Ground Monitoring to Support ARAIM for Military Users: Alternatives for Rapid and Rare Update Rates

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Outline

- Background to ARAIM for Military Users
- ARAIM Integrity Support Message (ISM) and Ground Monitoring Concepts
  - Internal to satellite constellations
  - External with batch or sequential filtering
  - External SBAS-like snapshot estimation
- Review Military ARAIM Simulation Results
- SBAS-like Ground Monitoring Results
- Summary and Ongoing Work

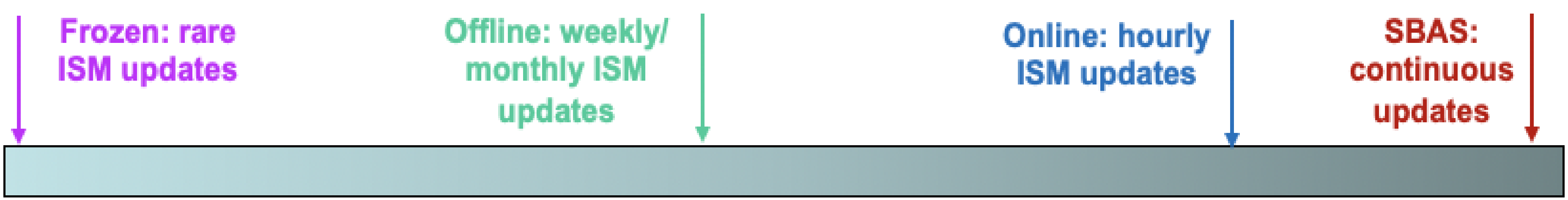
Background to Military ARAIM

- **Extend dual-frequency (L1/L5) ARAIM developed for civil aviation to M-code (L1/L2) for military users.**
- **Civil ARAIM typically requires multiple GNSS constellations to achieve high vertical navigation (VNAV) availability (e.g., for LPV approaches).**
- **In contrast, Military ARAIM needs to provide acceptable VNAV availability with GPS only.**
- **Both types of ARAIM require an Integrity Support Message (ISM) to provide satellite fault probabilities, alerting times, and signal-in-space (SIS) error bounds.**
- **Previous work (ION ITM 2021 [1]) has examined Military ARAIM performance with GPS only and with "Galileo constellation check" augmentation.**

ARAIM ISM Update Intervals

- **ISM parameter values and resulting user performance vary depending on ISM update protocol, e.g.:**

  1. **"Frozen": ISM parameters are fixed and are only updated unexpectedly (due to urgent need) or during software updates.**
  2. **"Offline": ISM is updated regularly but infrequently (e.g., weekly, monthly, or quarterly).**
  3. **"Online": ISM is updated very often (e.g., hourly) with updated clock and ephemeris messages to reduce fault probabilities, error bounds, etc.**



"Frozen" ISM for Civil Aviation

- Civil aviation service providers have agreed to base ARAIM ISM on GNSS constellation commitments and internal monitoring by these constellations.

- Thus, satellite and constellation failure probabilities are fixed based on existing commitments and are unlikely to change (unless commitments are updated)

  - ➢ Commitments represented by Default Integrity Support Data (ISD), without necessarily needing an ISM

- Per-satellite signal-in-space error bounds (URA) broadcast in navigation data are valid for ARAIM.

Constellation Integrity Support Parameter Commitments (from [2])

DF = dual-frequency SF = single-frequency

Parameter	GPS	Galileo	GLONASS	Beidou
URA	in Nav Data (ICD table)	6 m DF, 7.5 m SF	18 m	in Nav Data (ICD table)
URA Threshold	4.42 × URA	4.17 × URA (25, 31.3 m)	70 m (3.89 × URA)	4.42 × URA
R_{sat}	10^{-5} / hour	not specified	not specified	not specified
P_{sat}	10^{-5}	3×10^{-5}	10^{-4}	10^{-5}
P_{const}	10^{-8} (†)	2×10^{-4}	10^{-4}	6×10^{-5}
MFD	1 hour	not specified	not specified	not specified
TTA	10 seconds	not specified	10 seconds	10 seconds
Sources	SPS PS [4] and NSP6_wp2 [5]	NSP6_wp4 [6]	NSP6_wp3 [7]	NSP6_wp5 [8]

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

"Offline" and "Online" Protocols for Greater Control and Lower Error Bounds

- **If external control and monitoring of ISM is maintained, ISM could be updated ~ monthly ("offline") or ~ hourly ("online").**

- **This provides a defense against constellation provider failure to meet commitments due to unforeseen problems.**

- **This also allows lower satellite fault probabilities and error bounds where warranted, avoiding conservatism in constellation provider commitments.**

- **What degree of external monitoring is needed to provide these benefits?**

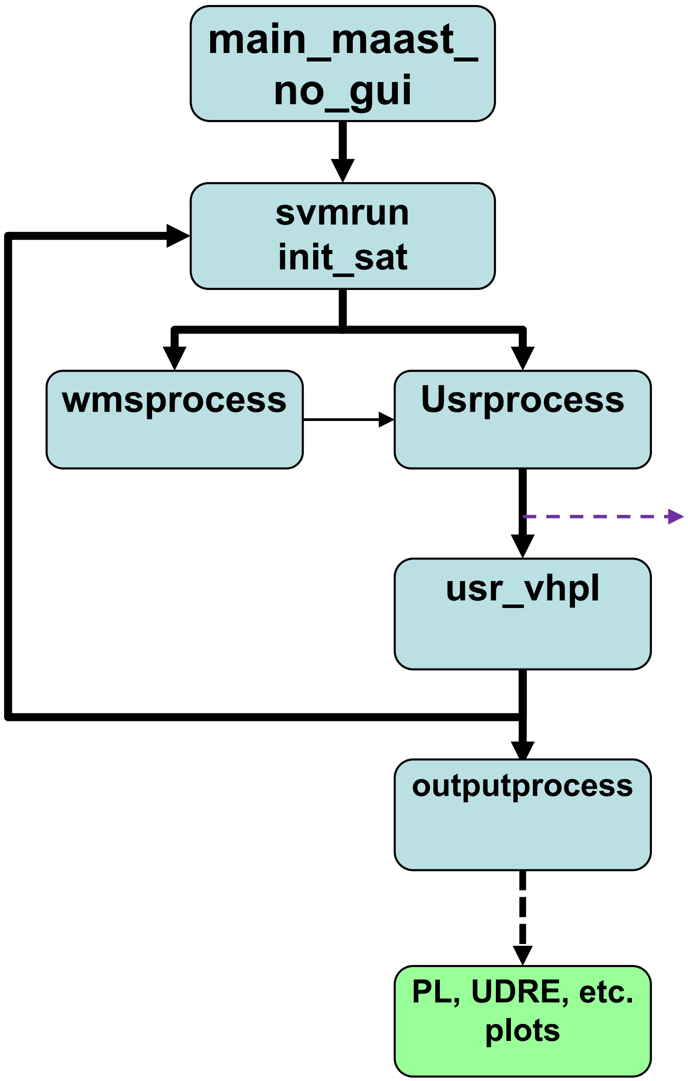
Batch Fit Monitoring of Satellite Clock and Ephemeris State Errors (adapted from [3])

Perform satellite monitoring over time by batch fit or sequential estimation of satellite clock and ephemeris states.

RS PRs from SV 1, *t* = 1 to *k* -------- **RS PRs from SV 2, *t* = 1 to *k*** -------- • • • -------- **RS PRs from SV *N*, *t* = 1 to *k***	**=**	**Geometry Matrix**	**SV *x*,*y*,*z* ephem- eris states** -------- **SV clock states** -------- **RS clock states** -------- **RS-SV cycle ambi- guities**	**+**	**RS PR ε_s from SV 1, *t* = 1 to *k*** -------- **RS PR ε_s from SV 2, *t* = 1 to *k*** -------- • • • -------- **RS PR ε_s from SV *N*, *t* = 1 to *k***

Suited to "offline" ISM updates as often as every few hours, but slower than "snapshot" (per measurement epoch) approach.

"SBAS-like" Snapshot Monitoring of Satellite Errors: MAAST Simulation



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)

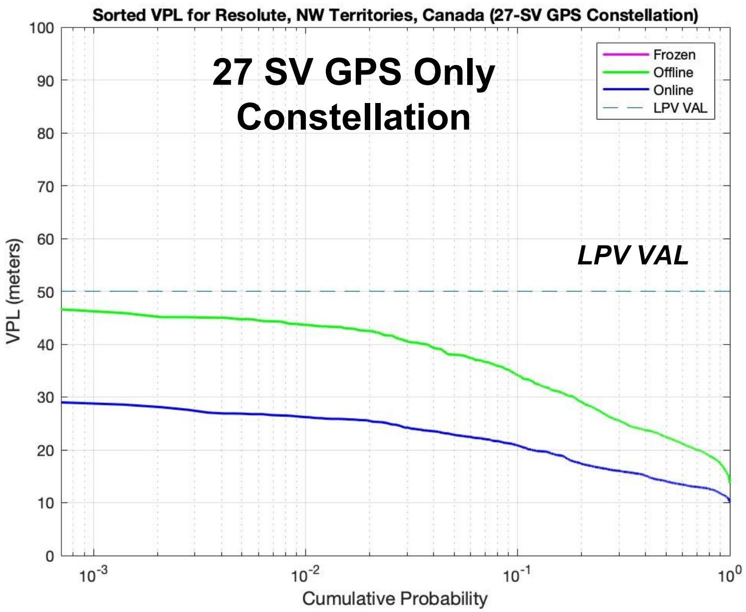
Load Matlab data files and plot results (for dual frequency, UDRE = DFRE)

GPS M-Code Error Model Parameters used in Previous ARAIM Studies [1]

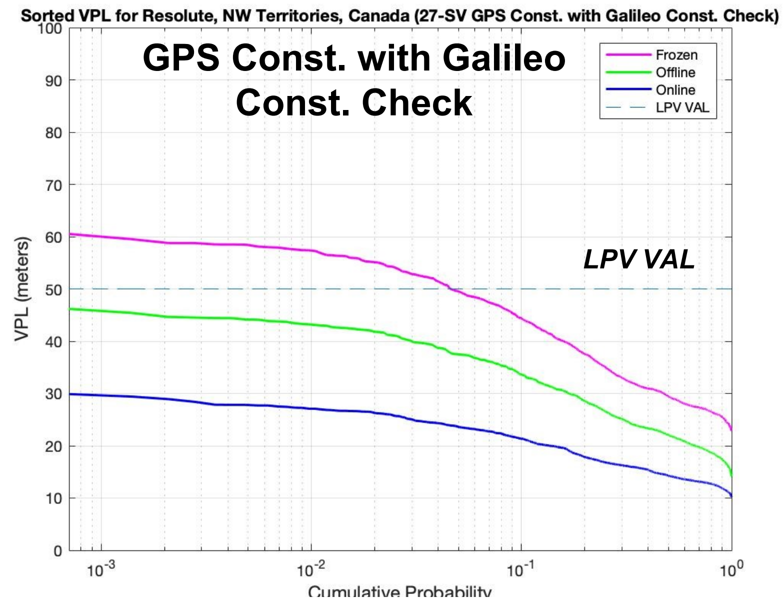
Parameter	Frozen	Offline	Online
URA	1.60 m	1.30 m	1.00 m
URE	1.07 m	0.87 m	0.63 m
b_{nom}	0.75 m	0.50 m	0.35 m
P_{sat}	5.0×10^{-5} / SV	1.0×10^{-5} / SV	5.0×10^{-7} / SV
P_{const}	5.0×10^{-6}	7.0×10^{-8}	2.5×10^{-9}
Mean Fault Duration (MFD)	1.0 hrs	1.0 hrs	0.6 hrs
$K_{mcode\text{-}air}$	0.8	0.8	0.8

Multiplier of airborne error sigma to reflect M-code v/s C/A-code

Military ARAIM Results from [1] (Baseline ISM at NW Territories)

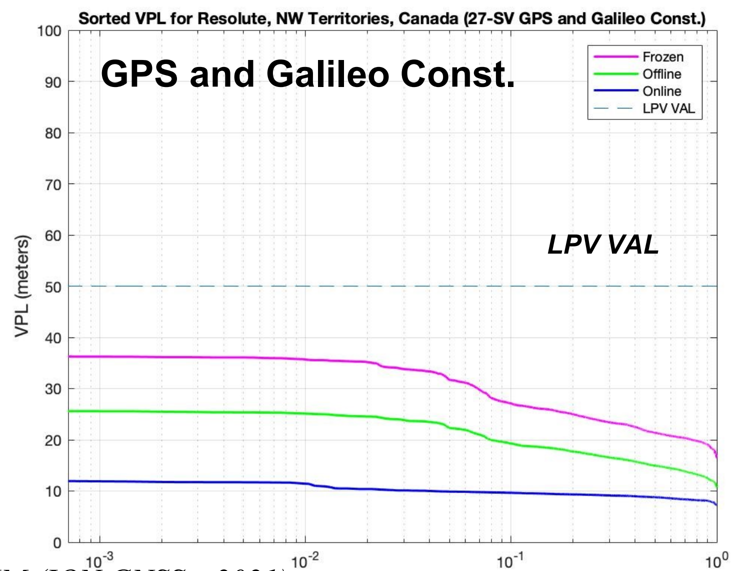


(No "frozen" result above due to GPS $P_{const} > 10^{-7}$)



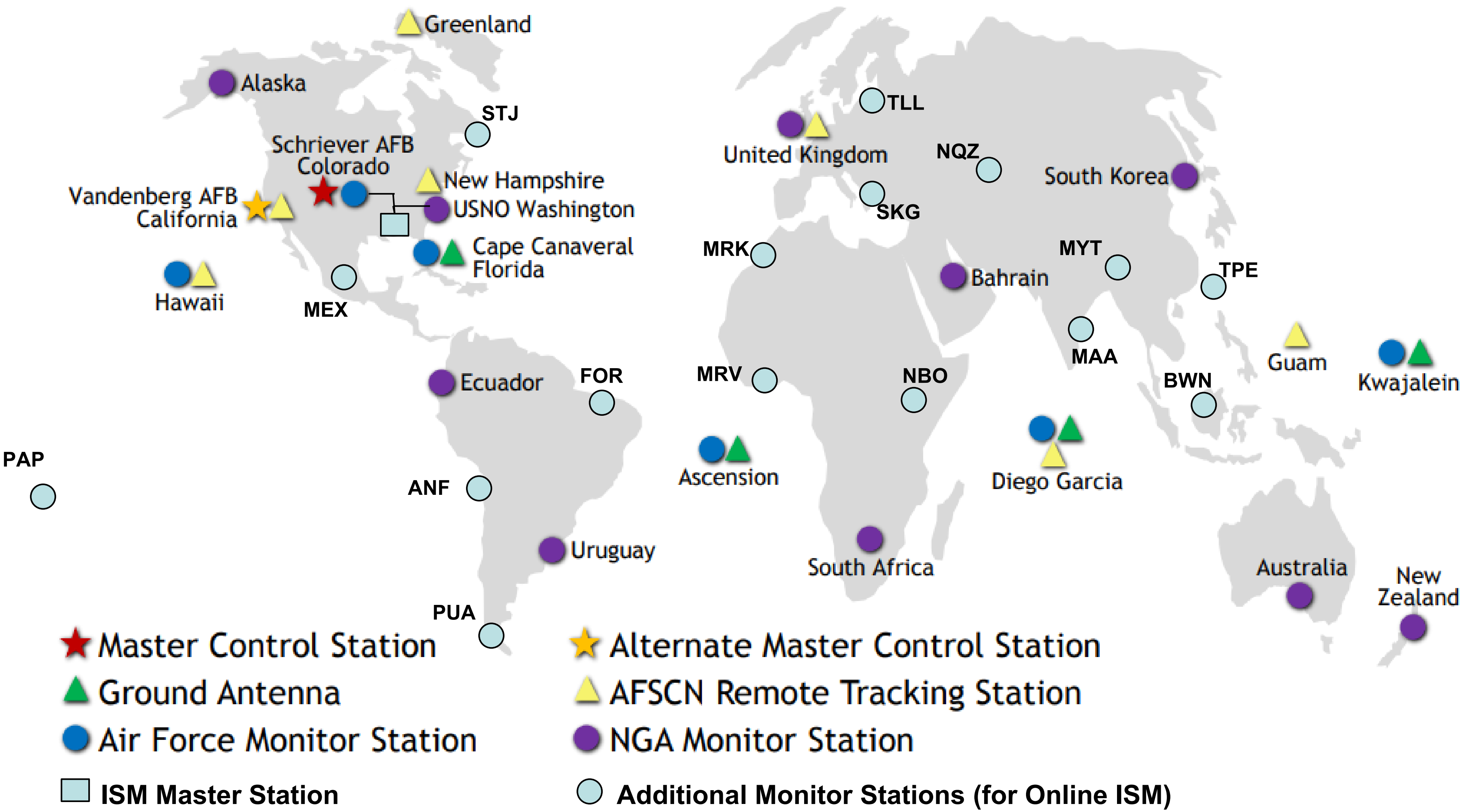
VPL Comparison at NW Territories

- "Frozen" ISM Updates
- "Offline" ISM Updates
- "Online" ISM Updates



Example 33-Station ARAIM Ground Monitoring Network

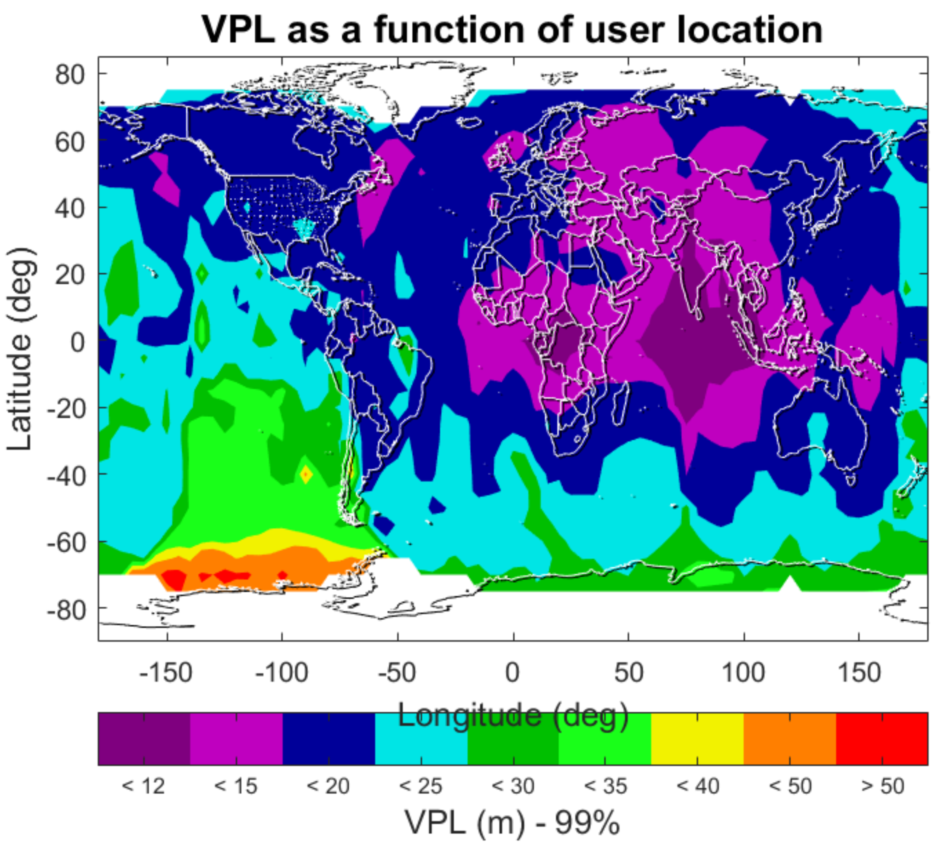
Graphic source: https://www.gps.gov/multimedia/images/GPS-control-segment-map.pdf

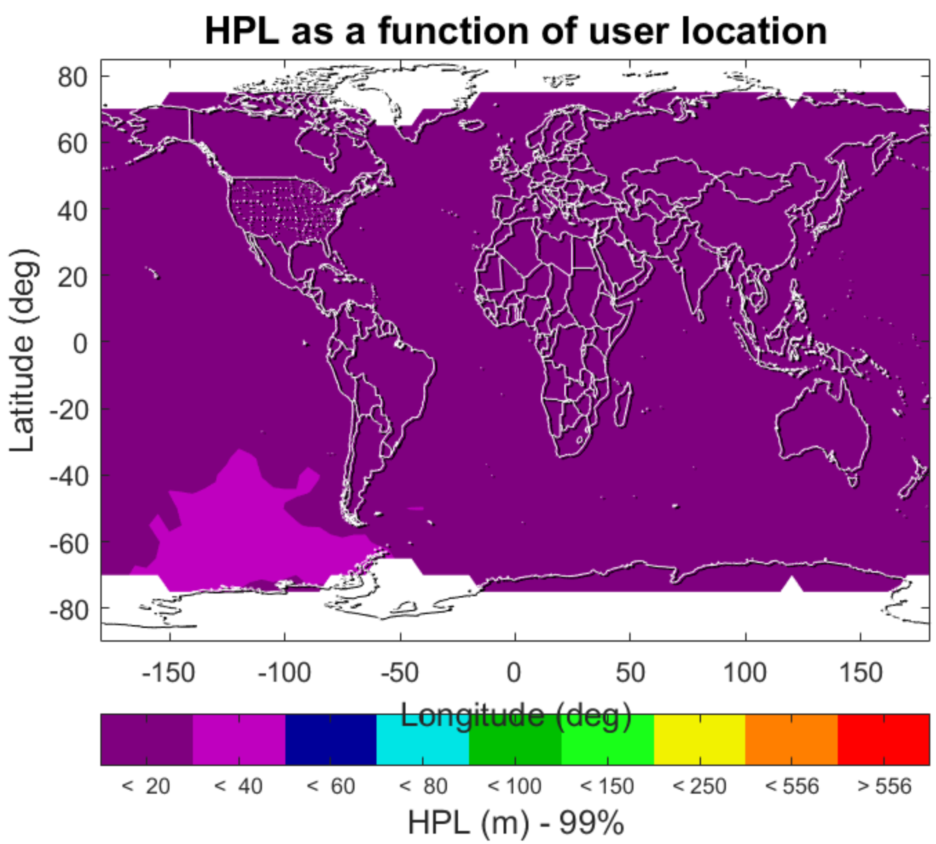


SBAS MAAST Simulation Parameters

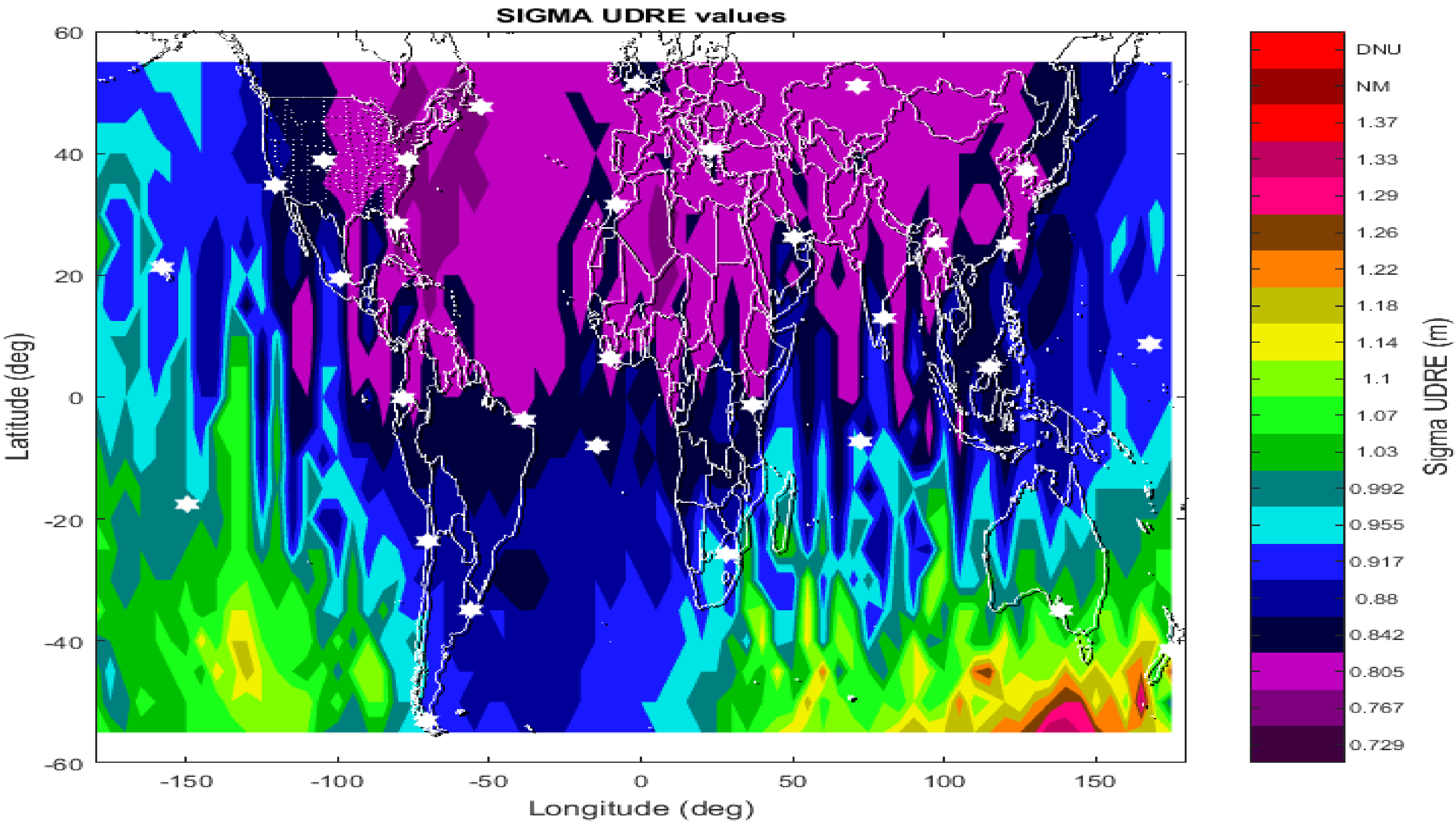
Parameter	Setting
GPS Constellation	SBAS MOPS [9] (24-SV Primary Orbit Slots from SPS PS [4])
SBAS Constellation	9 GEO SV's (see notes)
SBAS SV Ranging	Included with (constant) higher UDRE
Reference Network	33 stations (on previous slide)
User Locations	$5^o \times 5^o$ grid in latitude and longitude
Reference Station Error Models	Recent WAAS Standard (proprietary)
Time Step	288 seconds (300 epochs per 24-hour day)

SBAS Protection Level Results





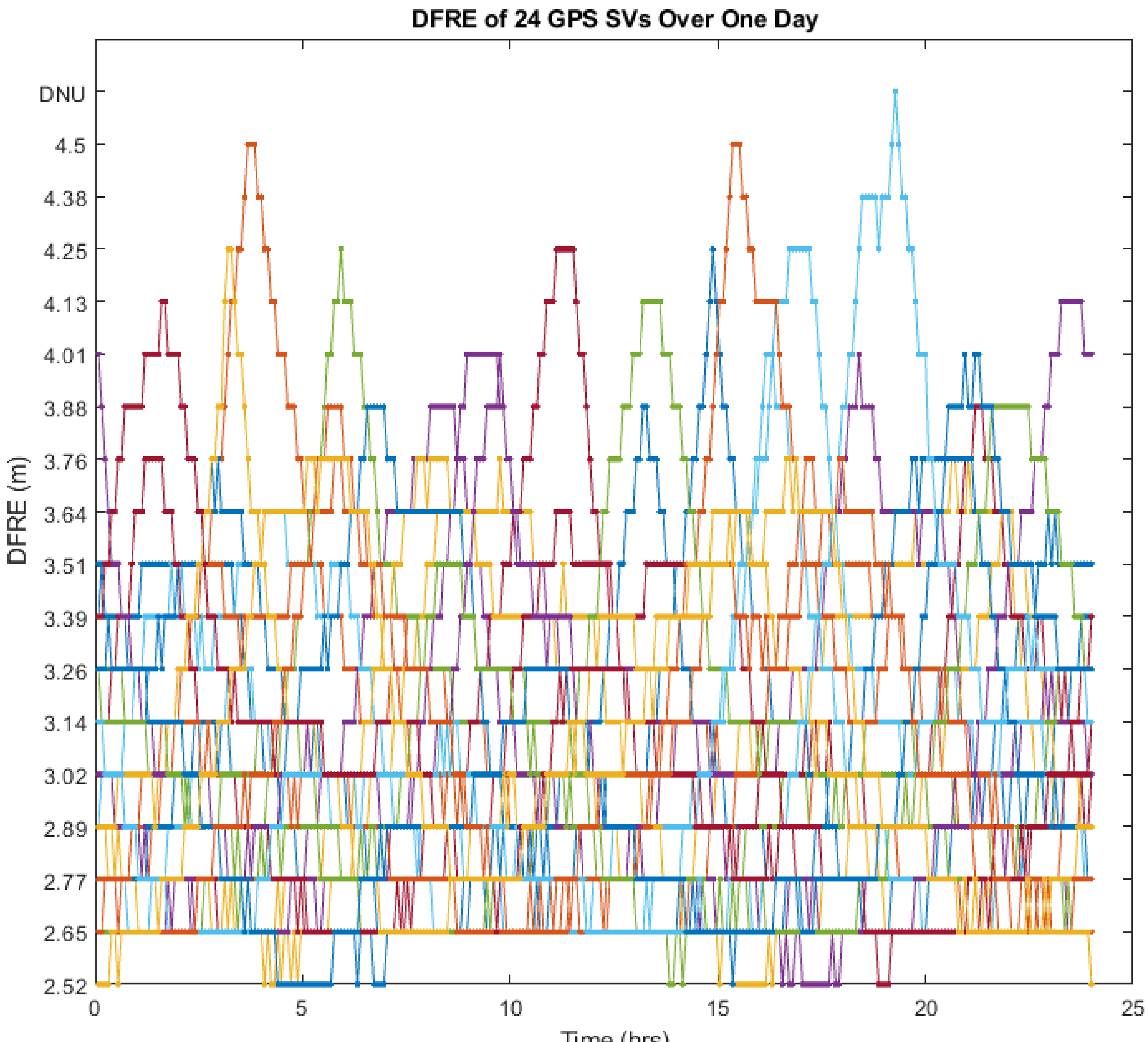
SBAS σ_{UDRE} (σ_{DFRE}) Results



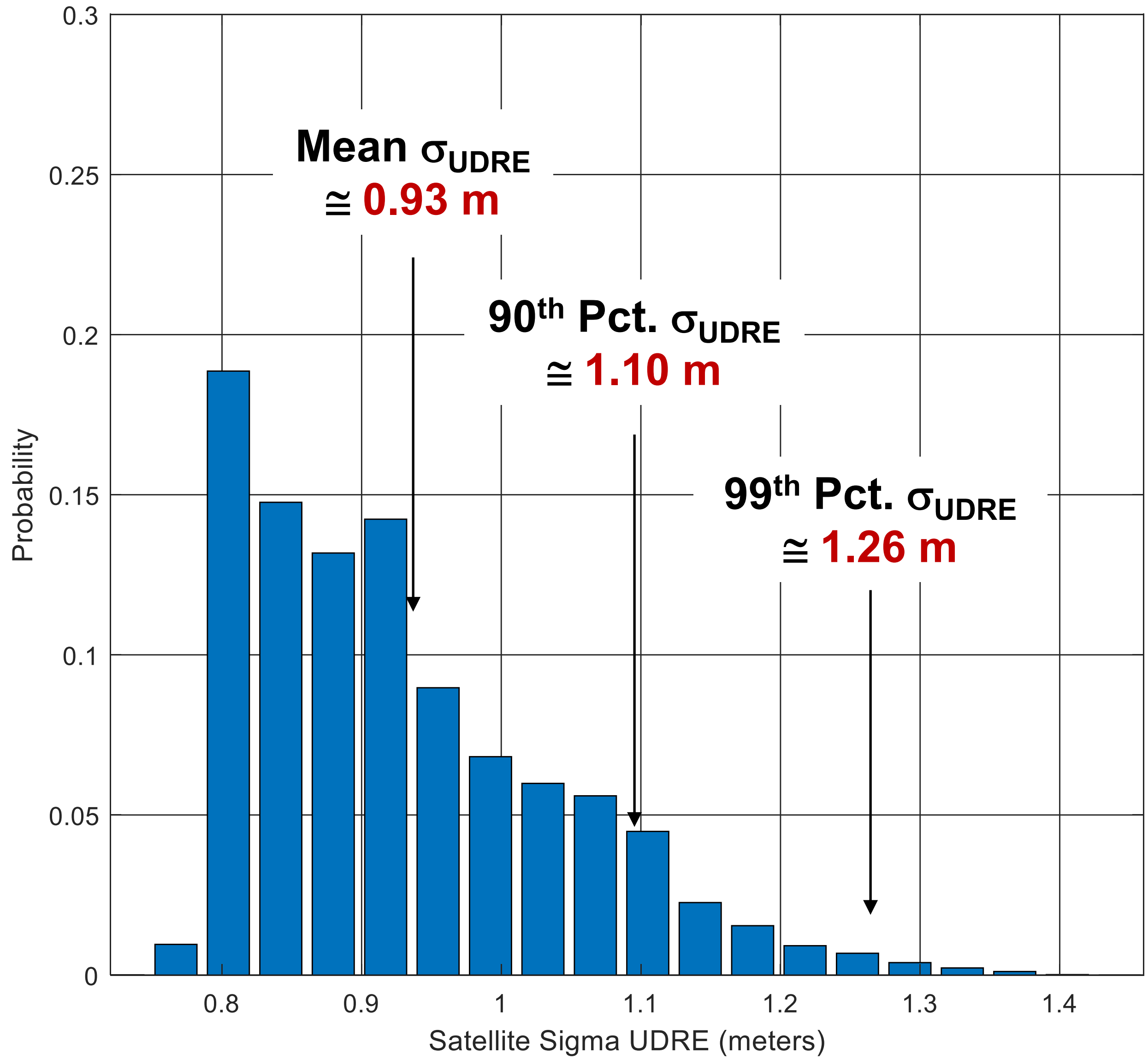
99th-percentile σ_{UDRE} discretized from 0.75 to 1.40 in 20 bins
σ_{UDRE} contours discretized into 20 colors

σ_{UDRE} = UDRE / 3.29

UDRE vs. Time for All 24 GPS Satellites



σ_{UDRE} Histogram Over All Satellites



Comparison to Previous ARAIM Error Parameters

- **Compare simulated results of SBAS-like monitoring to previous assumed values for satellite SIS errors:**

SBAS Monitoring	"Online" ISM	"Offline" ISM
σ_{UDRE} (mean) ≅ 0.93 m	URE = 0.63 m	URE = 0.87 m
σ_{UDRE} (90^{th} pct) ≅ 1.10 m	URA = 1.00 m	URA = 1.30 m
σ_{UDRE} (99^{th} pct) ≅ 1.26 m	b_{nom} = 0.35 m	b_{nom} = 0.50 m

- **The results for SBAS-like monitoring are consistent with "online" model for military ARAIM.**

Summary and Ongoing Work

- **ARAIM requires external monitoring to support ISM parameters provided to users.**
  - **Civil ARAIM relies on satellite constellation commitments supported by internal constellation monitoring.**
  - **Military ARAIM could do the same but would benefit from less-conservative values provided by its own monitoring.**
- **SBAS-like "snapshot" monitoring evaluated in this presentation.**
  - **Results support Sigma_DFRE values of about 1 meter**
  - **Sufficient to meet previous assumptions for "online" ARAIM**
- **In ongoing work, examine smaller reference networks and compare "snapshot" results to batch or sequential estimation with slower updates.**

References (1)

Thank you for your attention!

Please e-mail the first author, Sam Pullen (spullen@stanford.edu) with any questions.

[1] A. Katz, S. Pullen, et al., "ARAIM for Military Users: ISM Parameters, Constellation-Check Procedure and Performance Estimates," *Proc. ION ITM 2021*, January 2021. http://web.stanford.edu/group/scpnt/gpslab/pubs/papers/Katz_ION_ITM2021_Military_ARAIM.pdf

[2] T. Walter, "Bounding Satellite Fault Probabilities," Stanford University, August 2021 (unpublished).

[3] Y. Zhai, S. Kiarash, et al., "A Dedicated ARAIM Ground Monitor to Validate the Integrity Support Message," *Proc. ION GNSS+ 2017*, Portland, OR., September 2017. https://doi.org/10.33012/2017.15175

[4] *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)

Thank you for your attention!

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[5] "Proposed amendments to Annex 10, Volume I: Global Positioning System (GPS) provisions," ICAO Navigation Systems Panel (NSP), Sixth Meeting, WP 2, November 2020.

[6] "Proposed amendments to Annex 10, Volume I: Galileo system provisions," ICAO Navigation Systems Panel (NSP), Sixth Meeting, WP 4, November 2020.

[7] "Proposed amendments to Annex 10, Volume I: Global Navigation Satellite System (GLONASS) provisions," ICAO Navigation Systems Panel (NSP), Sixth Meeting, WP 3, November 2020.

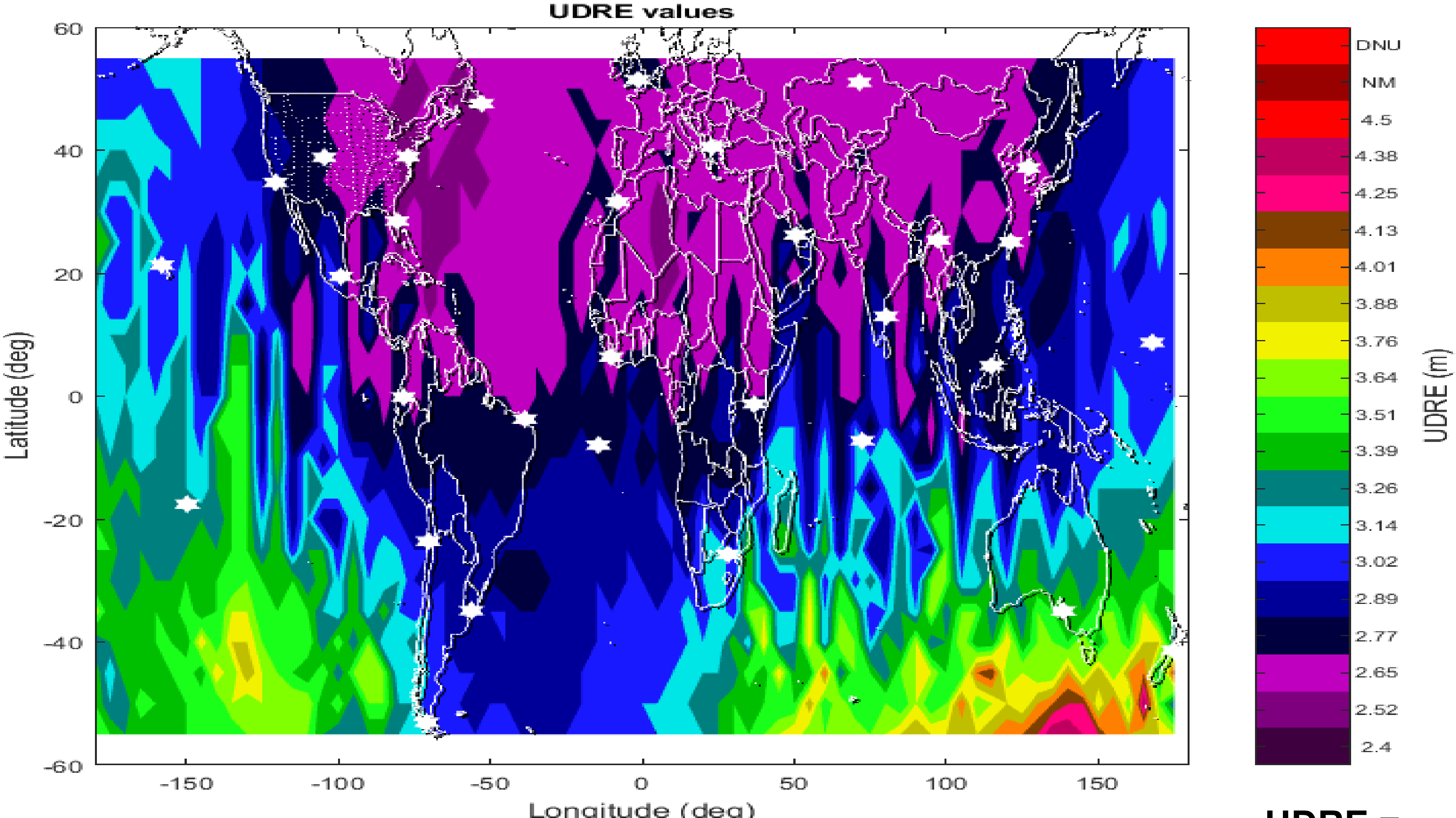
[8] "Proposed amendments to Annex 10, Volume I: BeiDou Navigation Satellite System (BDS) provisions," ICAO Navigation Systems Panel (NSP) Sixth Meeting, WP 5, November 2020.

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

Backup Slides

Backup Slides follow…

SBAS UDRE (DFRE) Results



UDRE = 3.29 σ_{UDRE}

99th-percentile UDRE discretized from 2.4 to 4.5 meters in 20 bins
UDRE contours discretized into 20 colors

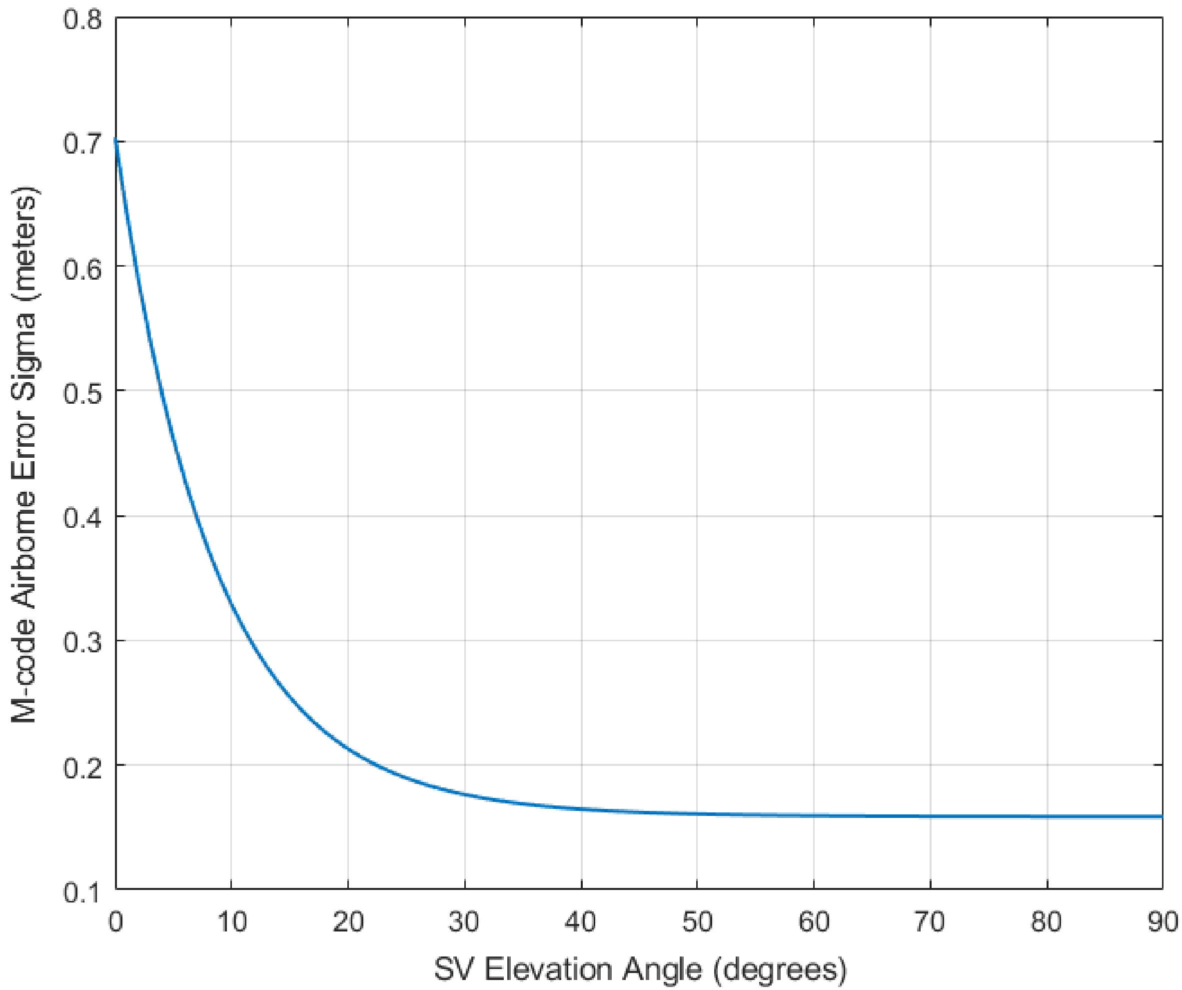
Galileo E1/E5 Error Model Parameters used in Previous ARAIM Studies [1]

Only P_{sat} and P_{const} (blue numbers) change from GPS.

Parameter	Frozen	Offline	Online
URA	1.60 m	1.30 m	1.00 m
URE	1.07 m	0.87 m	0.63 m
b_{nom}	0.75 m	0.50 m	0.35 m
P_{sat}	1.0×10^{-4} / SV	3.0×10^{-5} / SV	1.0×10^{-6} / SV
P_{const}	1.0×10^{-5}	1.0×10^{-6}	1.0×10^{-8}
Mean Fault Duration (MFD)	1.0 hrs	1.0 hrs	0.6 hrs
$K_{mcode\text{-}air}$	0.8	0.8	0.8

Multiplier of airborne error sigma to reflect M-code v/s C/A-code

M-code σ_{air} vs. Elevation Angle



$$\sigma_{air}^2 = K_{mcode\_air}^2 \left[\left(0.15 + 0.43\, exp(-\theta/6.9)\right)^2 + \left(0.13 + 0.53\, exp(-\theta/10.0)\right)^2 \right]$$

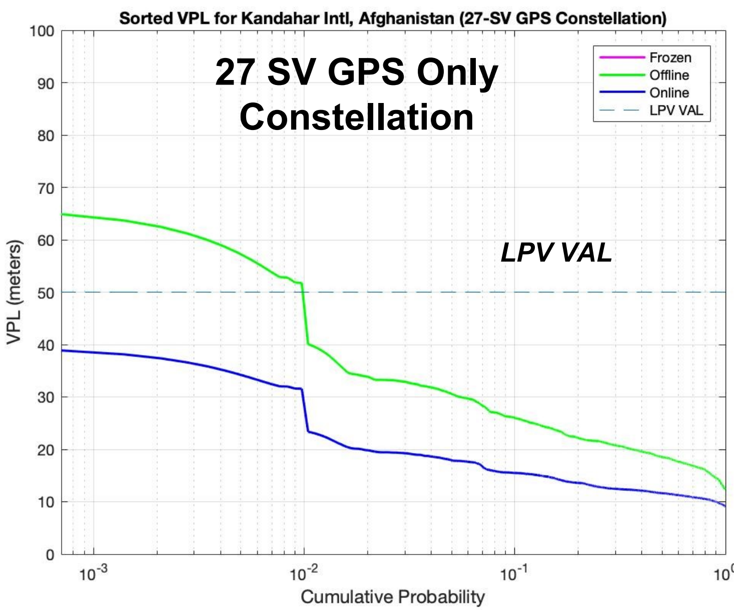
noise + divergence term (AAD B) **multipath term**

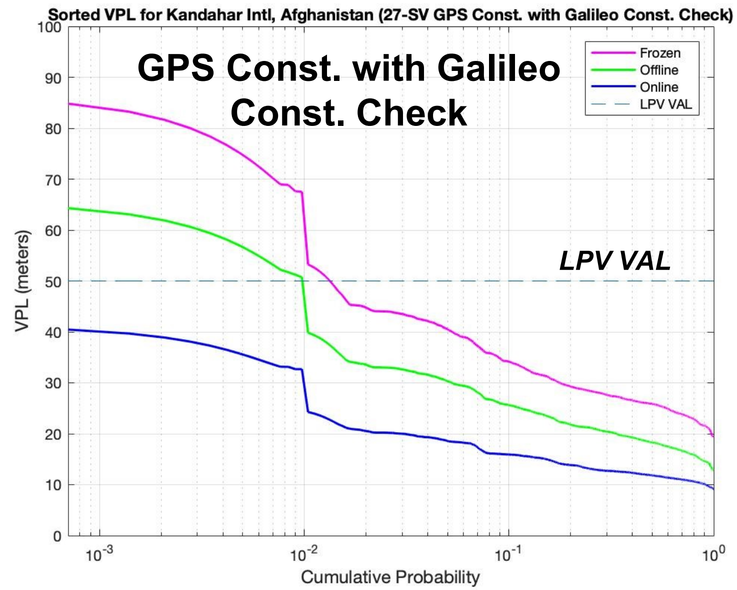
θ = satellite elevation angle in degrees

Three Sets of GPS/Galileo ARAIM Results

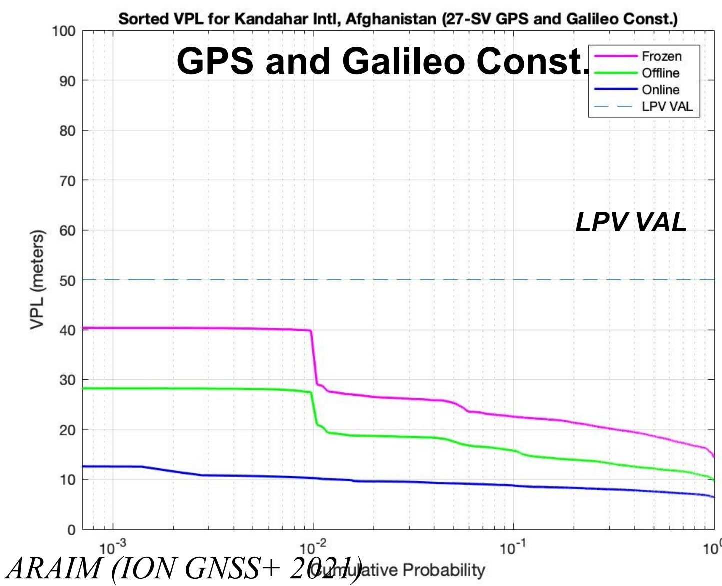
- **GPS: GPS SPS standard "expanded" 27-satellite constellation only (same as in previous results)**
- **GalC: Also track and solve for position states using assumed 27-satellite Galileo Open Service (E1/E5) and compare GPS and Galileo position estimates.**
  - **This comparison reduces the impact of a GPS constellation failure and allows P_{const} for GPS or Galileo to exceed 10^{-7}.**
- **GGal: As for GalC, but use Galileo satellites interchangeably with GPS satellites (control case).**
  - **GPS and Galileo satellites contribute similarly to position estimates.**
  - **Outages of individual Galileo satellites evaluated within ARAIM (as performed by civil ARAIM).**

Previous M-code ARAIM Results (Baseline ISM at Kandahar) [1]





(No "frozen" result above due to $P_{const} > 10^{-7}$)



VPL Comparison at Kandahar

- "Frozen" ISM Updates
- "Offline" ISM Updates
- "Online" ISM Updates