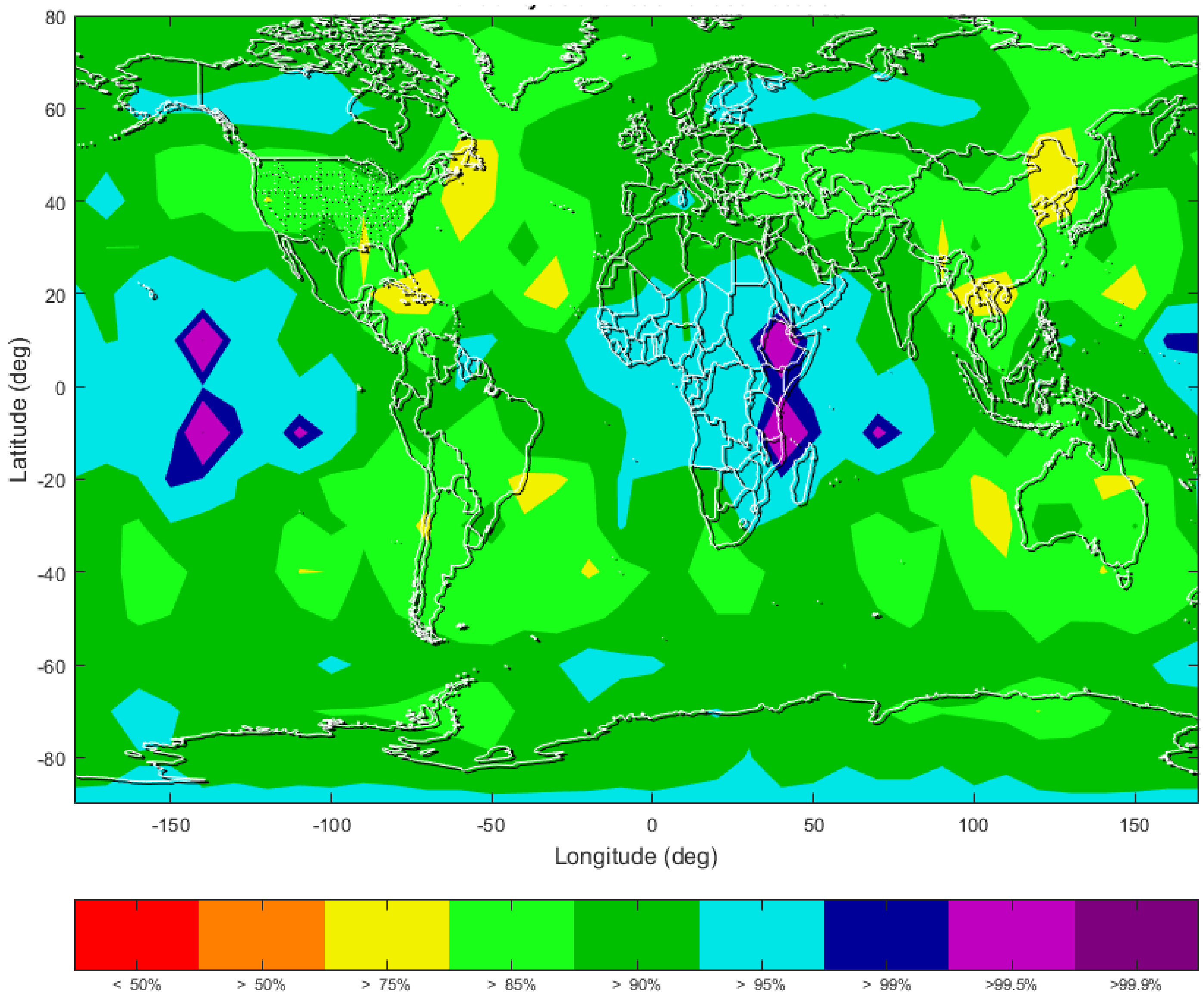
VPL



HPL



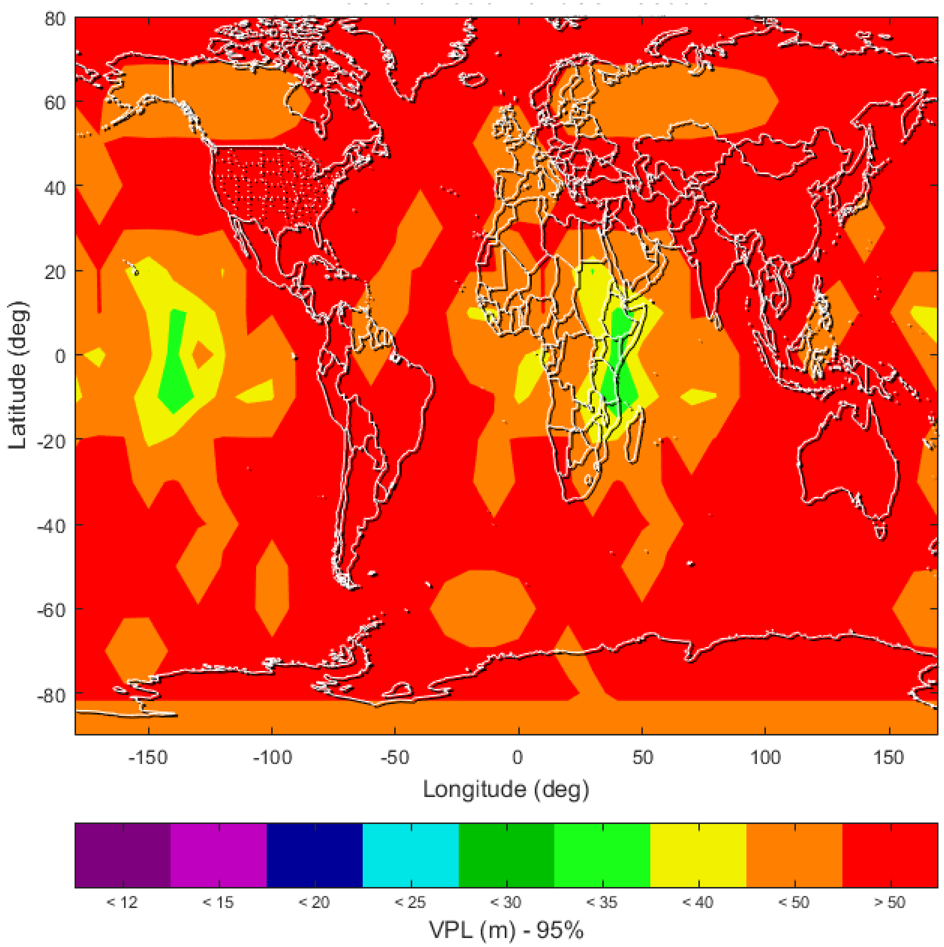
ARAIM LPV Approach Availability (24-SV Standard GPS Const, *6 I-GEOs*)



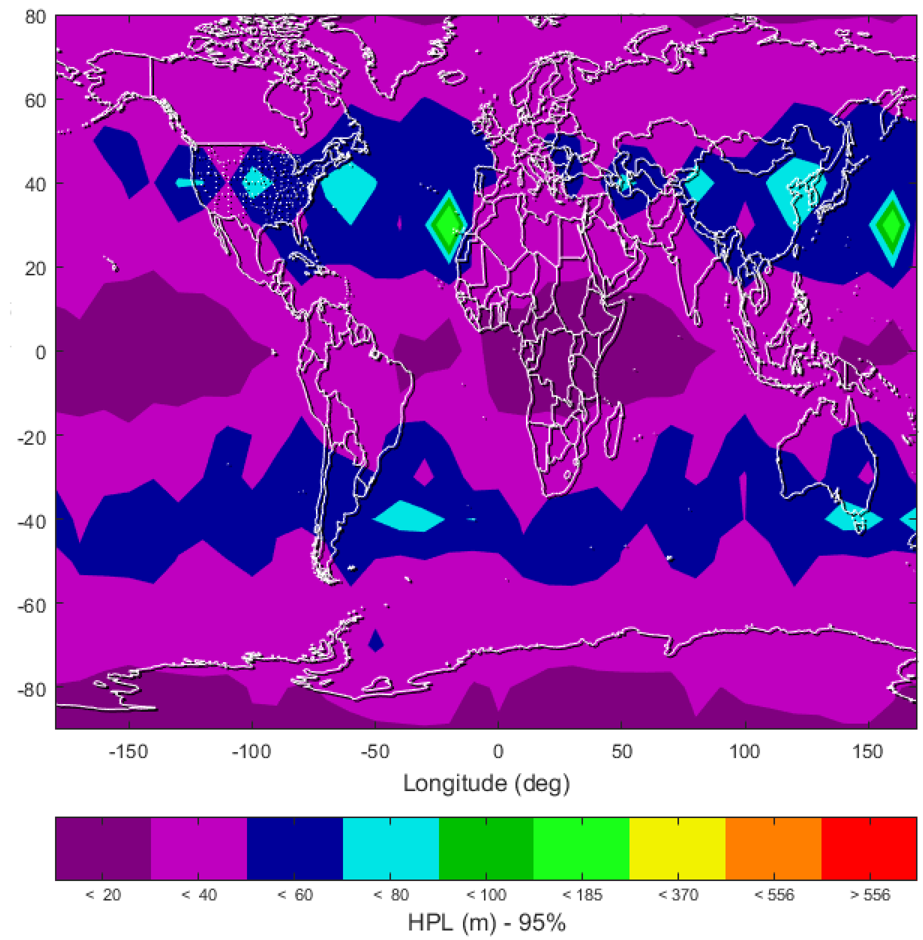
VAL = 50, HAL = 40, EMT_{th} = 100000, σ_{acc} = 10000, Coverage(95%) = 23.1%

ARAIM Protection Level Results (24-SV Standard GPS Const, *6 I-GEOs*)

VPL



HPL



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Summary

- **Proposed inclined-GEO augmentation significantly improves protection levels and LPV availability when combined with worldwide ground monitoring.**
- **Inclined GEOs provide performance improvements by:**
  - **Serving as sources of additional range measurements**
  - **Providing consistently low error bounds due to increased visibility to ground network**
- **Additional range measurement redundancy is of particular importance for ARAIM (with GPS only).**
- **A network of 25 worldwide ground monitor stations should be sufficient (with near-ideal distribution).**
  - **But 20 or fewer would leave significant gaps**

Ongoing Work

- **Investigate additional I-GEO plus non-GEO satellite constellation architectures.**
  - **e.g., 4th I-GEO plane, I-GEO plus LEO const.**
  - **Note: results for I-GEO plus 18/3/1-SV MEO const. shown in backup slides**

- **Investigate sensitivity of results to model parameters (range-domain error models and fault probabilities):**
  - **Monitor station measurement errors for SBAS-like integrity**
  - **ISM parameters for ARAIM-like integrity.**

References

[1] S. Pullen, S. Lo, A. Katz, et al, "Ground Monitoring to Support ARAIM for Military Users: Alternatives for Rapid and Rare Update Rates," *Proceedings of ION GNSS+ 2021*, Kansas City, MO, Sept. 2021. http://web.stanford.edu/group/scpnt/gpslab/pubs/papers/Pullen_IONGNSS_2021_Mil_ARAIM.pdf

[2] A. Katz, S. Pullen, S. Lo, et al, "ARAIM for Military Users: ISM Parameters, Constellation-Check Procedure and Performance Estimates," *Proceedings of ION ITM 2021*, San Diego, CA, Jan. 2021. http://web.stanford.edu/group/scpnt/gpslab/pubs/papers/Katz_ION_ITM2021_Military_ARAIM.pdf

[3] *GPS Standard Positioning Service (SPS) Performance Standard (GPS SPS PS)*, Washington DC, U.S. Dept. of Defense, 5th Edition, April 2020. https://www.gps.gov/technical/ps/2020-SPS-performance-standard.pdf

References (2)

[4] *Minimum Operational Performance Standards (MOPS) for Global Positioning System/Satellite-Based Augmentation System Airborne Equipment*. Washington, DC, RTCA, Inc., DO-229F, June 11, 2020. https://my.rtca.org/NC__Product?id=a1B1R0000092uanUAA

[5] J. Blanch, T. Walter, P. Enge, et al, "Baseline Advanced RAIM User Algorithm and Possible Improvements," *IEEE Transactions on Aerospace and Electronic Systems,* Vol. 51, No. 1, Jan. 2015, pp. 713-732. https://doi.org/10.1109/TAES.2014.130739

Thanks for your attention!

Backup Slides follow…

SBAS MAAST Simulation Parameters [1]

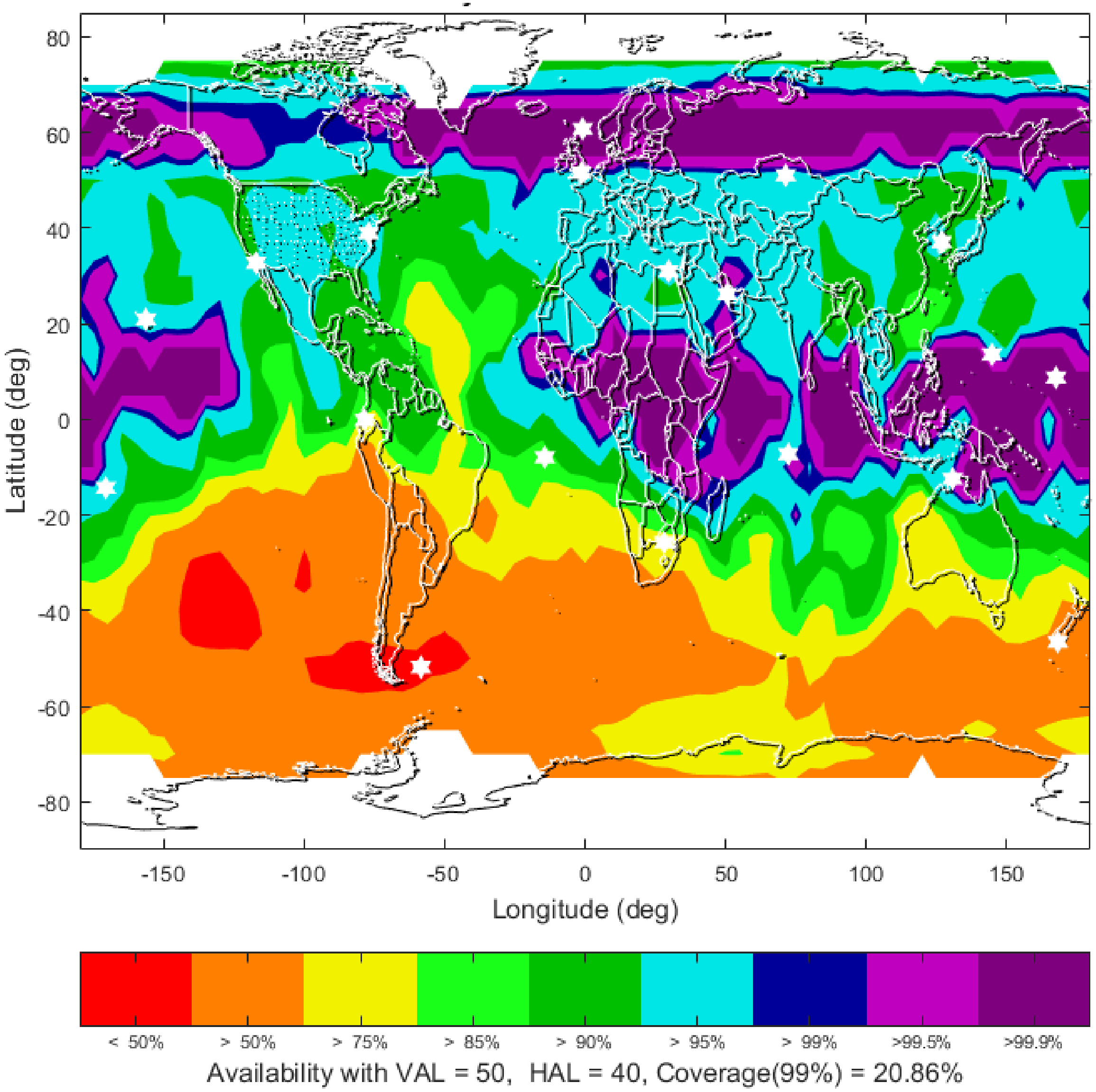
Parameter	Setting
GPS Constellation	WAAS MOPS (24-SV Primary Orbit Slots from SPS PS [3])
Inclined GEO Constellation	6 Inclined GEOs (55^o)
WAAS GEO Constellation	9 GEO SV's (see [1])
WAAS GEO SV Ranging	**Not included** – constant UDRE set to 'not monitored'
Reference Network	varies (12 / 19 / 30 stations)
User Locations	$5^o \times 5^o$ grid in latitude (± 55 deg) and longitude
Ref. Sta. Error Models	Recent WAAS Standard (proprietary)
Time Step	288 seconds

SBAS LPV Approach Availability
(*6 I-GEOs & 18-SV/3-plane MEO const.*)

MEO const.:

Walker delta 55º: 18/3/0

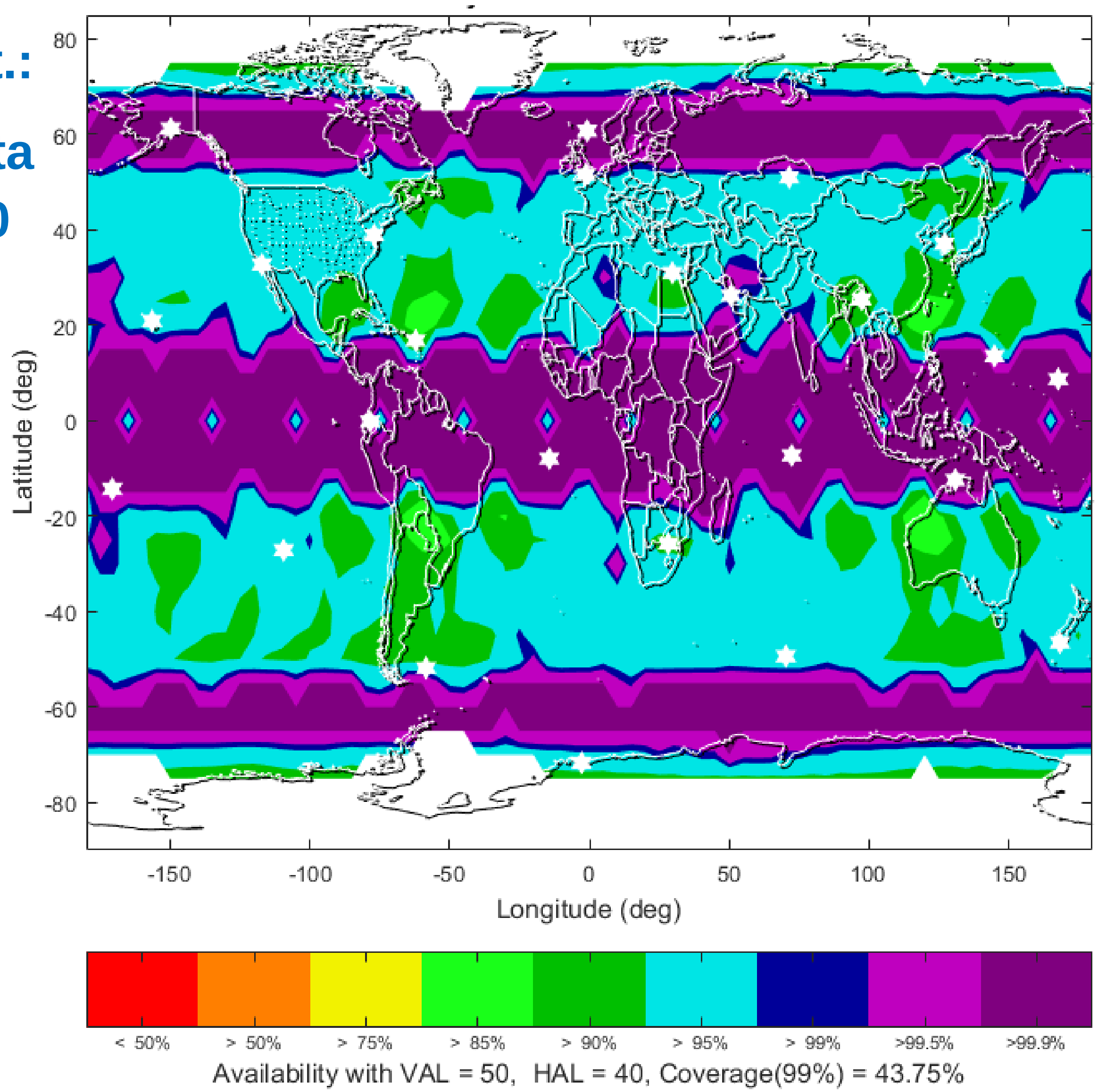
19 RS



SBAS LPV Approach Availability
(*6 I-GEOs & 18-SV/3-plane; 25 Ref. Sta.*)

MEO const.:

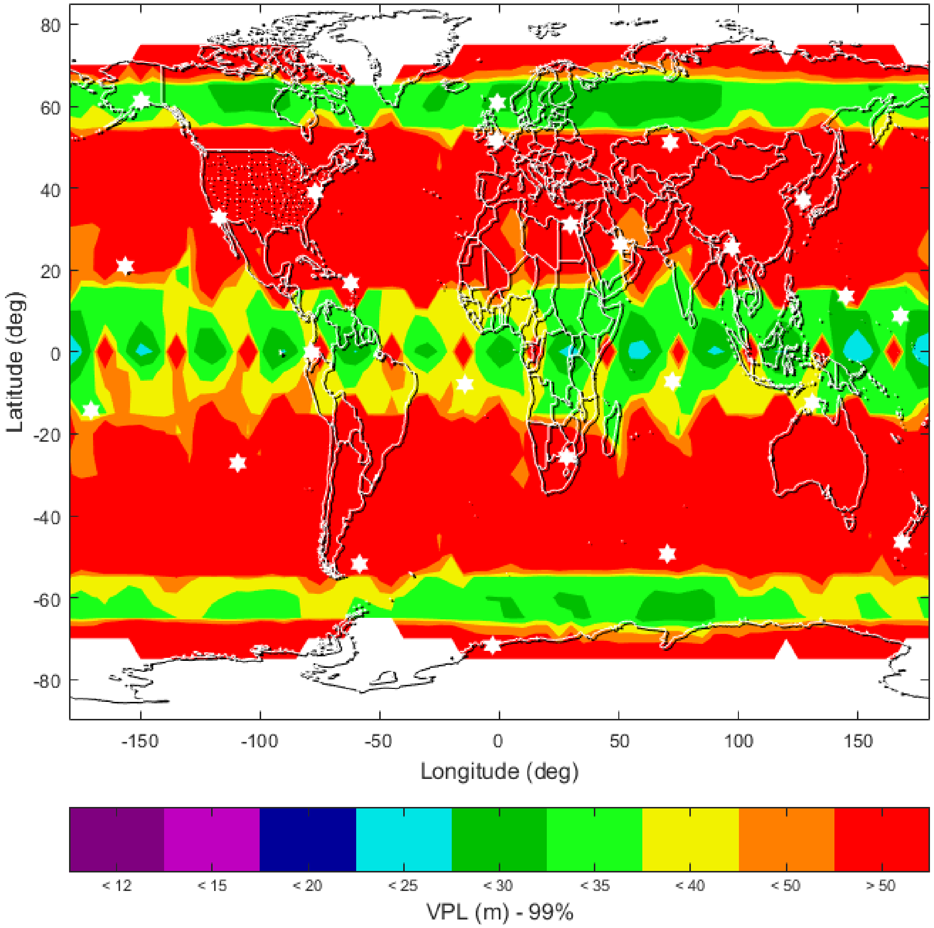
Walker delta 55º: 18/3/0



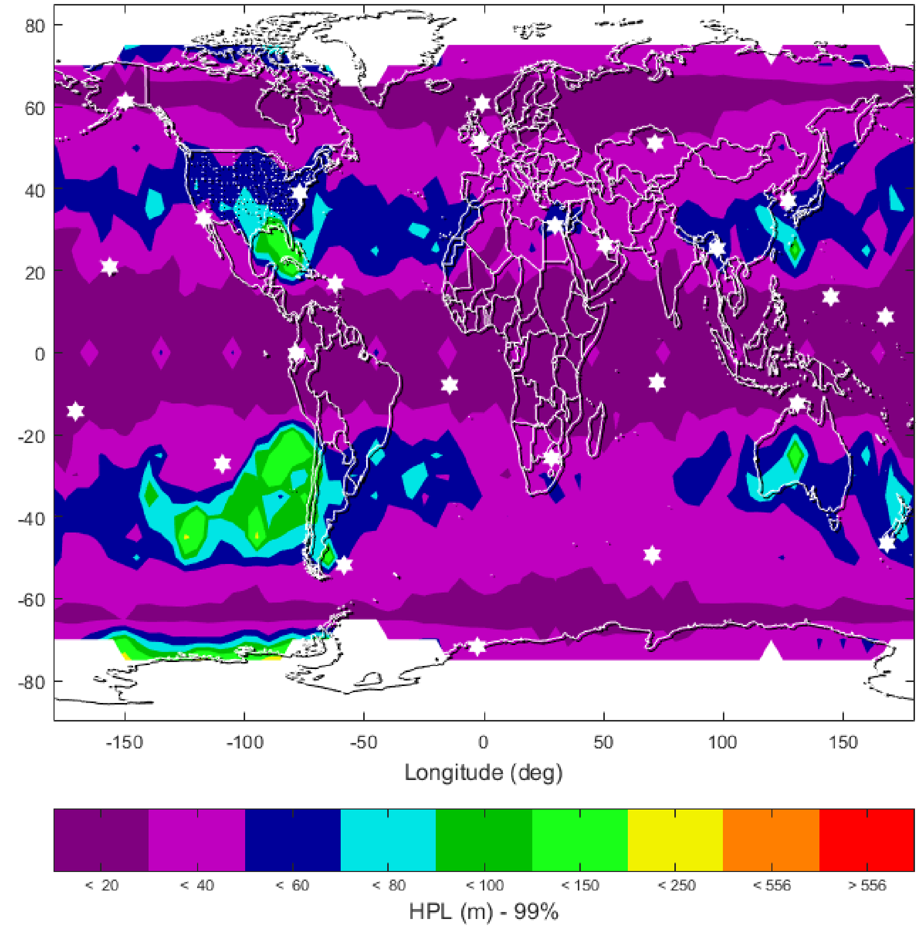
25 RS

SBAS Protection Level Results
(*6 I-GEOs & 18-SV/3-plane; 25 Ref. Sta.*)

VPL

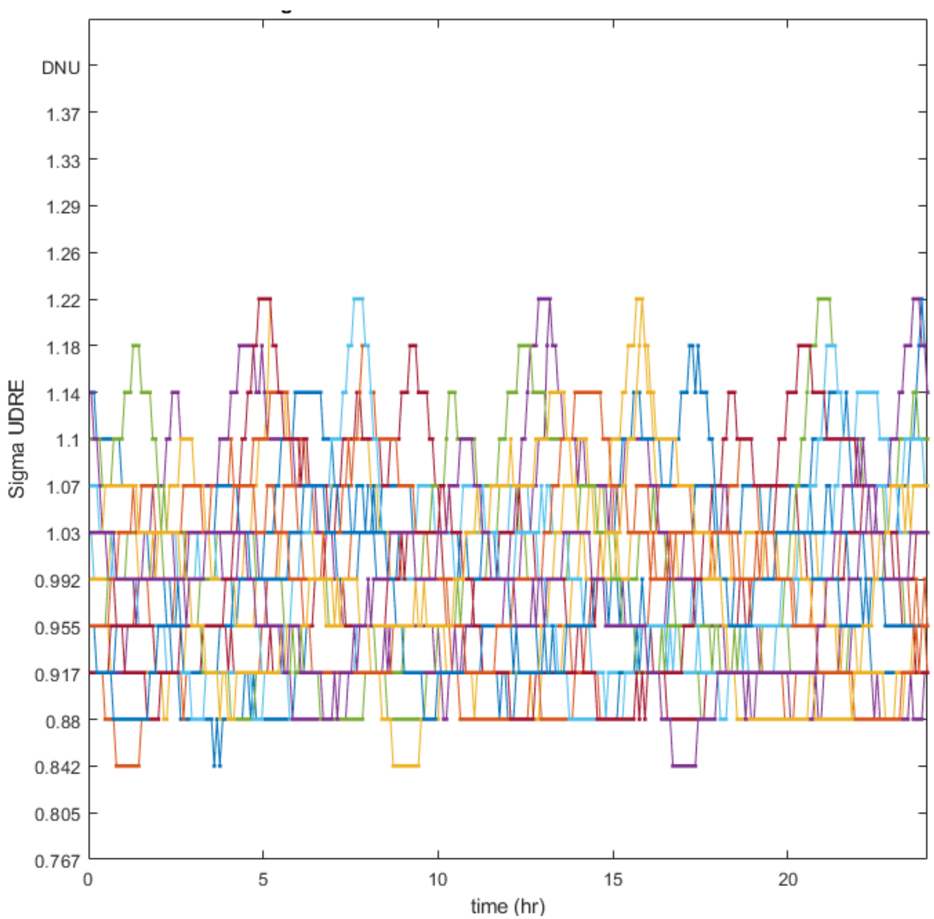


HPL



SBAS-like Sigma UDRE vs Time: *Comparison of MEO and I-GEO; 25 RS*

MEO SVs



I-GEO SVs