Equatorial Plasma Bubble Effects on GBAS and Its Mitigation Techniques

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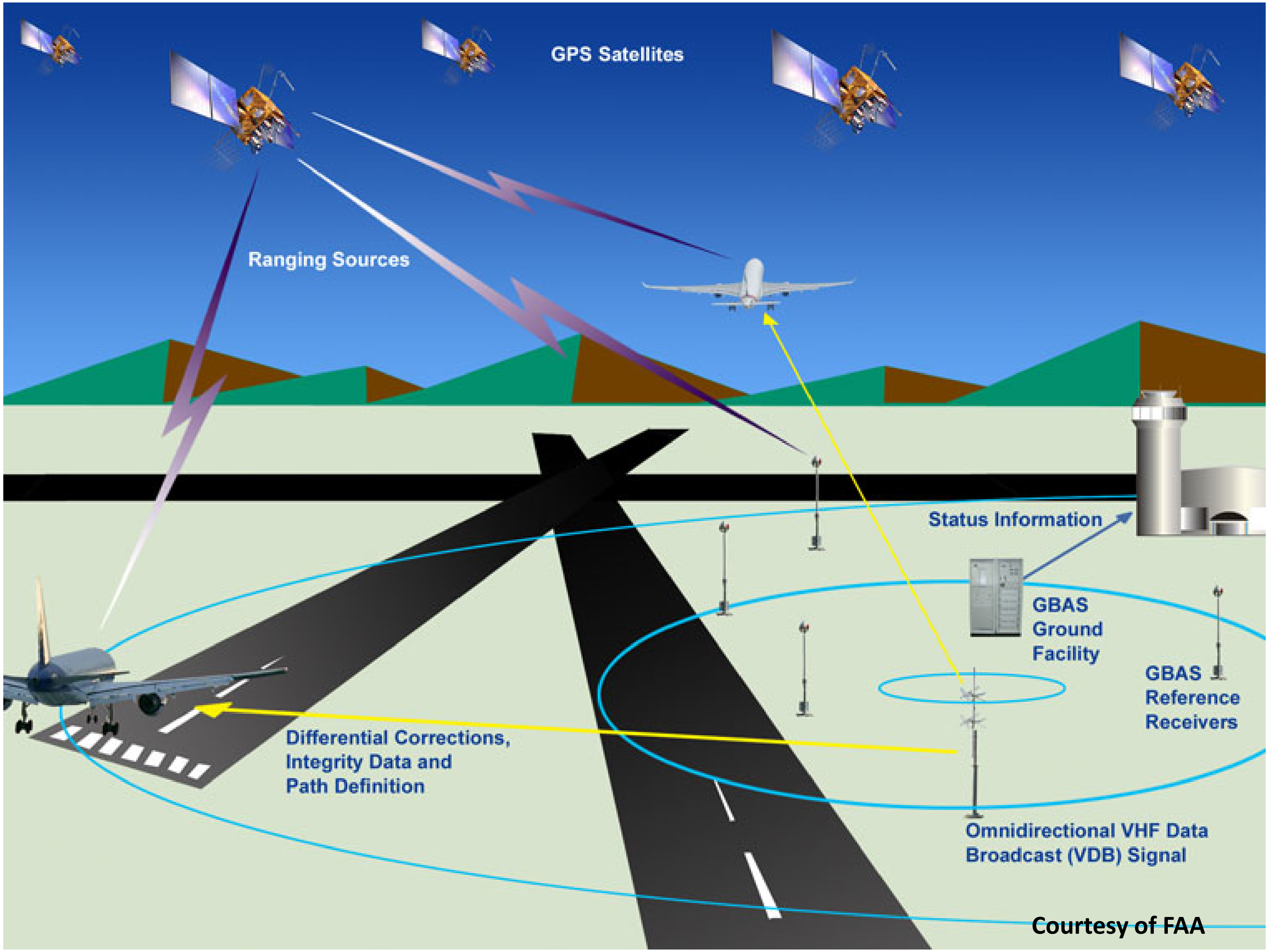
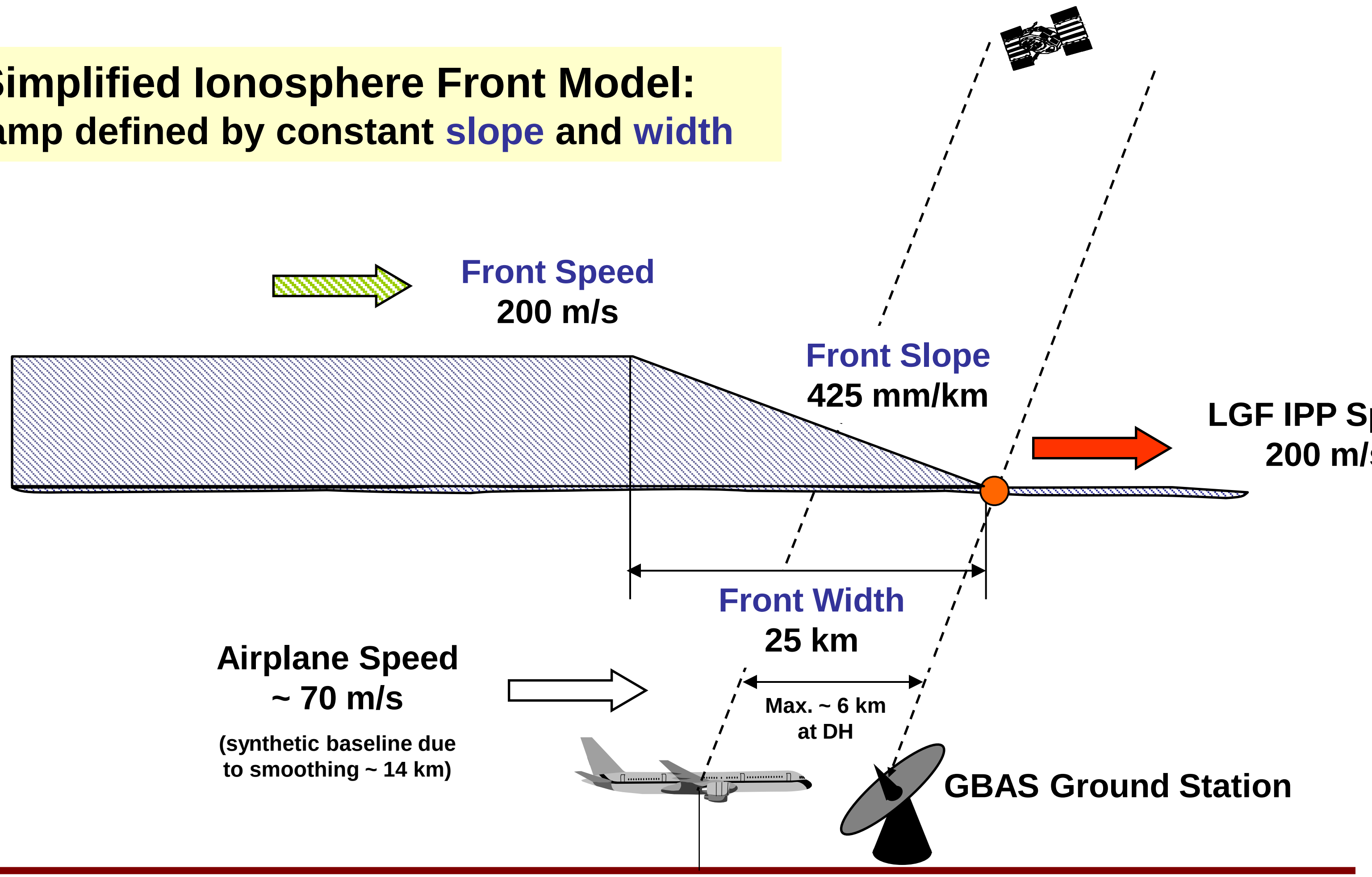
Ground Based Augmentation Systems (GBAS) and Global Implementation Status



Ionosphere Anomaly Front Model:
Potential Impact on a GBAS User

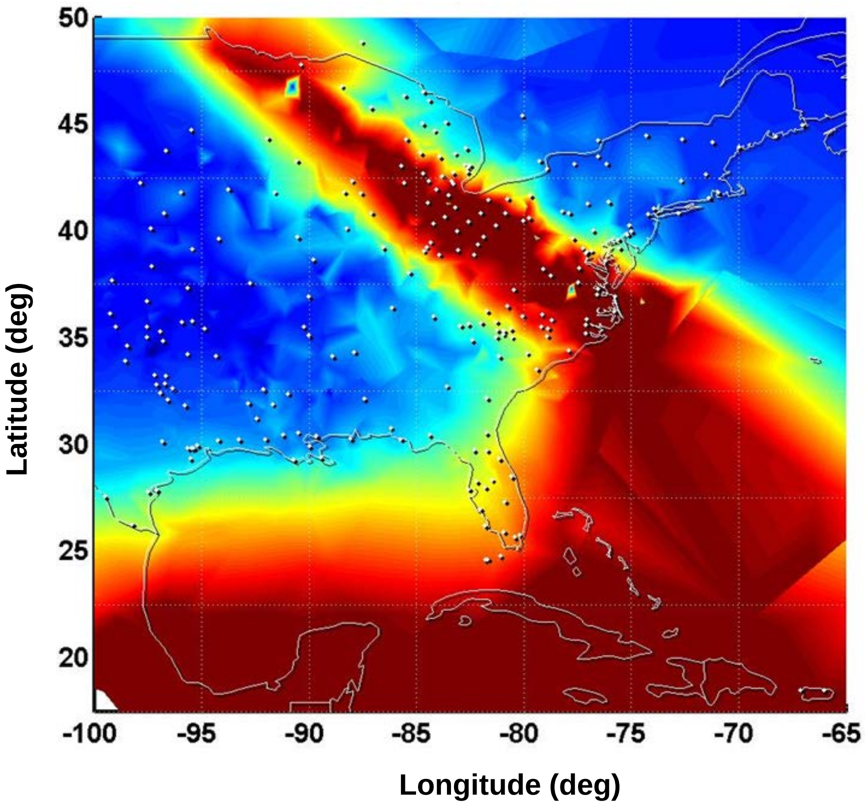
Simplified Ionosphere Front Model:
a ramp defined by constant slope and width



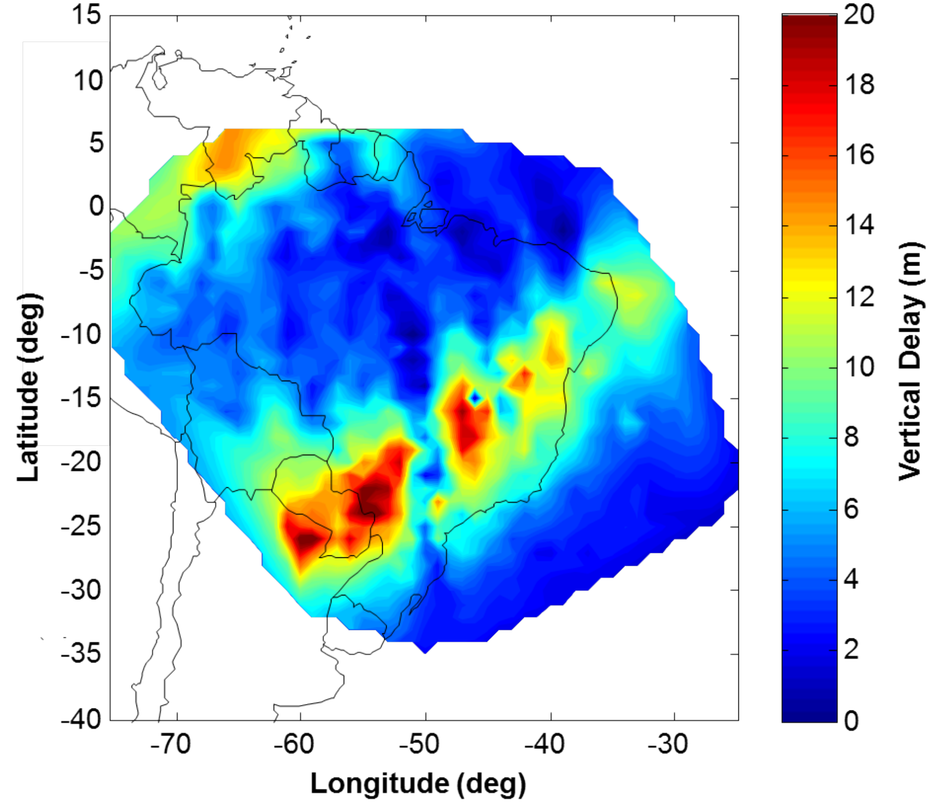
***Stationary Ionosphere Front Scenario*:**
Ionosphere front and IPP of ground station IPP move with same velocity.
Maximum Range Error at DH: 425 mm/km × 20 km = 8.5 meters

Abnormal Gradients:
Mid-Latitudes vs. Low-Latitudes

Over CONUS
(11/20/2003, 20:15 UT)
425 mm/km max.



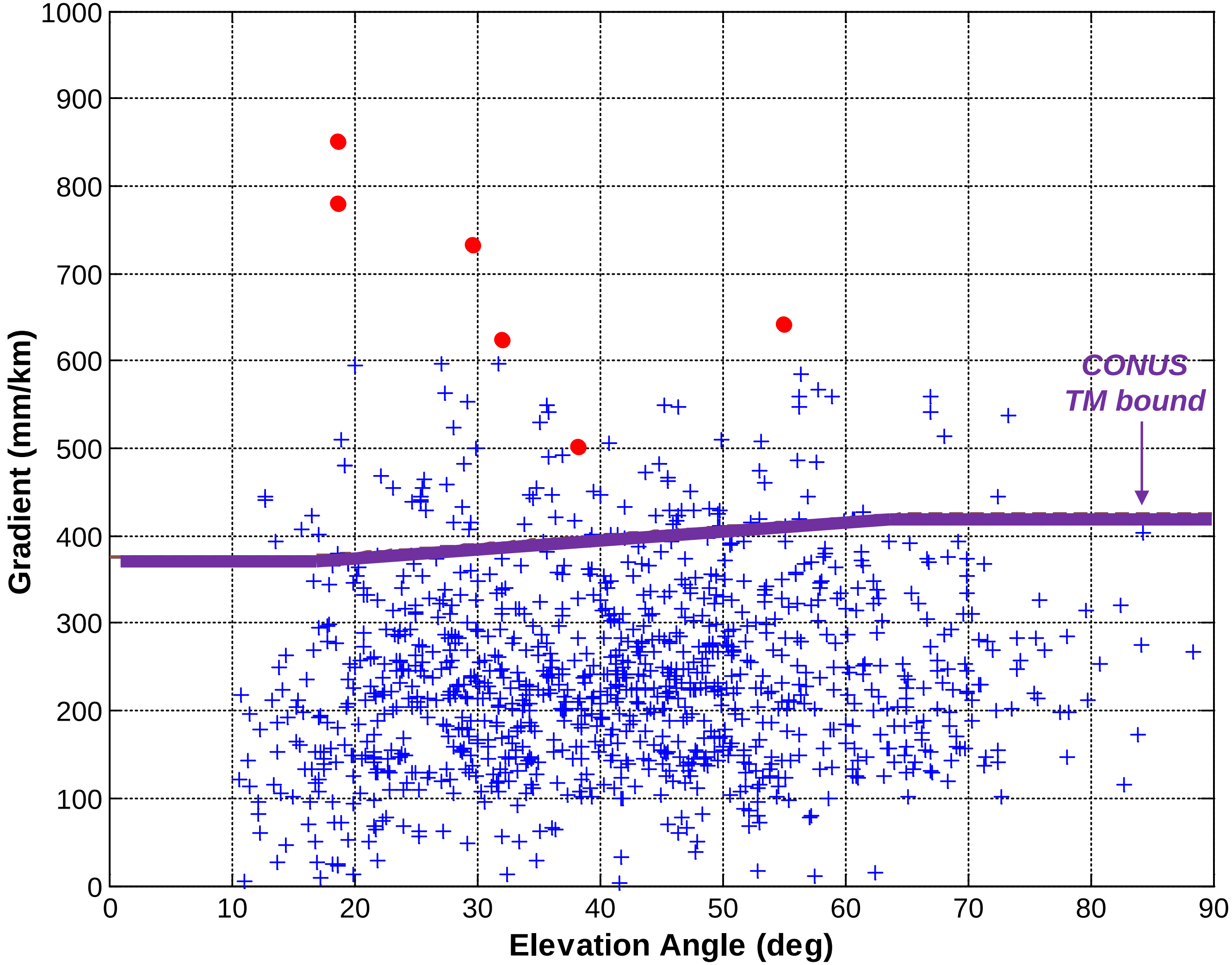
Over Brazil
(3/1/2014, 01:00 UT)
850 mm/km max.



GBAS Brazilian Ionospheric Threat Model Study (Phase 1)

- **Project conducted as an international, interagency effort**
  - **Teams involved: DECEA, ICEA, INPE, FAA Technical Center, Stanford, Boston College, NAVTAC, Mirus, and KAIST**
- **120+ active ionosphere days were identified during the peak of the current solar cycle (March 2011 – April 2014)**
  - **Data collection from multiple Brazilian GNSS station networks**
  - **85 scintillating, 8 non-scintillating, and 33 stormy days**
- **Threat points generated from LTIAM processing and verified by manual inspection**
  - **30 points > 500 mm/km; 5 points > 600 mm/km**
  - **Maximum gradient $\cong$ 850 mm/km**
  - **Significantly exceeds the maximum gradient of the CONUS threat model (375~425 mm/km)**

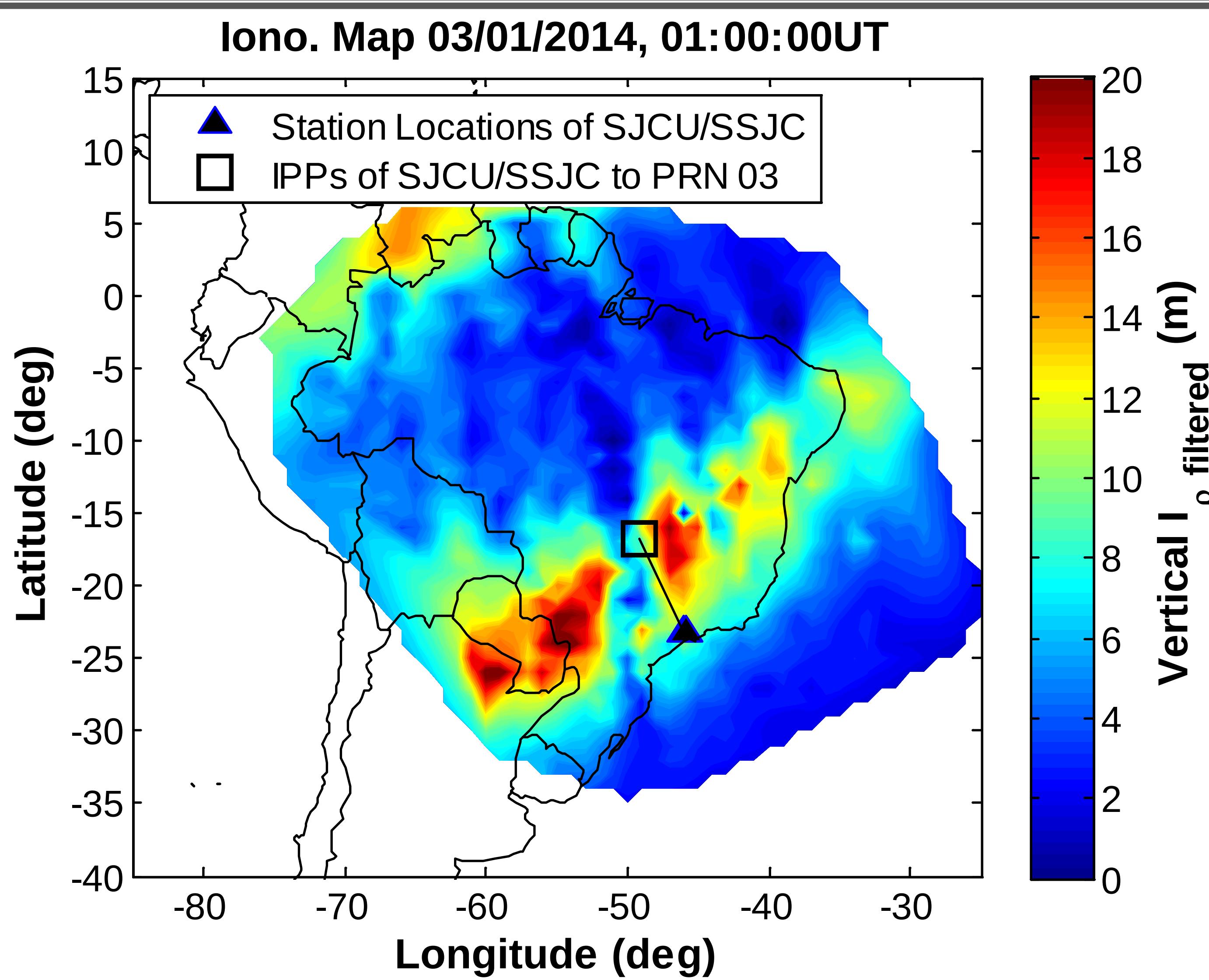
Large Brazilian Gradients Observed
(Phase 1 of Brazil Ionospheric Study)



Threat points shown with (•) validated via multi-dimensional approach (see ION Pacific PNT 2015 paper) to confirm these are actual ionospheric events.

SJCU-SSJC, PRN 03

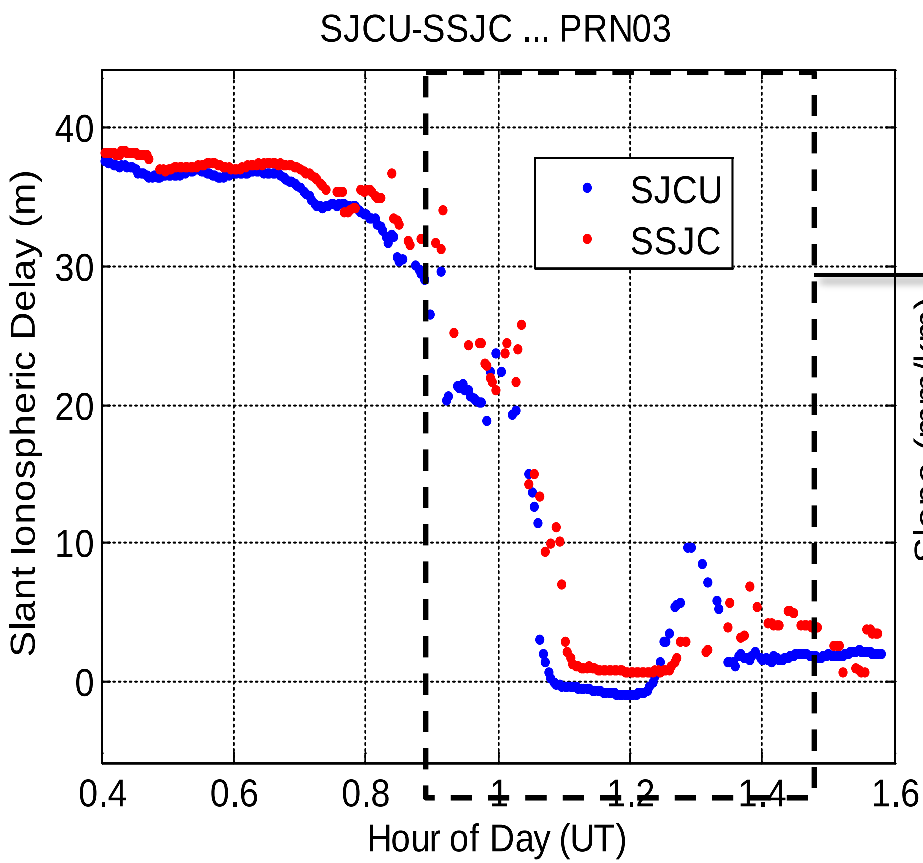
Regional Ionospheric Map (01:00:00 UT)

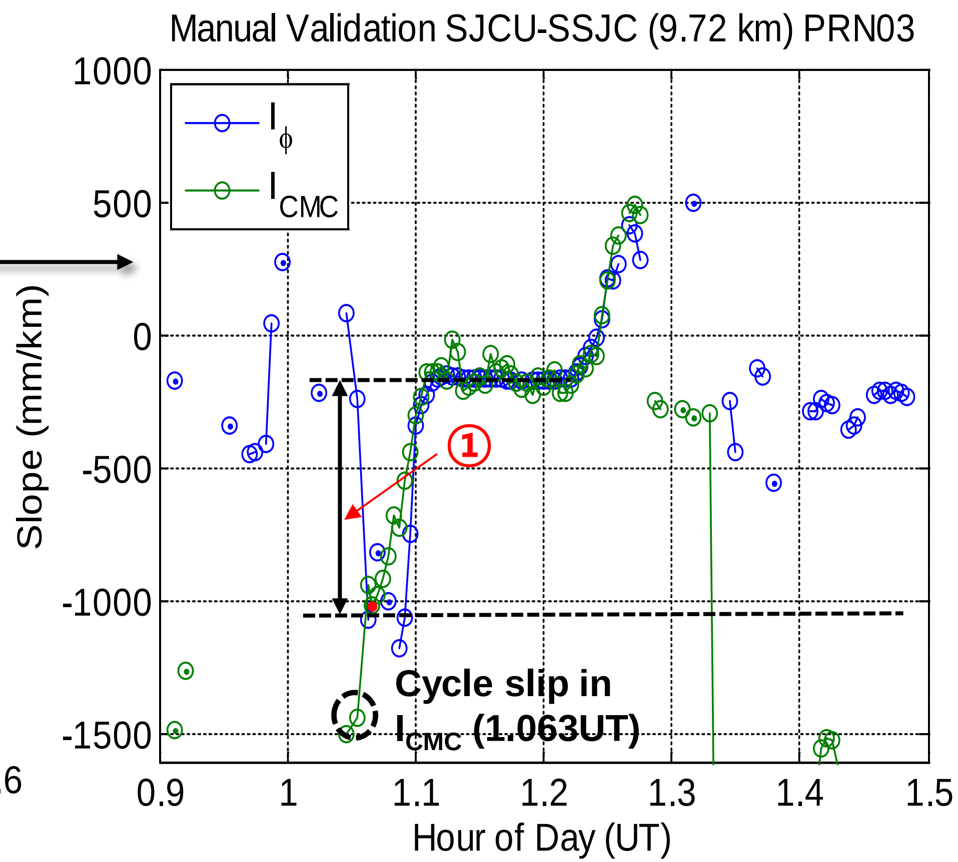


The EPB with a vertical depletion of ~15 m (or 35 m in slant domain) impacts the IPPs (SJCU-SSJC to PRN 03)

SJCU-SSJC, PRN 03
Delay and Gradient Estimates

Ionospheric delays	***Ionospheric gradients***

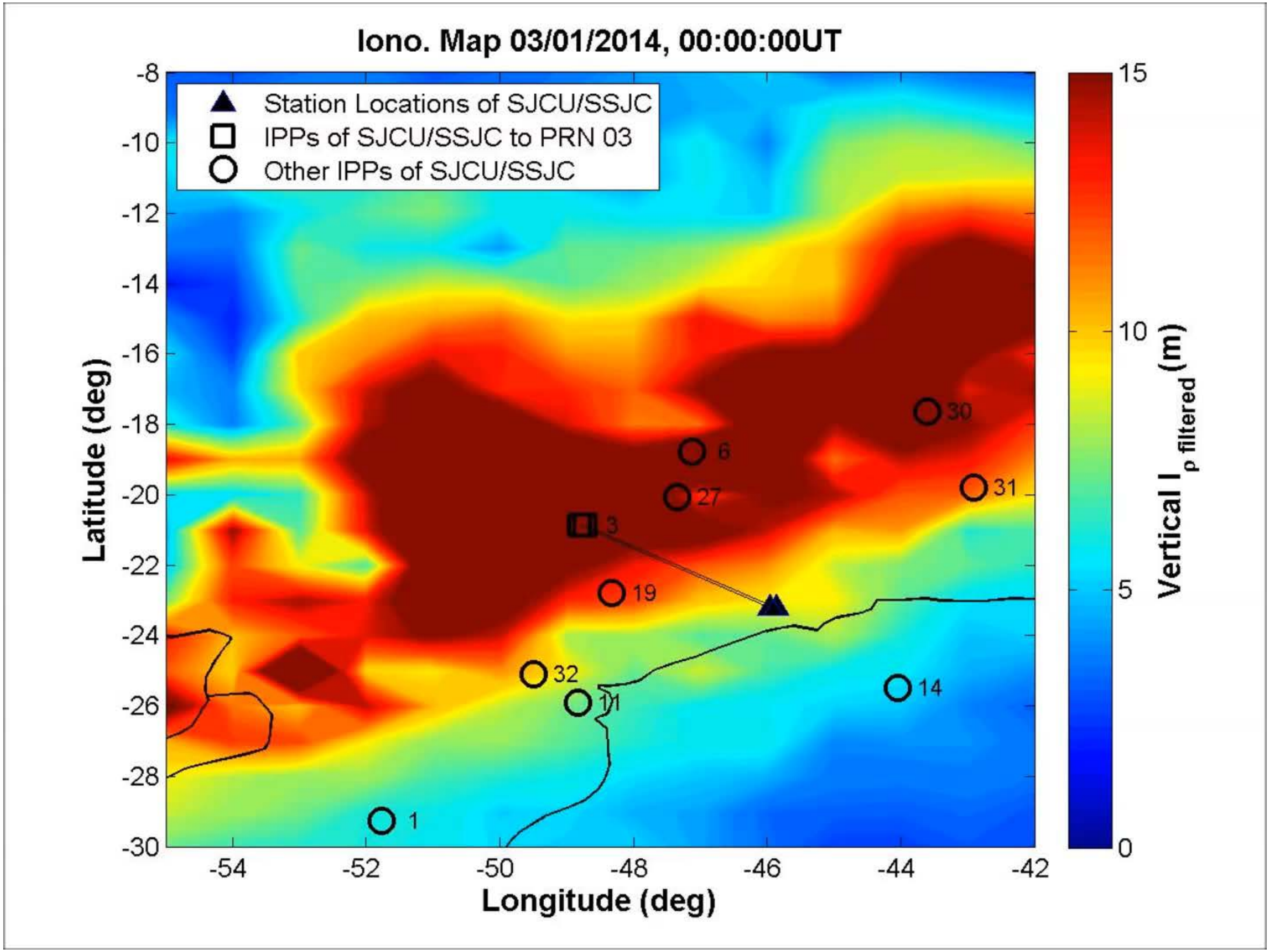




① abs[-1016.0 - (-165.3)] = 850.7 mm/km

※ measured with L1-CMC

Regional Ionospheric Delay Map (Video)



Mitigation Approach I:

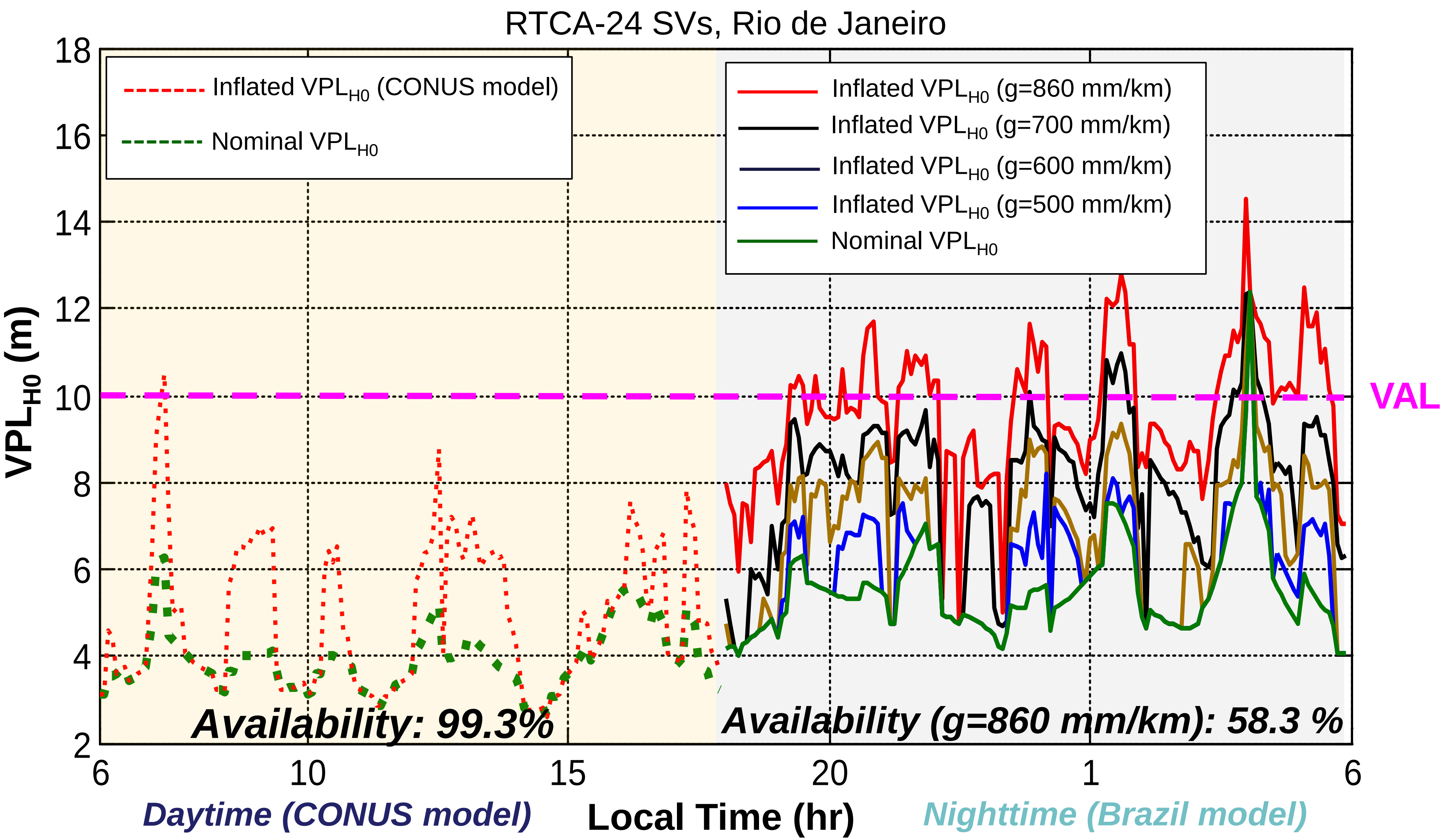
Worst-Case Gradient Simulation and Position Domain Geometry Screening (PDGS)

Position Domain Geometry Screening (Worst-Case Ionospheric Mitigation)

- **Identify undetected ionosphere-induced errors using user geometry and ionospheric wave front simulations.**
  - **Safety assessment is based on the parameter combination causing the largest GBAS vertical position error (“MIEV”).**
  - **No probabilistic “averaging” among the many parameter combinations inside the threat model bounds.**

- **If needed, inflate broadcast integrity parameters to exclude geometries with potentially unsafe errors (i.e., max. MIEV > TEL).**
  - **This is a direct extension of the approach used in CONUS.**
  - **Resulting inflation is very conservative, as in CONUS → *many good geometries are removed as well (availability loss)***

Inflated VPL_{H0} (all-in-view): *4-km DH*



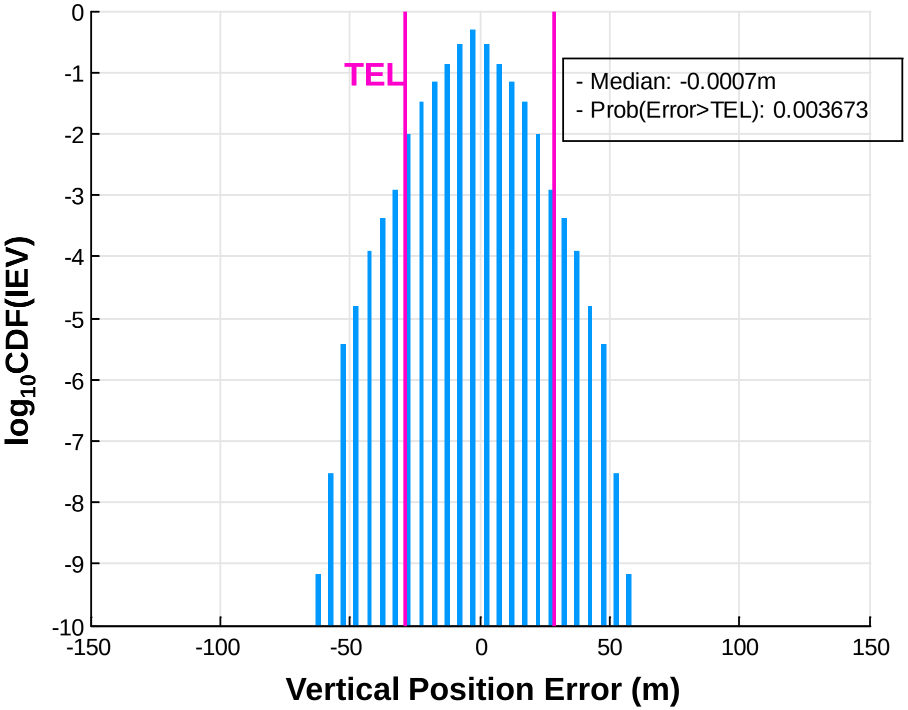
Assessment Approach II: Monte Carlo Simulation and Real-time Threat Mitigation

Monte Carlo Simulation Concept

- **Assess the overall (ensemble) user impact by running many anomalous ionospheric trials through the use of randomly generated threat parameters.**
- **For each time epoch and subset geometry:**
  - **Randomly-sampled EPB parameters, including tilt angle, width, velocity, and gradients (SV-specific), are selected.**
  - **One SV is assumed to be affected by the worst-case EPB with the maximum gradient of 860 mm/km.**
- **After simulating all possible geometries at each epoch, we examine the probability of distribution of ionospheric induced vertical errors and TEL bounding.**
  - ***"Worst-case impact"* should be approximated by inclusion in distribution of simulation results.**

TEL Bounding Results:
CDF of Iono-induced Vertical Errors at 4-km DH

Worst Gradient Impact on 1SV



Prob(Error >TEL) ≅ 0.0037

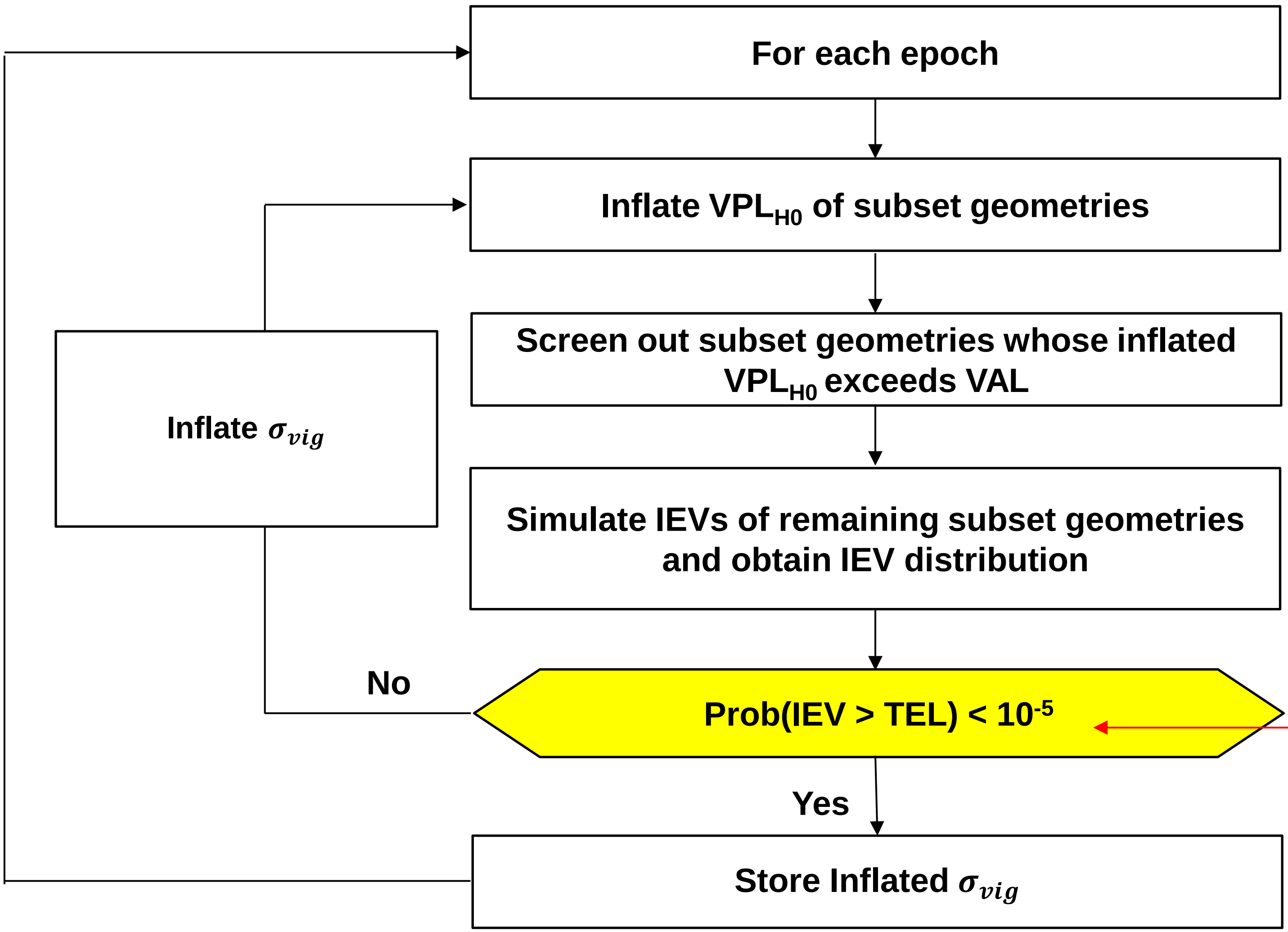
$$P_{loss\ of\ integrity}$$

$$10^{-8}$$

$$= P_{unsafe\ error} \times P_{a-prior}$$

$$10^{-2} \qquad 10^{-6}$$

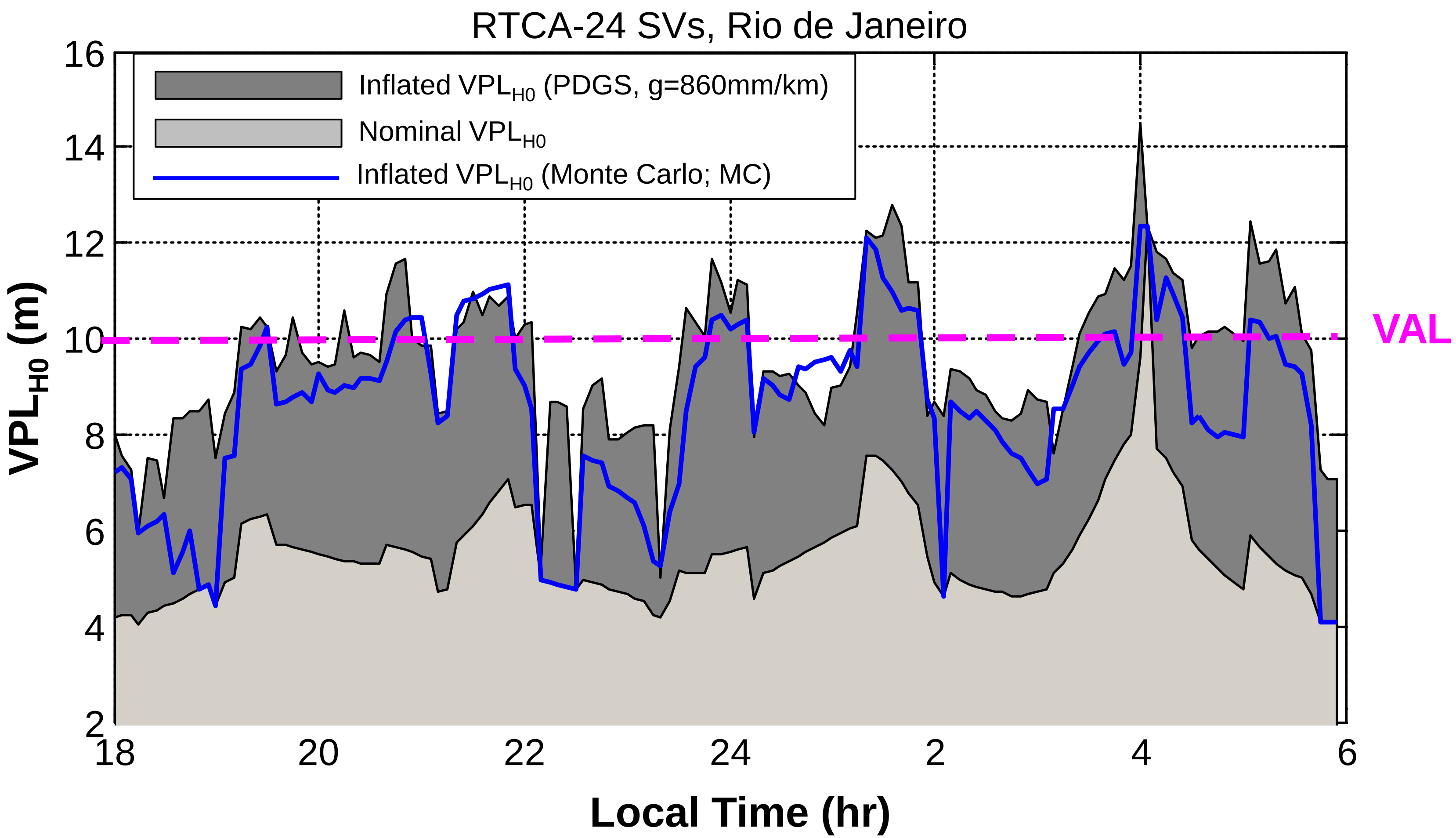
Real-Time Threat Mitigation Concept using Monte Carlo Simulation



$$\frac{P_{loss\ of\ integrity}}{P_{a-prior}} = \frac{10^{-8}}{10^{-3}}$$

Inflated VPL_{H0} (all-in-view):

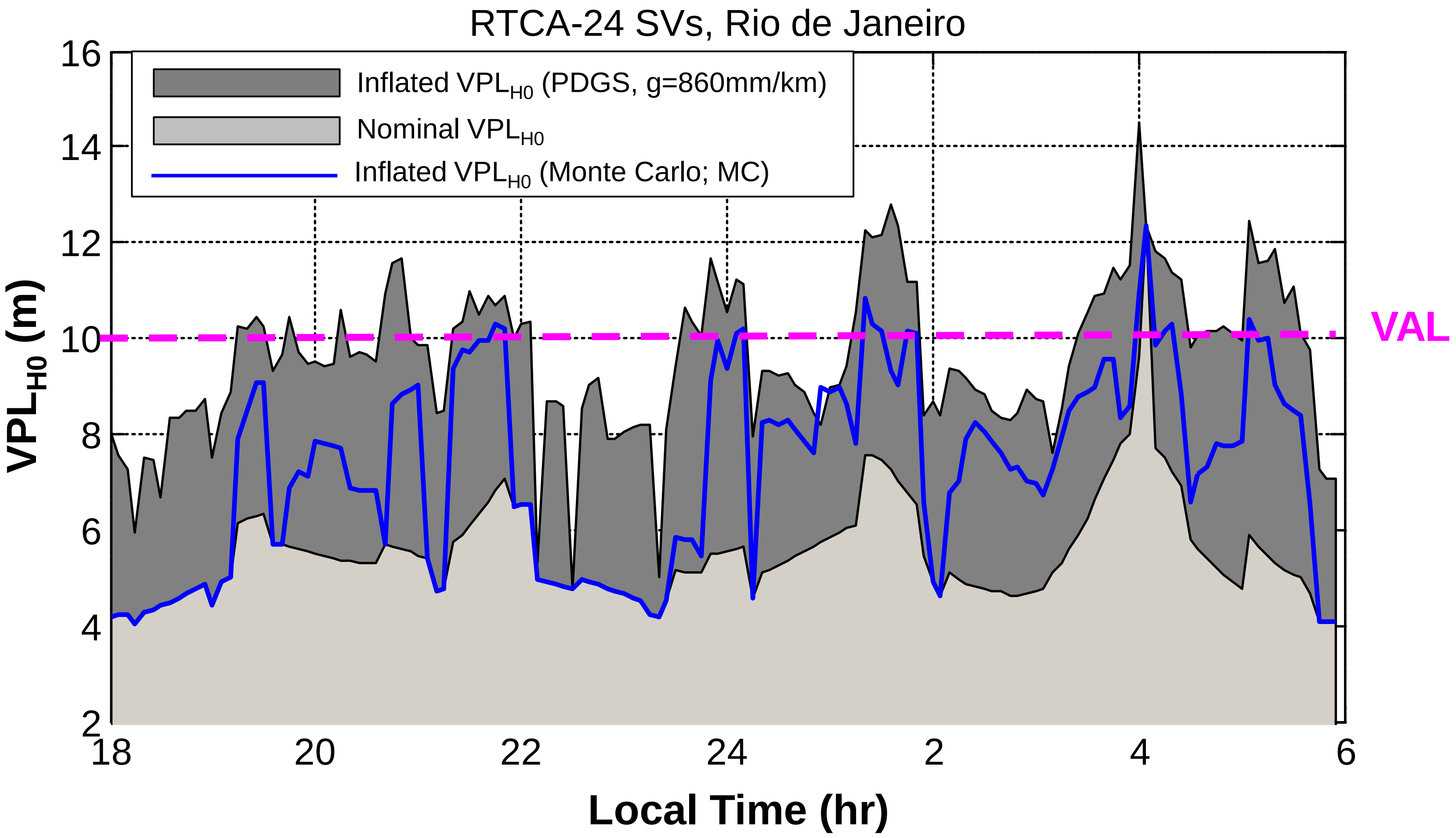
4-km DH, $P_{a\text{-}prior} = 10^{-3}$



Availability Results

PDGS - 58.33 % VS. MC - 75.00 %

Inflated VPL_{H0} (all-in-view):
4-km DH, $P_{a\text{-}prior} = 10^{-5}$



Availability Results

PDGS - 58.33 % VS. MC - 89.58 %

Conclusions

- **The behavior of plasma bubbles in low-latitude regions is different from that of ionospheric storms in mid-latitudes.**
  - **Maximum spatial gradients in Brazil are considerably higher than that in CONUS.**
- **The potential impacts of the EPB-induced ionospheric gradients are significant for CAT-I GBAS users.**
- **Real time threat mitigation concept using "Monte-Carlo" simulation was developed**
  - **Additional monitoring/screening applied to GAST-D GBAS should make this threat less significant.**

Thank you for your attention!

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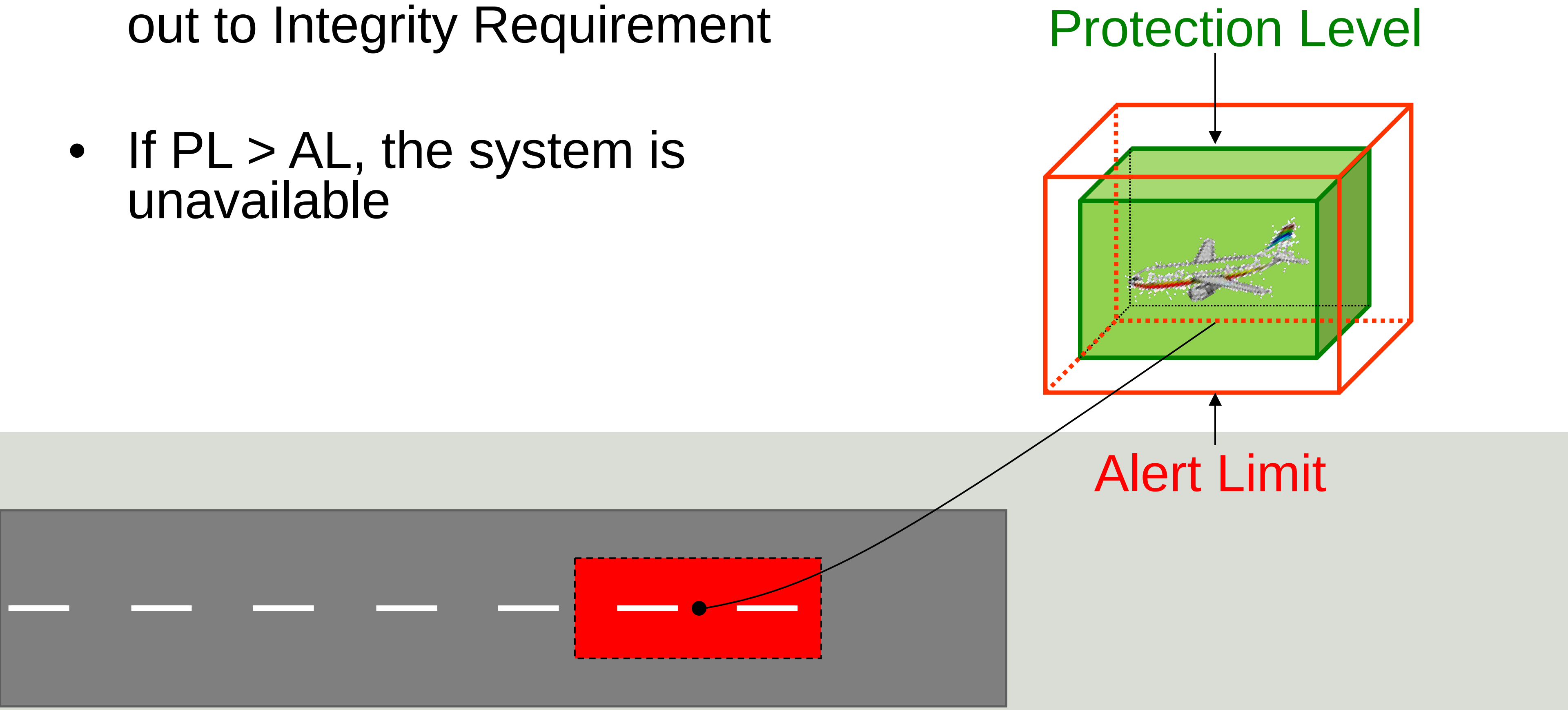
Backup Slides

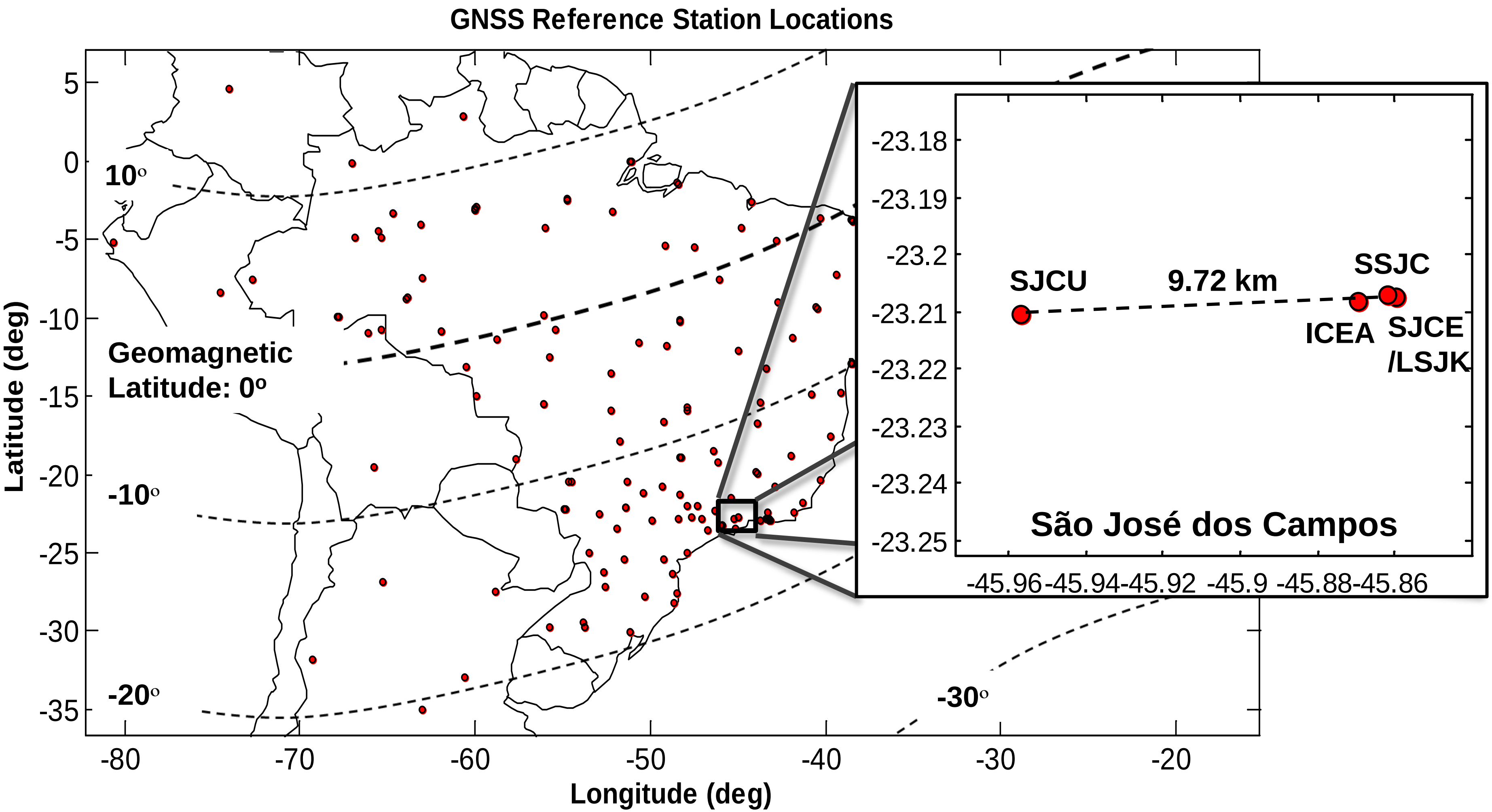
- **Backup slides follow…**

Protection Level and Alert Limit

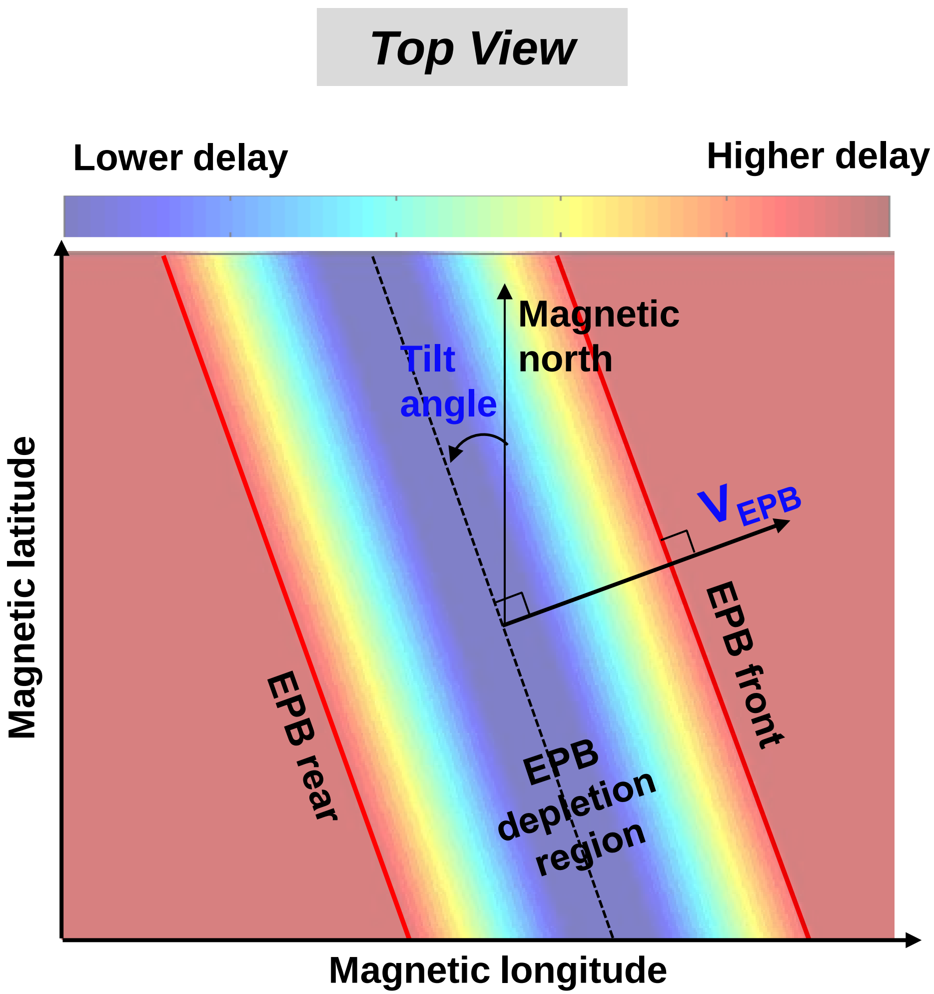
- GBAS Provides Protection Level that Bound Residual User Errors out to Integrity Requirement
- If PL > AL, the system is unavailable

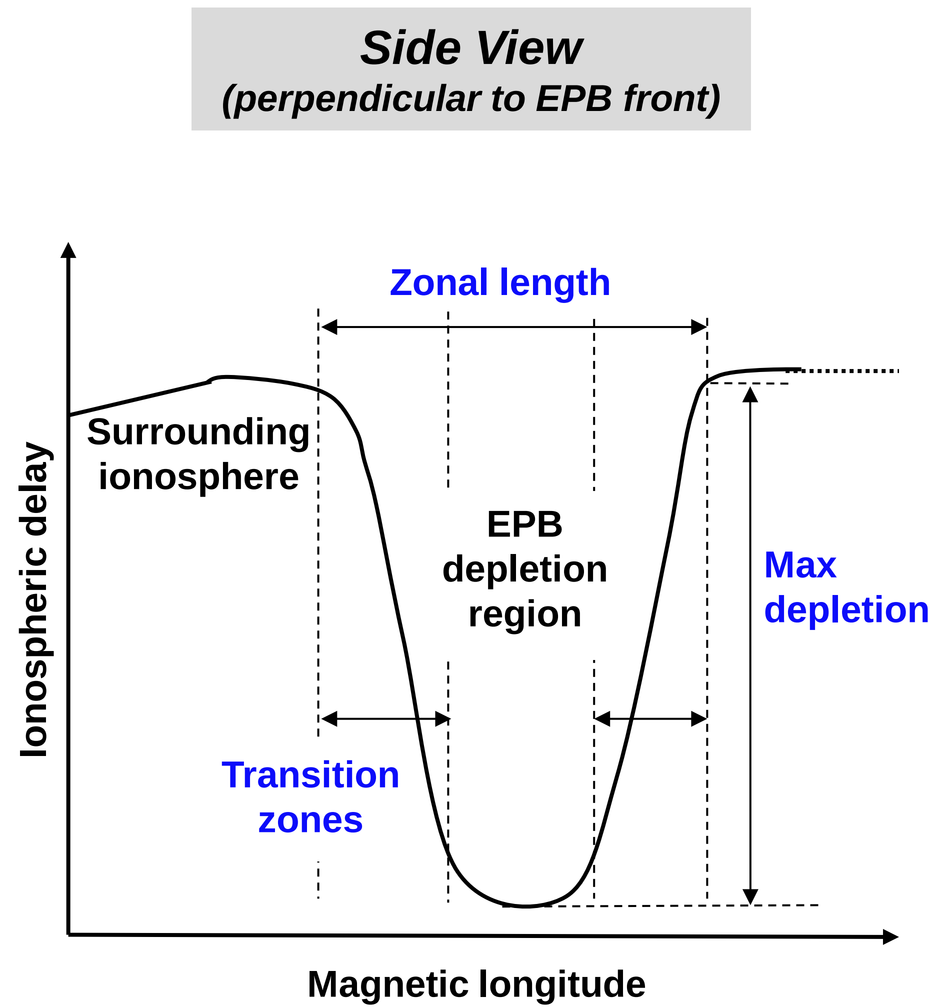


Brazilian GNSS Reference Stations



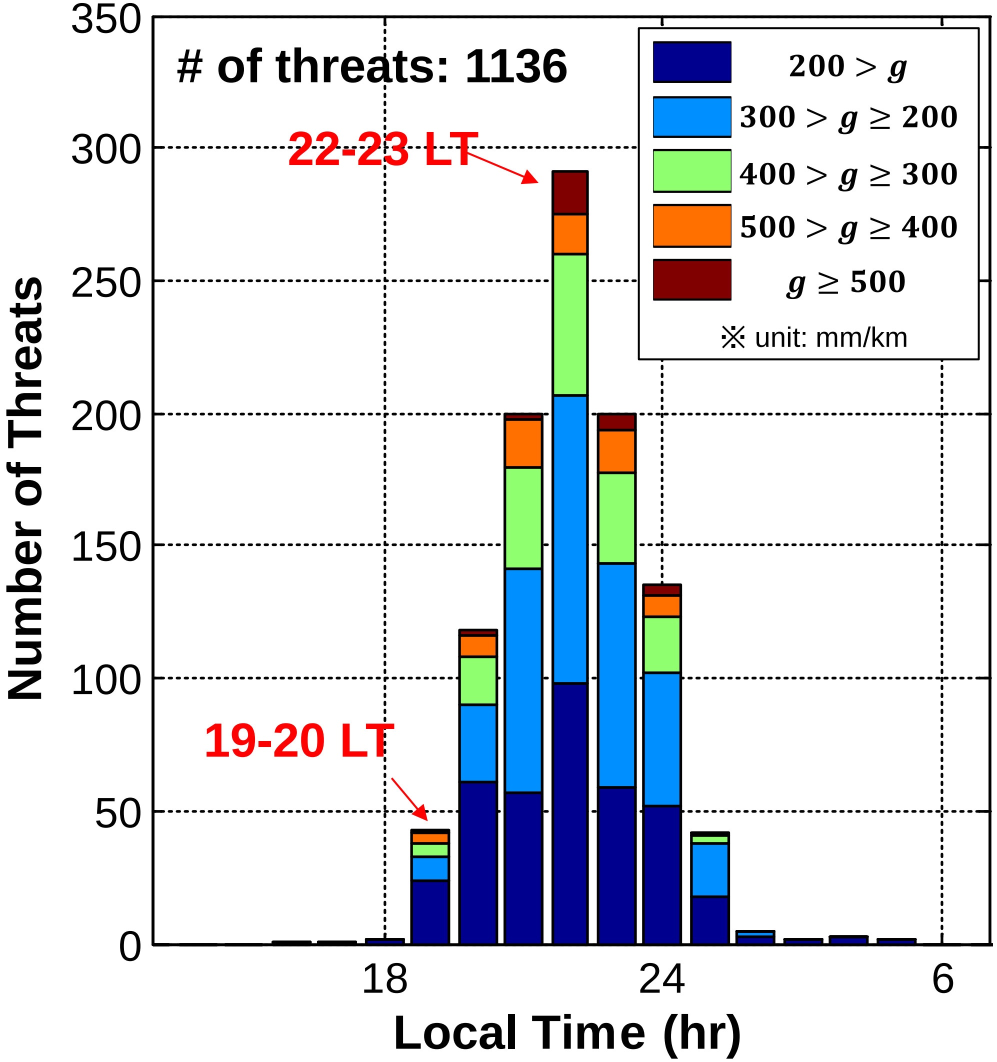
EPB Parameters



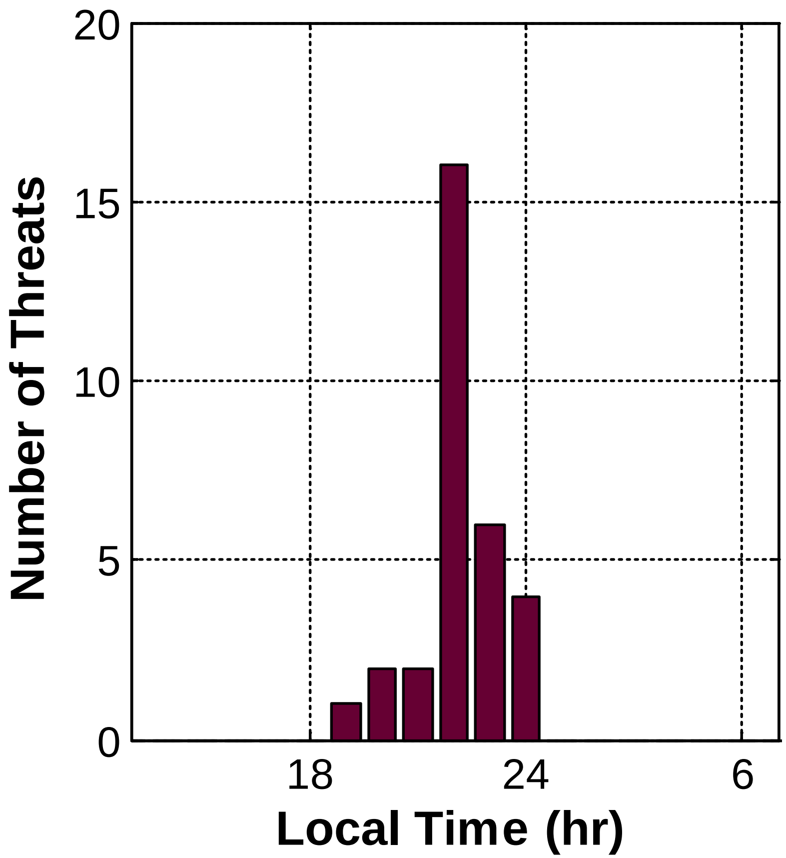


Occurrence Times of Large Gradients

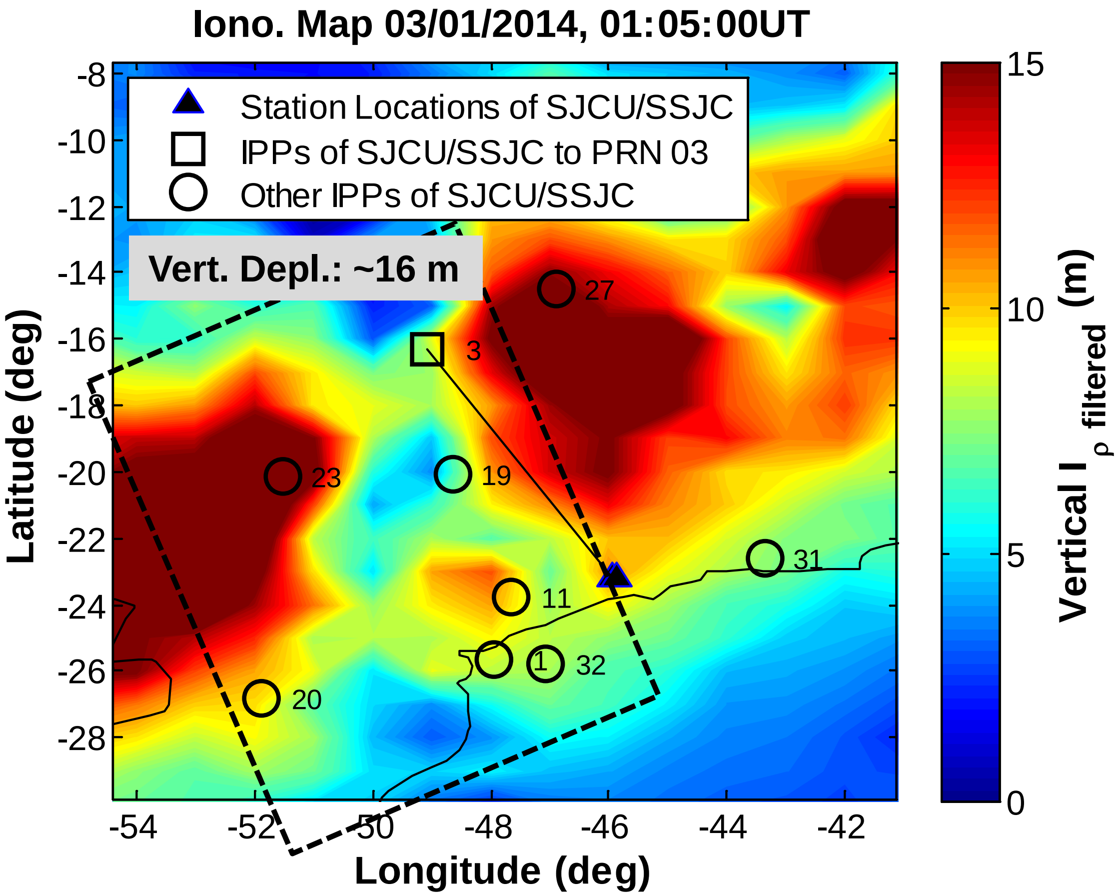
All identified gradients



gradients > 500 mm/km



Simultaneous Impacts of a Single EPB



Max. gradient (~ 850.7 mm/km) observed on PRN 3 at 1.067 UT

Max. gradients observed within ± 75 sec of 1.067 UT

PRN	Time (UT)	Gradient (mm/km)
3	*1.067*	*850.7*
11	1.083	465
19	1.050	77

Max. gradients observed within ± 2.5 min of 1.067 UT

PRN	Time (UT)	Gradient (mm/km)
3	*1.067*	*850.7*
11	1.083	465
19	1.025	571

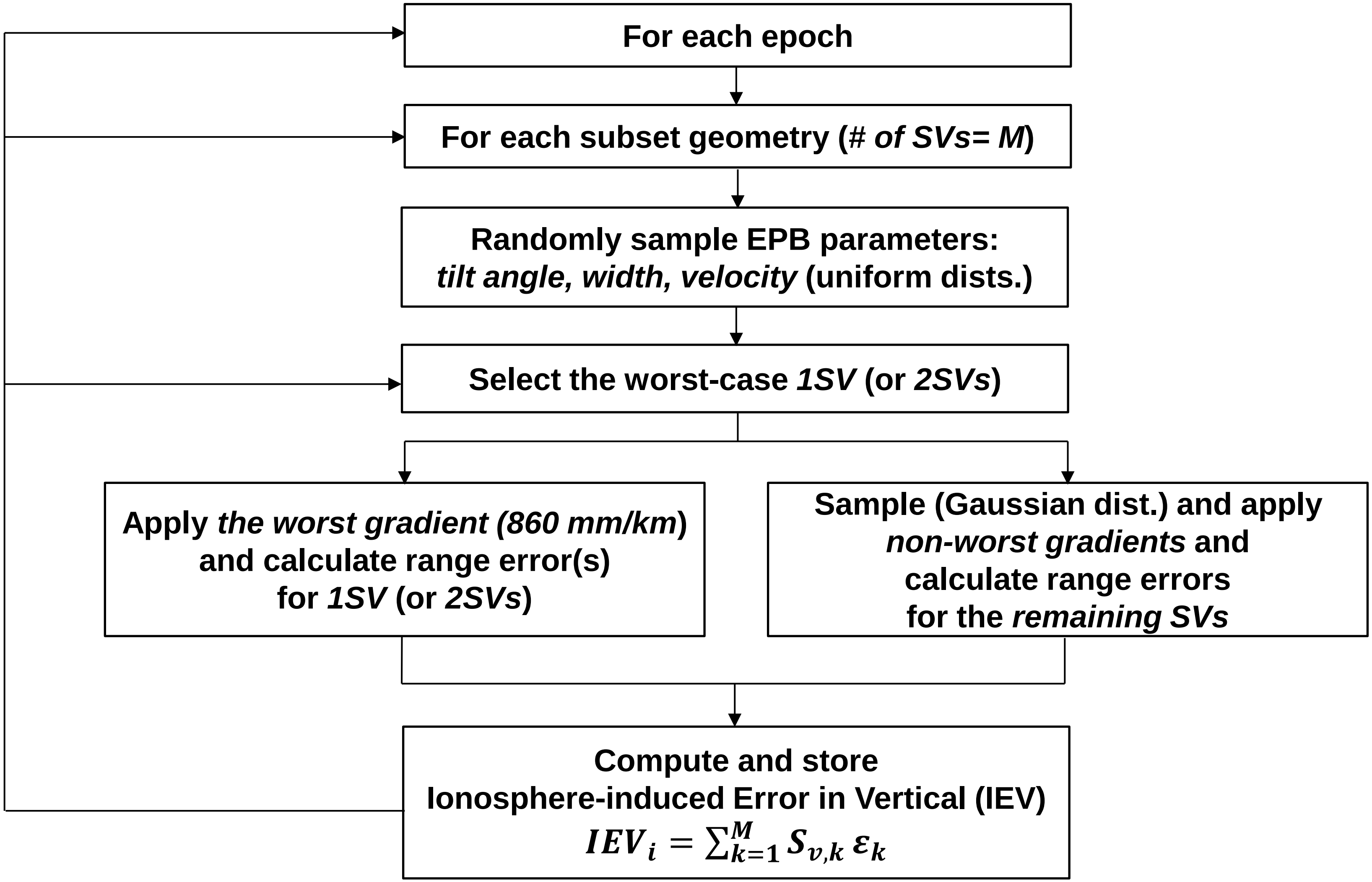
Summary of Brazil Threat Model (Preliminary) Comparison with CONUS TM

Parameter	CONUS TM	Brazil TM
Ionospheric gradient	425 mm/km max.	860 mm/km max.
Max. depletion (delay)	50 m	20 m (primary); 35 m (total)
Speed	0 ~ 750 m/s	40 ~ 246 m/s
Transition zone length	25 ~ 200 km	11 ~ 186 km (primary); 22 ~ 454 km (total)
Anomaly time of day	Any time	Local night-time only(◊)
Anomaly approach direction	Any direction	Within tilt angle of magnetic equator (W-E)
Multiple-satellite impacts	Worst pair of 2 SVs	Multiple SVs depending on EPB and IPP locations

(◊) mid-latitude iono. storm model used during local day-time

[orange shading]: tighter constraints compared to CONUS TM

Monte Carlo Simulation Procedure



Monte-Carlo Simulation:
Dist. of Non-Worst-Case Iono. Gradients

- **Over 30 days from the *Phase 1 data subset of "scintillating days"* were selected to estimate distribution of non-worst-case gradients during local night-time.**
  - **Using the *station-pair* method, no gradient larger than 400 mm/km was observed on the selected days.**
  - ***Time-step* method used here; thus larger gradient estimates result.**