Ionospheric Studies with GNSS data : Better Understanding of Ionospheric Effects on GNSS Applications

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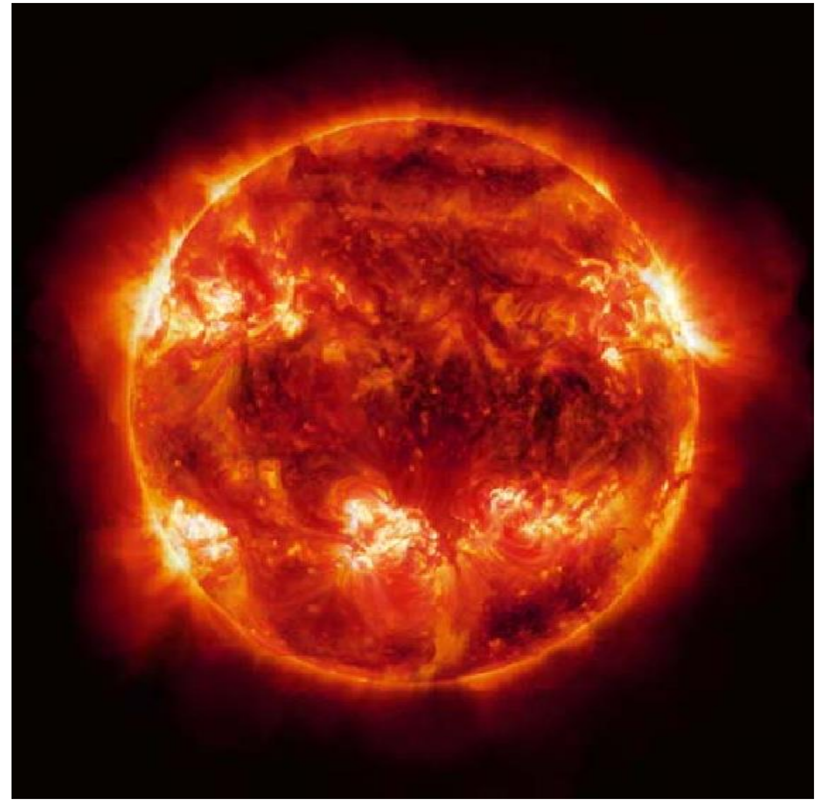
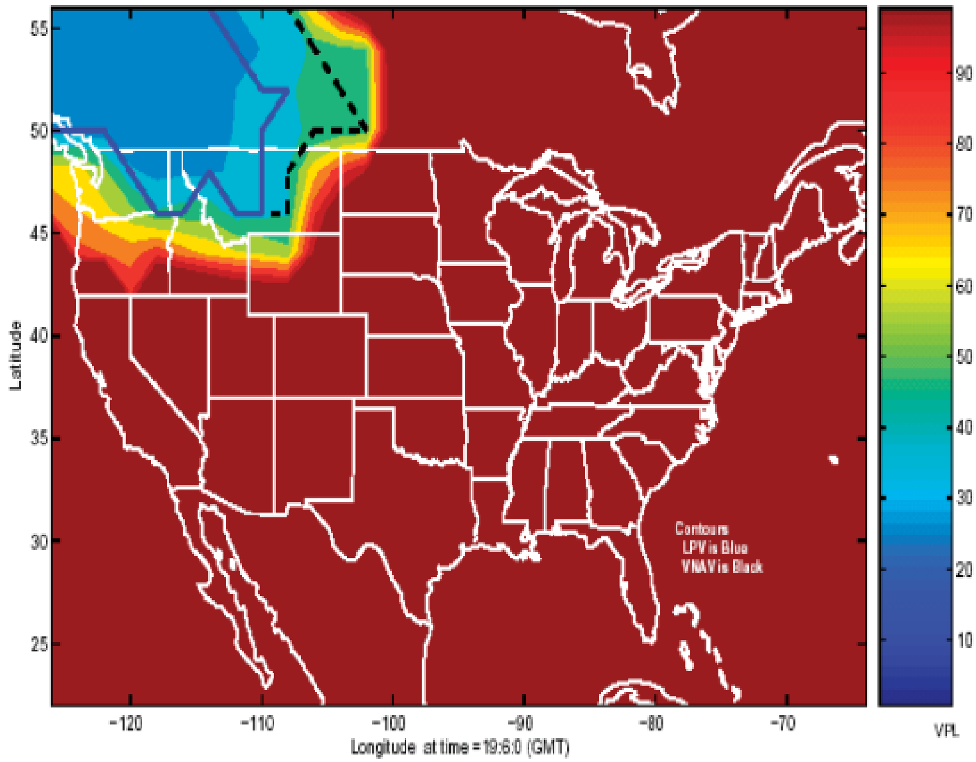


"Space weather is the largest contributor to single-frequency GPS errors and a significant factor for differential GPS"

-Report of Policy Workshop developed by AMS (2011)

Damages Caused by Extreme Solar Storms

- On October 2003, WAAS service stopped for 30 hours due to the solar storms
  (Severe space weather events - a workshop report _National Research Council, 2008)

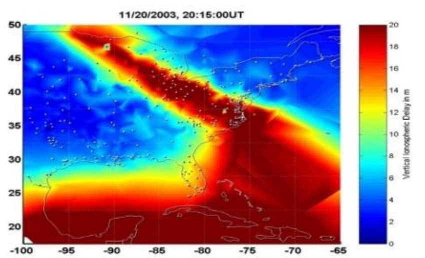


- On December 6, 2006, a solar flare created an unprecedented intense solar radio burst causing large numbers of receivers to stop tracking the GPS signal.
  (2007-04-04 NOAA Magazine)

Space weather effects on GPS

- GPS signal delay/signal loss ➡ PNT accuracy degradation
- Degrades system integrity/continuity/availability

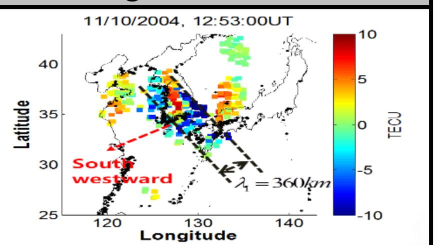
Storm Enhanced Density



- Ionospheric delay error of up to 40 ~ 50m→ accuracy degradation

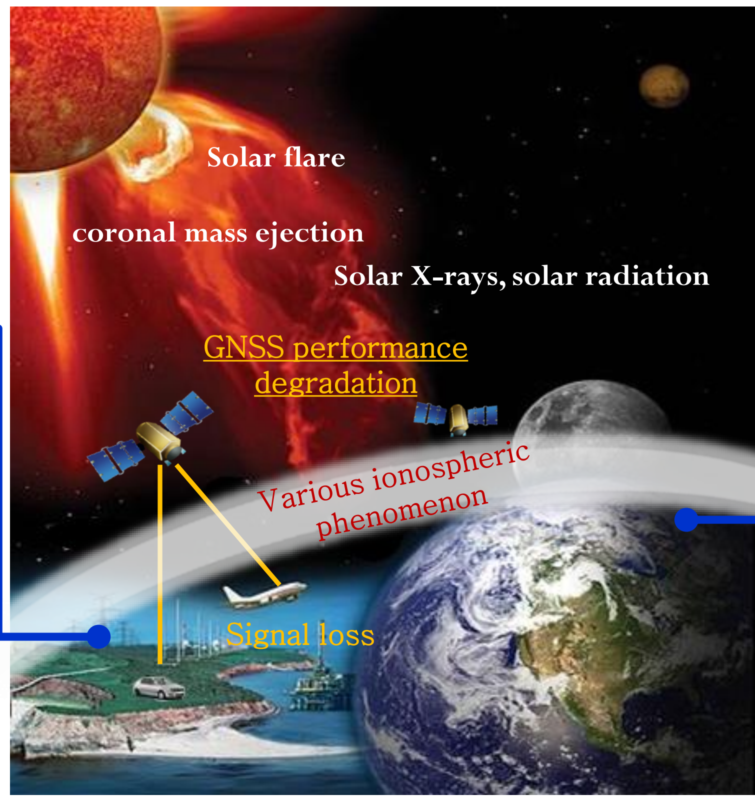
(Datta-Barua et al., 2010)

Traveling Iono. Disturbance

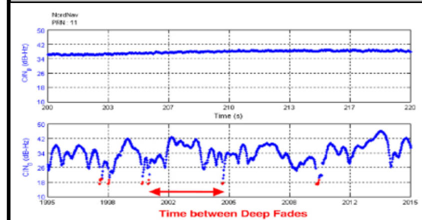


- Large delay variation and signal loss→ accuracy and continuity degradation

(Yoon and Lee, 2014)



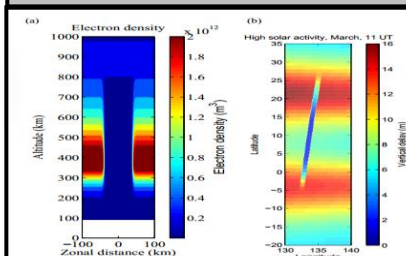
Scintillation



- Simultaneous satellite signal loss → accuracy and continuity degradation

(Seo et al., 2011)

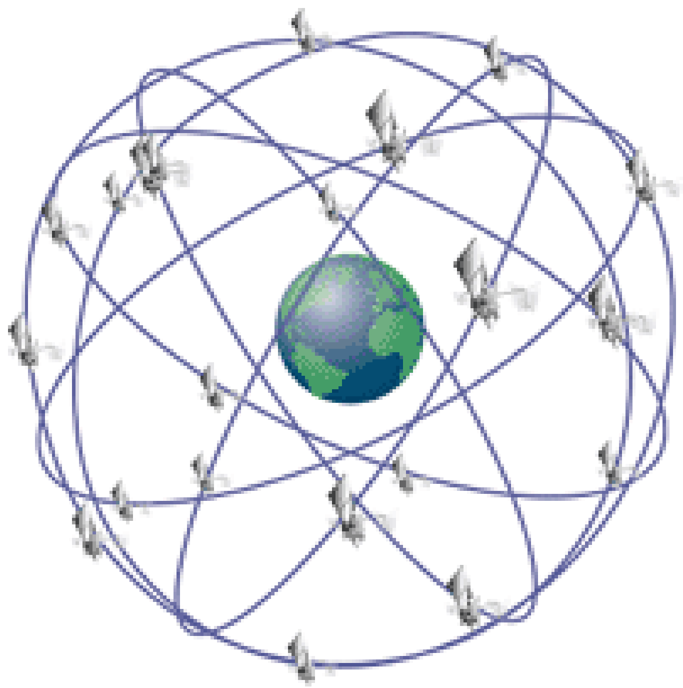
Plasma Bubble



- Large delay variation → accuracy and continuity degradation

(Saito et al., 2010)

GPS (Global Positioning System)



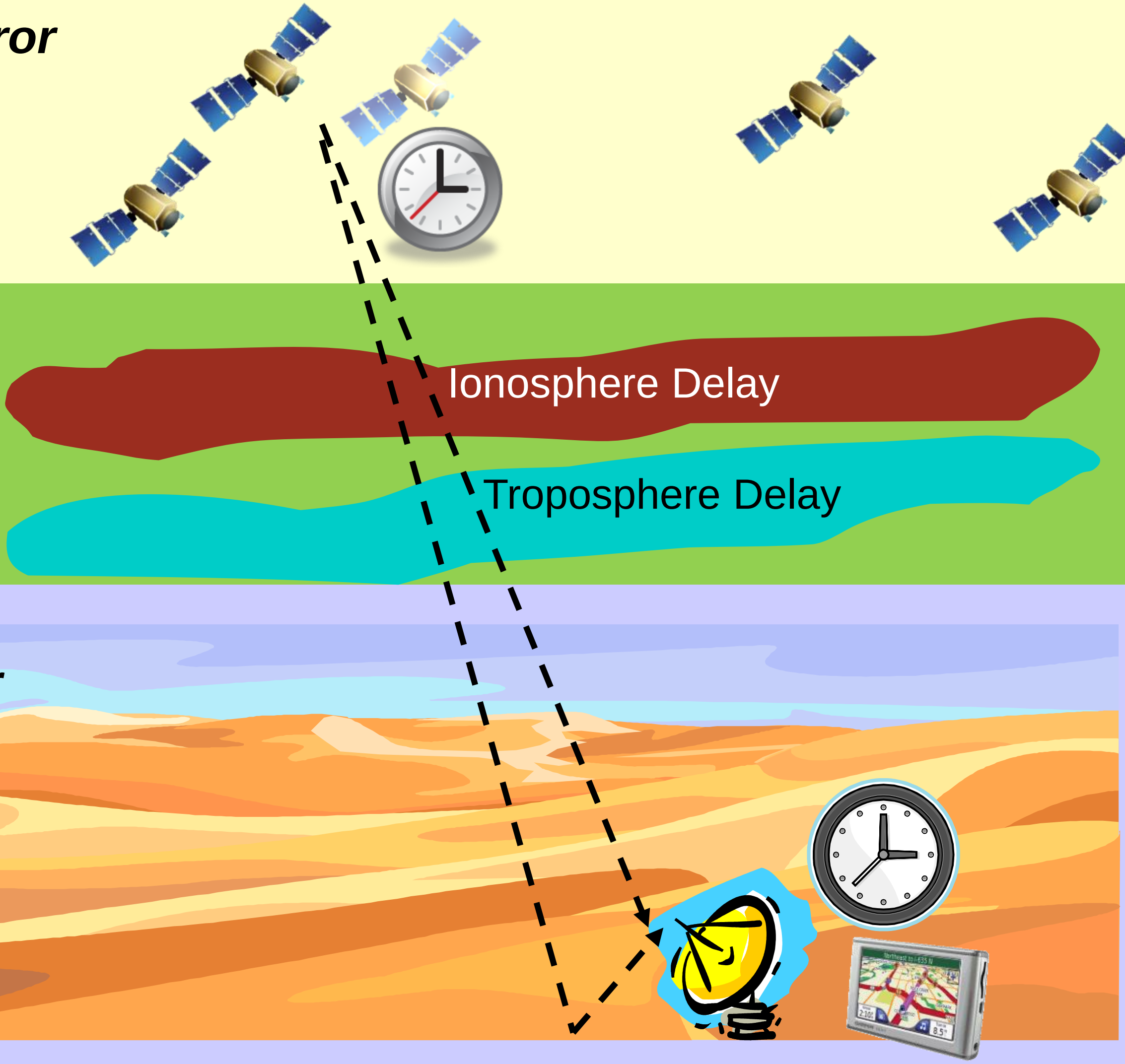
- 24+ Satellites since FOC in 1995 (space vehicles, or SVs)
- 6 orbit planes, 60 degrees apart
- 55 degrees inclination
- 12-hour (11 hr, 58 min) orbits
- 26,560 km from earth's center
- 20,182 km mean altitude
- moving ~2.7 km/sec

GPS error source

Signal in Space (SIS) error
- ephemeris
- satellite clock
- etc

Propagation error
- ionospheric delay
- tropospheric delay

Receiver and
Local environment error
- receiver noise
- multipath
- etc



Ionospheric Effects on GPS Propagation delay

- Due to a change in the speed of the signal
- Group delay and Phase advance

$$I_{\rho} = c \cdot \Delta\tau_{g} = \frac{40.3 \cdot TEC}{f^{2}} \qquad I_{\phi} = -\frac{40.3 \cdot TEC}{f^{2}}$$

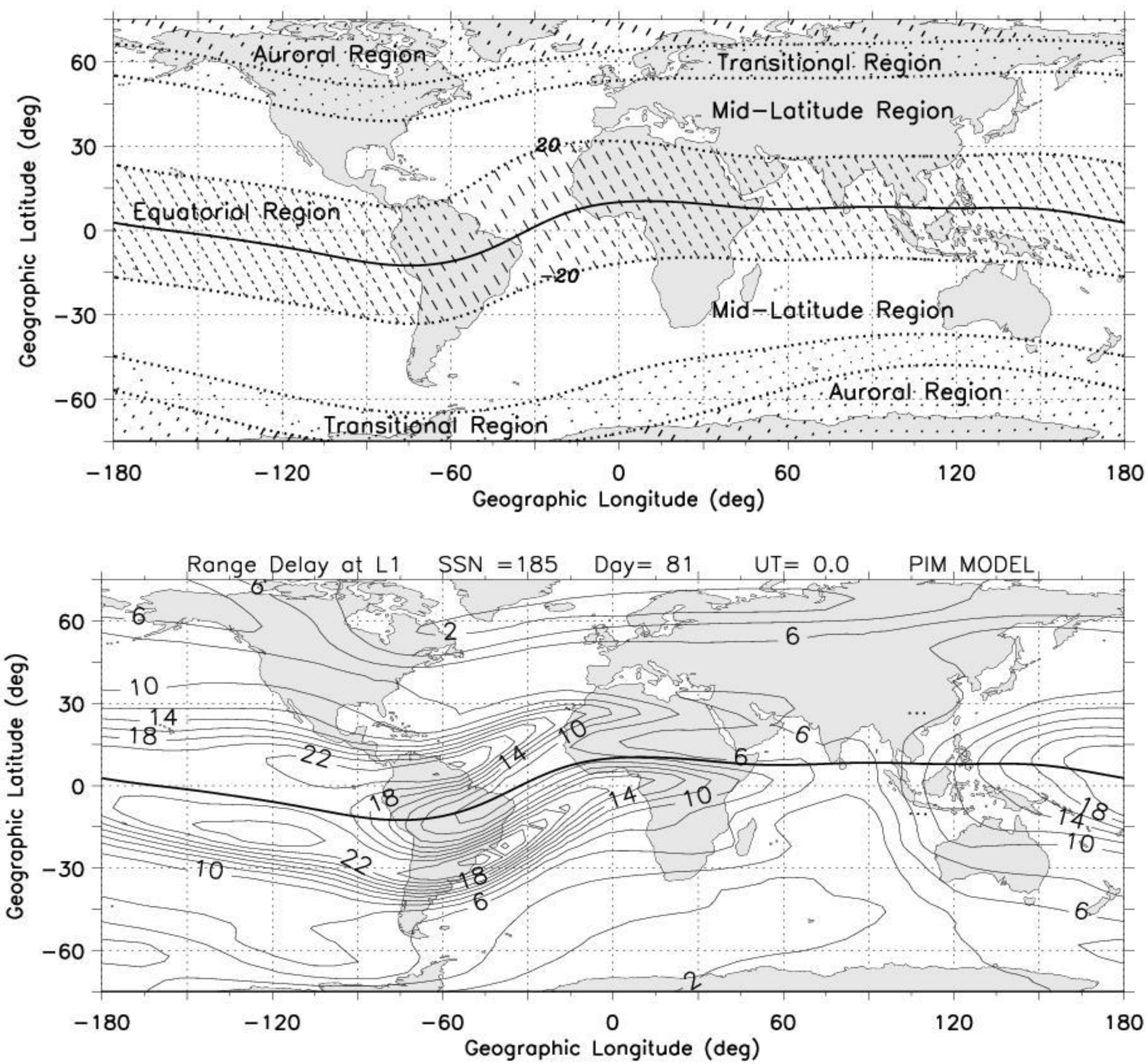
  - Depends on the number of free electrons in the path of signal (TEC: total electron content)
  - TECU: TEC unit
    - 1 TECU = 10^{16} electrons/m^2
    - 1 TECU corresponds to a change in ionospheric delay at L1 of about 16 cm

- Varies with location, local time, season, geomagnetic and solar activity

Ionospheric effects on GPS Scintillation

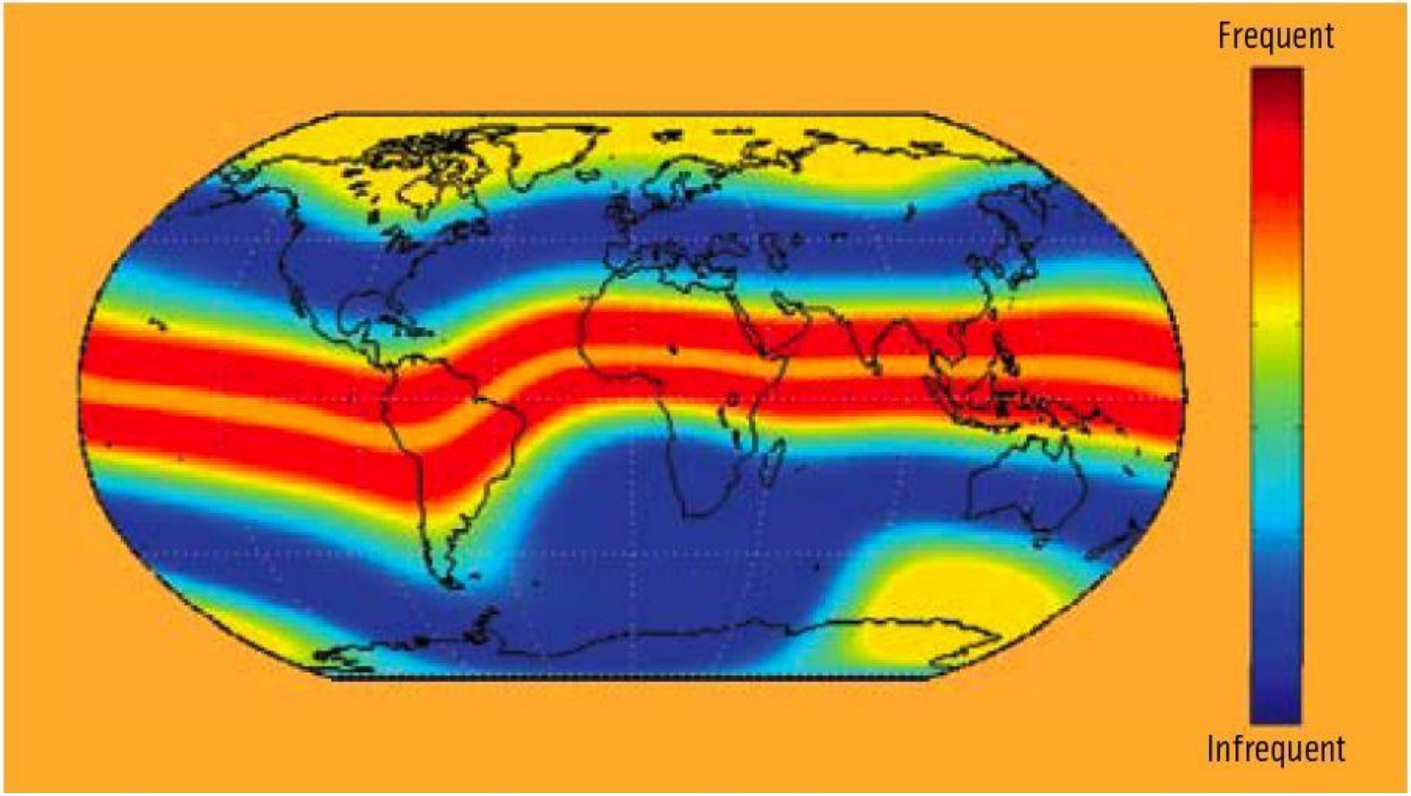
- Irregularities in the distribution of free electrons can scatter radio waves
- Rapid fluctuations in the amplitude and phase of received signals
- May induce loss of lock
- Characterized by Amplitude scintillation parameter, S4 and Phase scintillation parameter, σ_{ϕ},
- Rare at mid-latitudes
- Can be severe after local sunset in the equatorial regions, especially near the peak of solar cycle

Propagation delay as a function of (magnetic) latitude



Contours of equal vertical ionospheric range delay, in meters at L1, for typical solar maximum equinox conditions at 00 UT [SBAS Iono WG, 2003]

Scintillation as a function of (magnetic) latitude



(P. Kintner, et al.)

Ionospheric delay estimation - Standalone GPS

- Ionospheric delay estimation in a single frequency signal
  - Delay model is provided by Nav message. (ex. Klobuchar model)

$$\frac{\hat{I}_{z,L1}}{c} = \begin{cases} A_1 + A_2 \cos\left(\dfrac{2\pi(t - A_3)}{A_4}\right), & \text{if } \left|t - A_3\right| < \dfrac{A_4}{4} \\ A_1 & \text{otherwise} \end{cases}$$

Half-cosine in daytime
Constant at nighttime

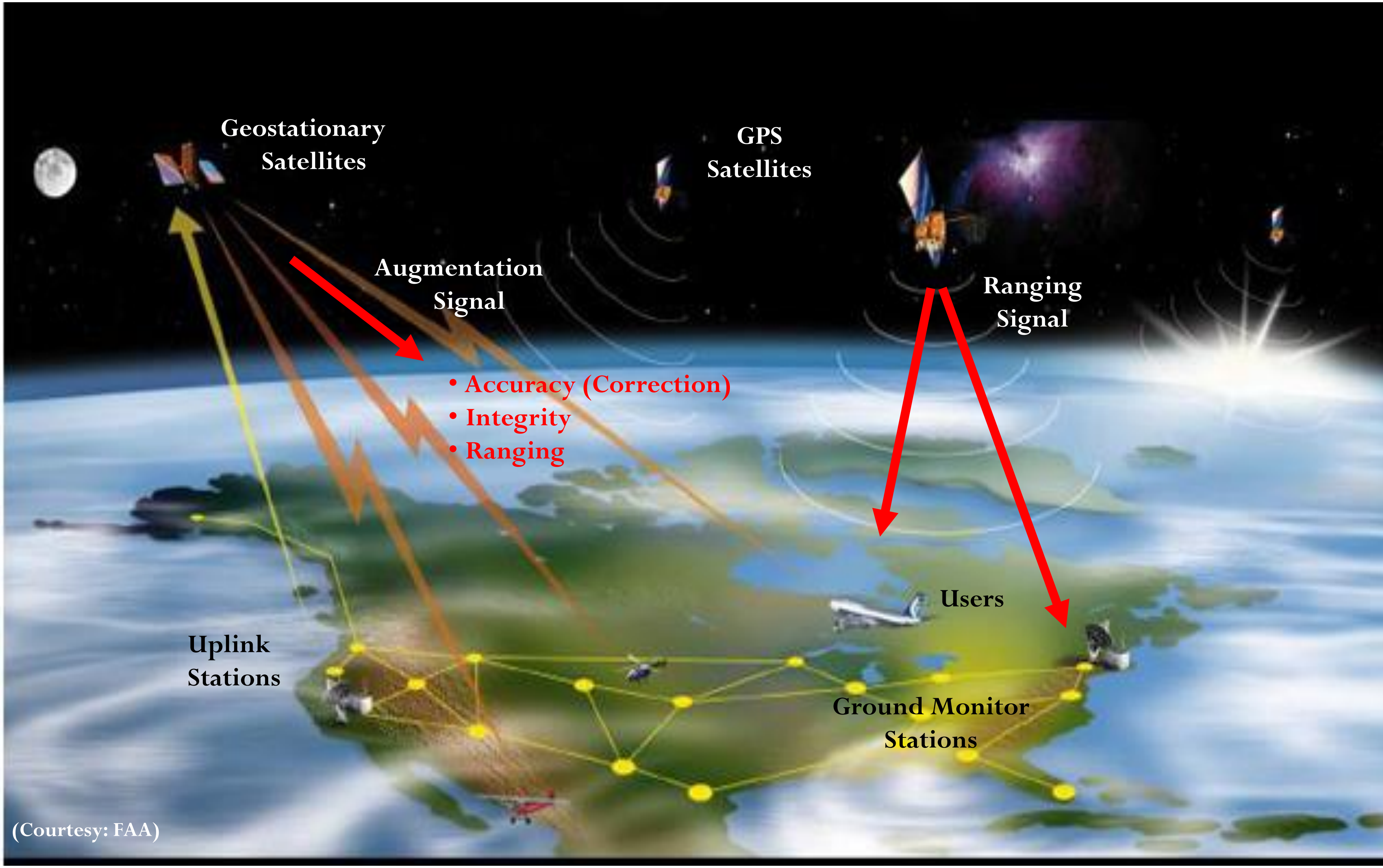
A2, A4: navigation message (A1, A3 are fixed)

$$OF_I(el) = 1.0 + 16.0 \times (0.53 - el)^3$$

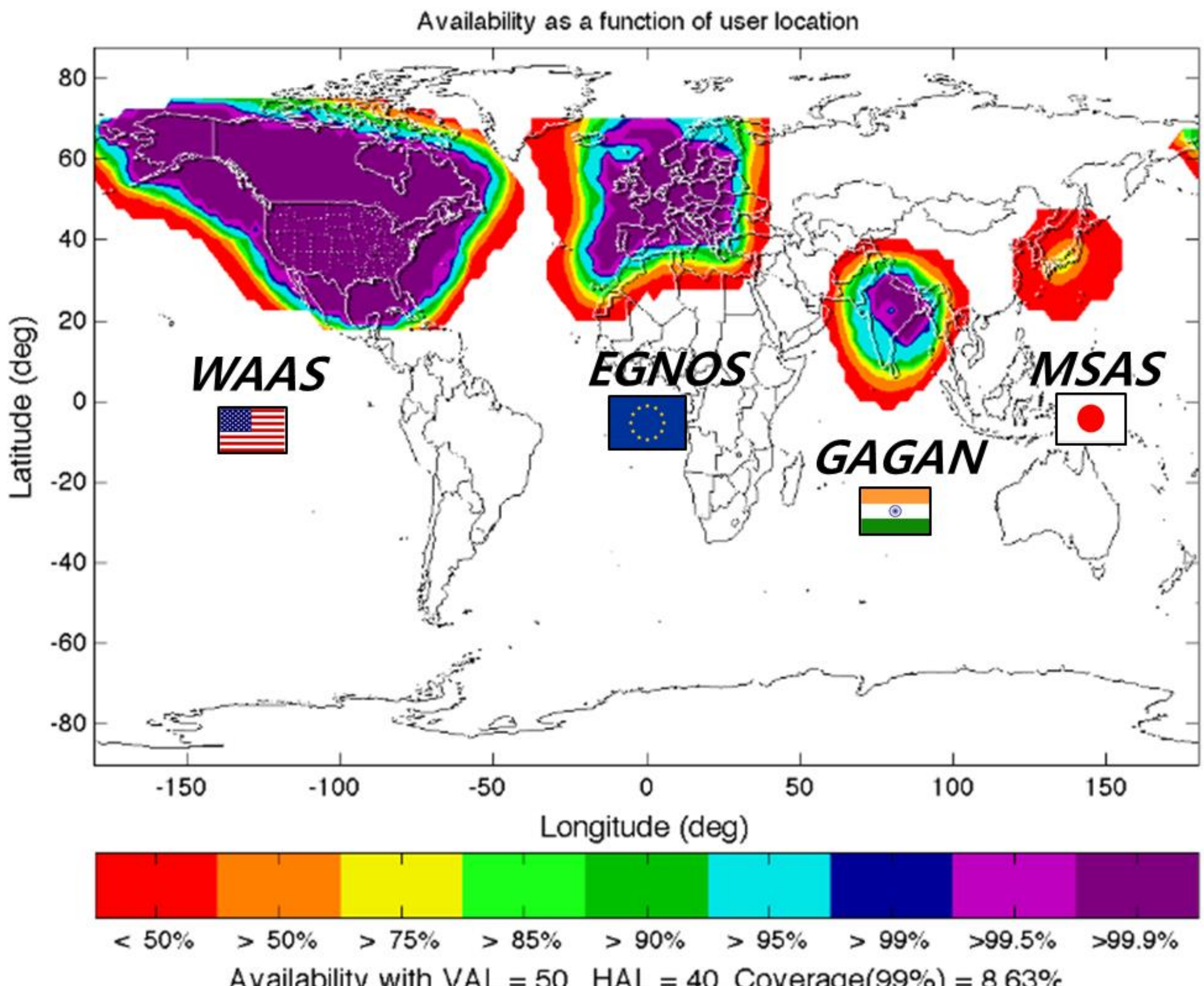
- Ionospheric delay estimation in a dual frequency signal
  - Estimation based on combination of dual frequency measurements

$$\rho_{IF} = \frac{f_{L1}^2}{f_{L1}^2 - f_{L2}^2}\rho_{L1} - \frac{f_{L2}^2}{f_{L1}^2 - f_{L2}^2}\rho_{L2},$$

Differential GPS – SBAS



SBAS APV-I Coverage (current)

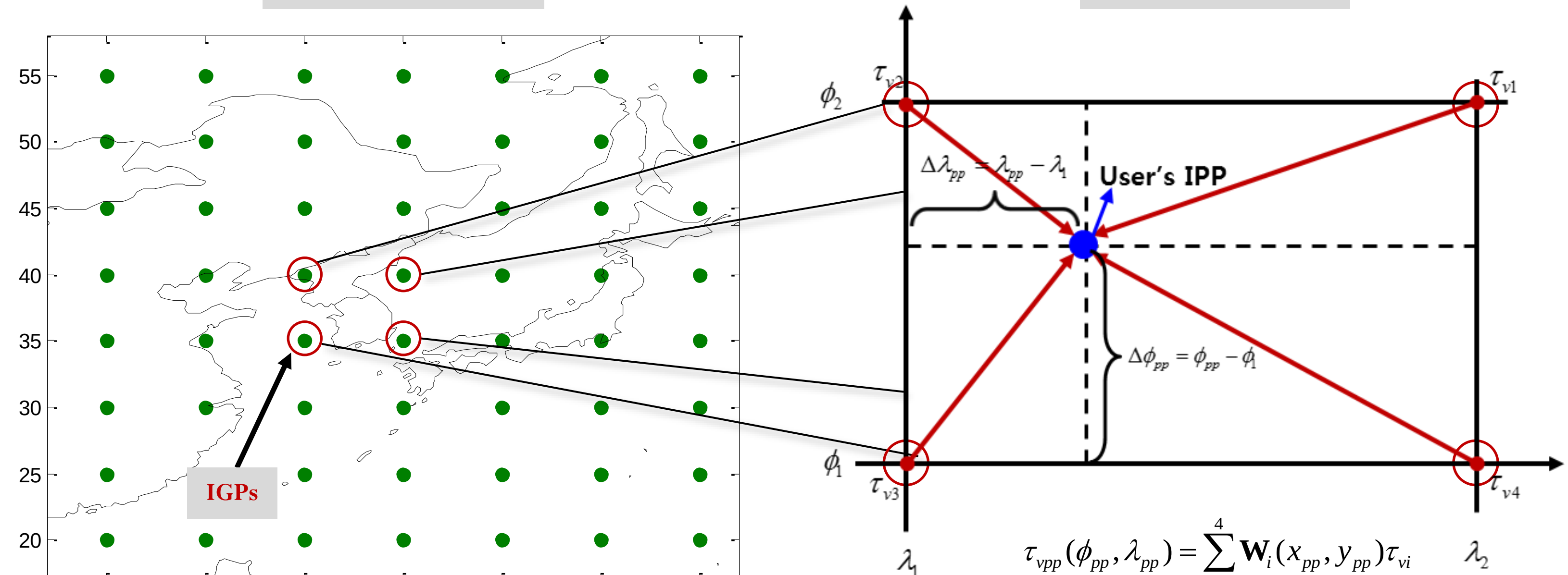


Source by T. Walter, Presented at ENAC 2014

Ionospheric Delay Estimation - SBAS

- Single frequency SBAS provides (vertical) ionospheric delay estimates at each IGPs (IGPs, Ionospheric Grid Points)
- Delay estimates from four IGPs around the user is used to compute Ionospheric delay corrections and user protection levels

IGP formation **User algorithm**

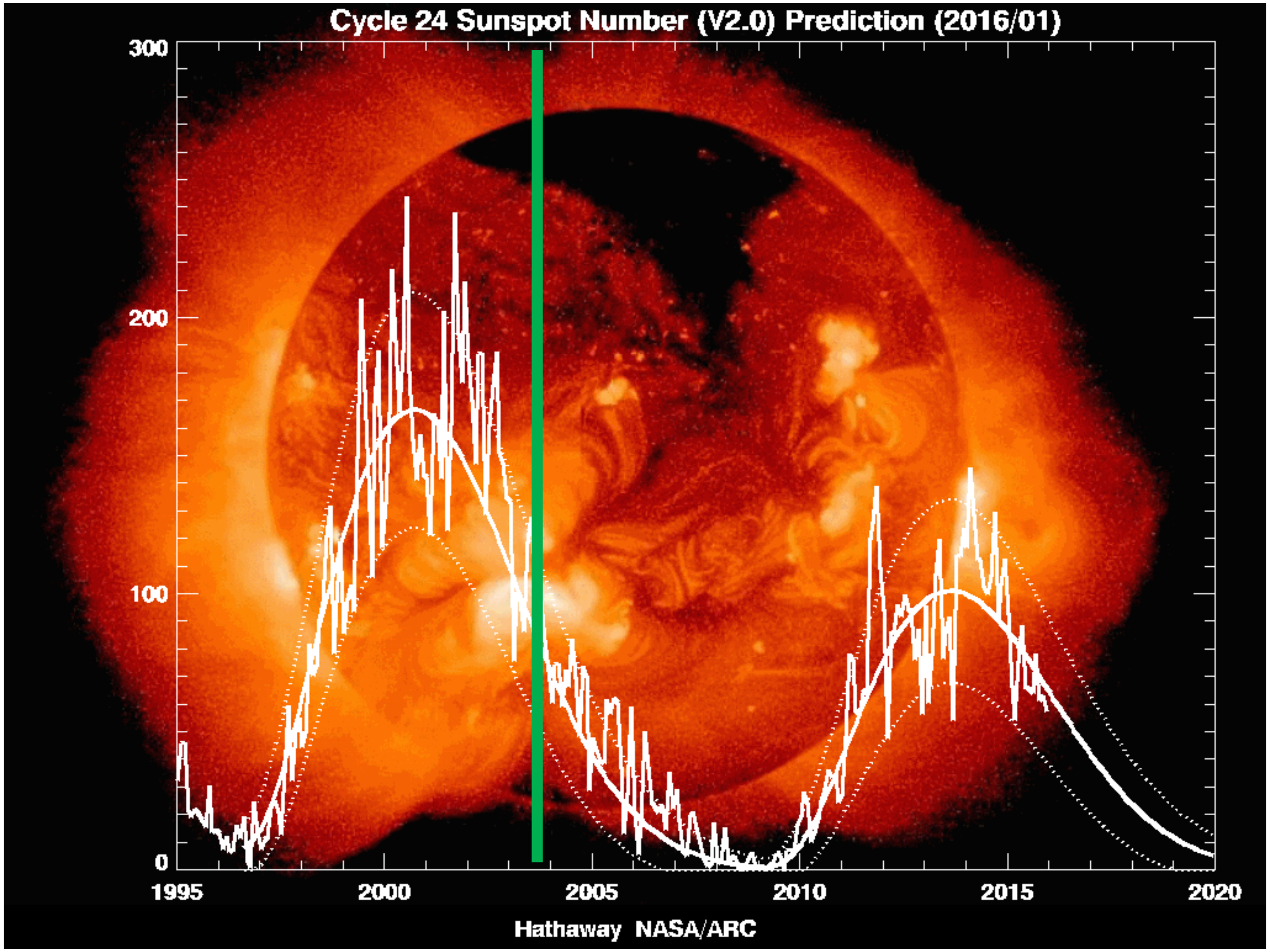


$$\tau_{vpp}(\phi_{pp}, \lambda_{pp}) = \sum_{i=1}^{4} \mathbf{W}_i(x_{pp}, y_{pp})\tau_{vi}$$

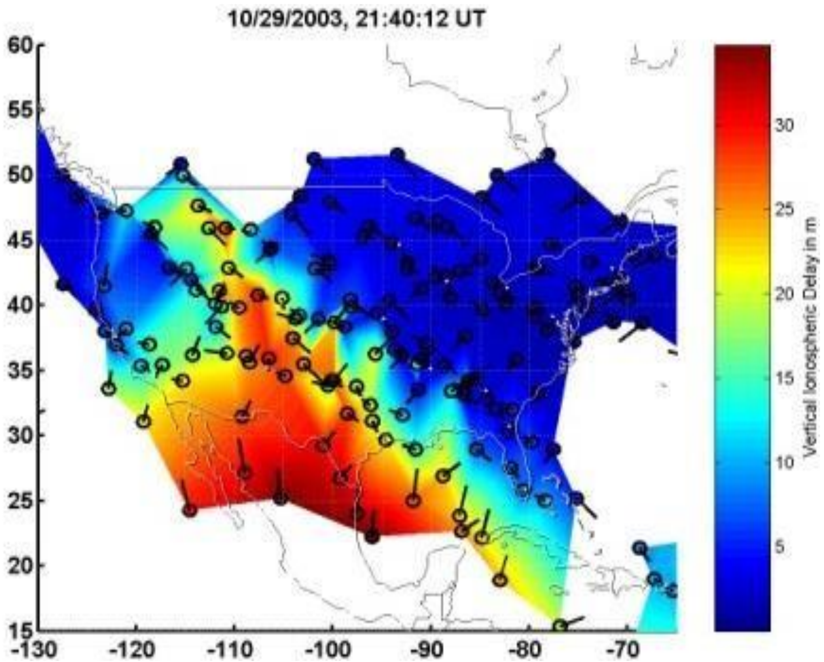
$$IC_i = -F_{pp} \cdot \tau_{vpp}(\lambda_{pp}, \phi_{pp})$$

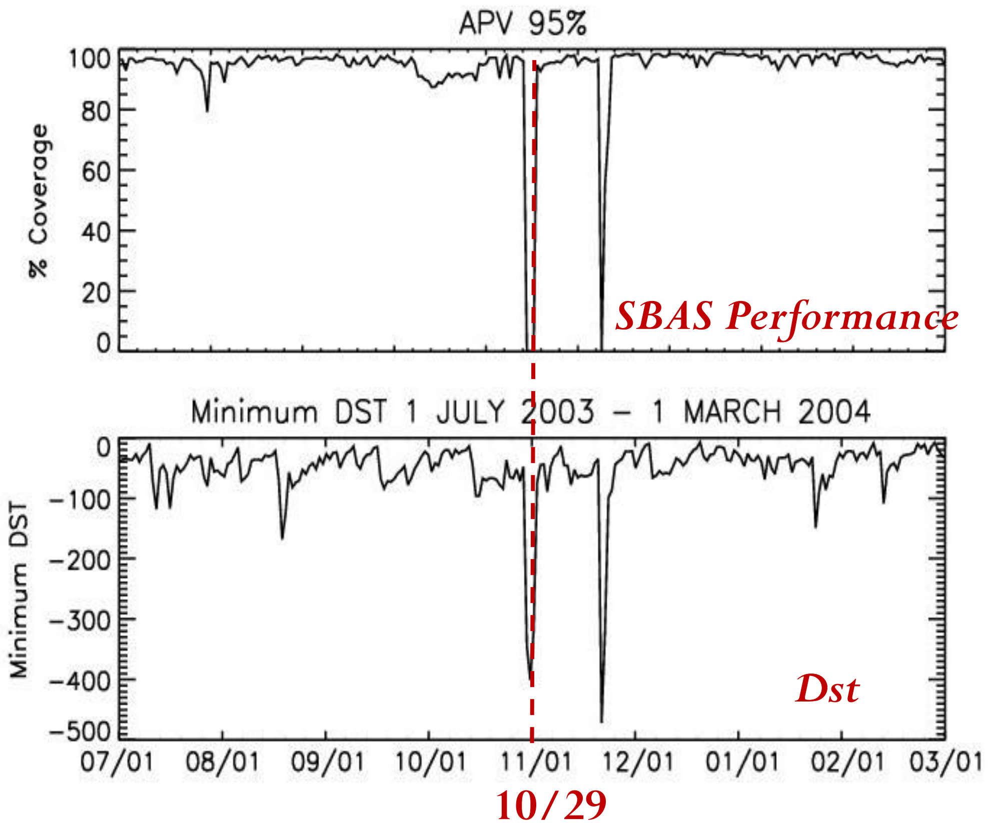
τ_{vpp} : IGP의 GIVE
W : 가중치
ϕ_{pp}, λ_{pp} : IPP 위/경도
F_{pp} :obliquity factor

Solar Cycle with Great Magnetic Strom



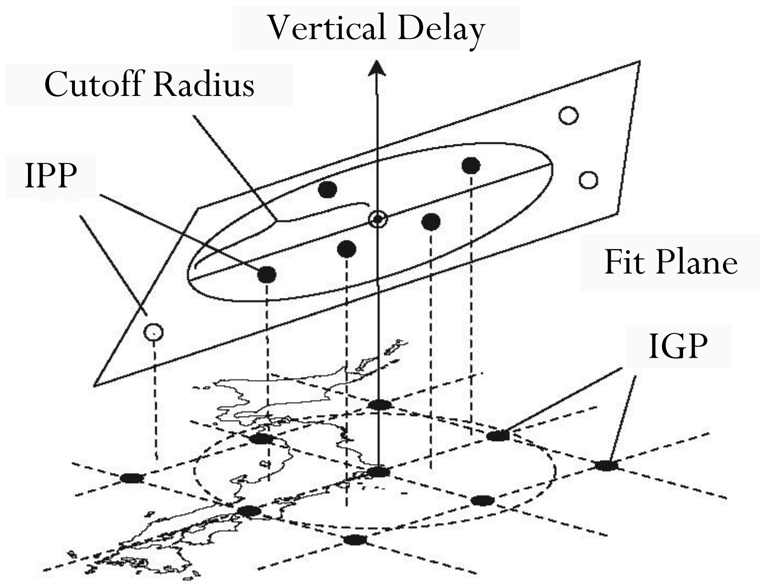
WAAS APV service vs. geomagnetic activity





Planar Fit and GIVE

***Source*: T. Sakai, *et al*, "Modeling Ionospheric Spatial Threat Based on Dense Observation Datasets for MSAS" ION GNSS 2011.c**



- **Developed for WAAS;**
- **MSAS employs the same algorithm;**
- **Assume ionospheric vertical delay can be modeled as a plane;**
- **GIVE (grid ionosphere vertical error): Uncertainty of the estimation including spatial and temporal threats.**

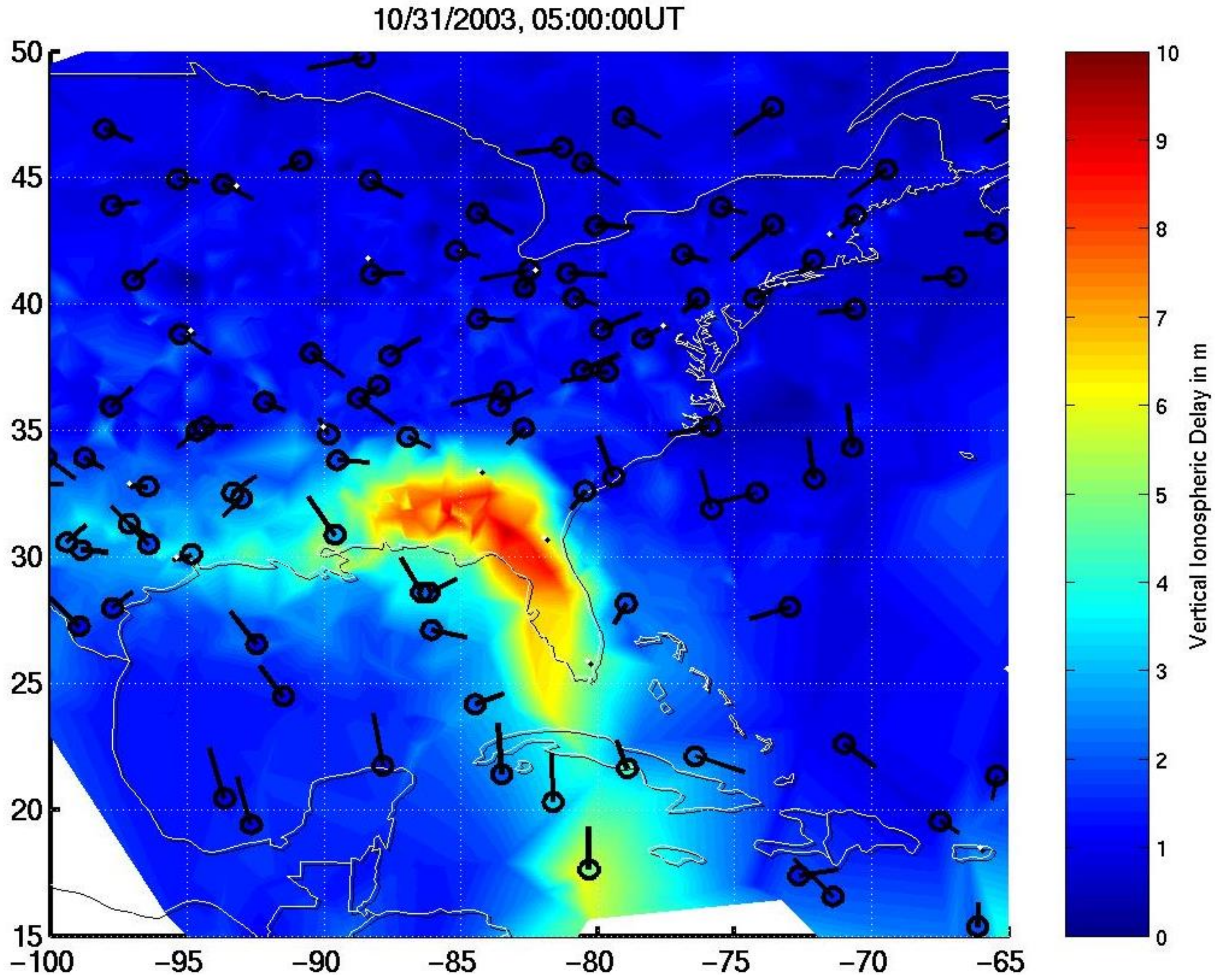
- **GIVE Equation**

Spatial Threat Model

$$\sigma_{GIVE}^2 = \underbrace{R_{irreg}^2 \sigma_{IGP_k}^2}_{\text{Formal Sigma}} + \underbrace{\max\left(R_{irreg}^2 \sigma_{decorr}^2, \sigma_{undersampled}^2\right)}_{\text{Spatial Threat}} + \underbrace{\sigma_{rate-of-change}^2}_{\text{Temporal Threat}}$$

Ionospheric Spatial Threats

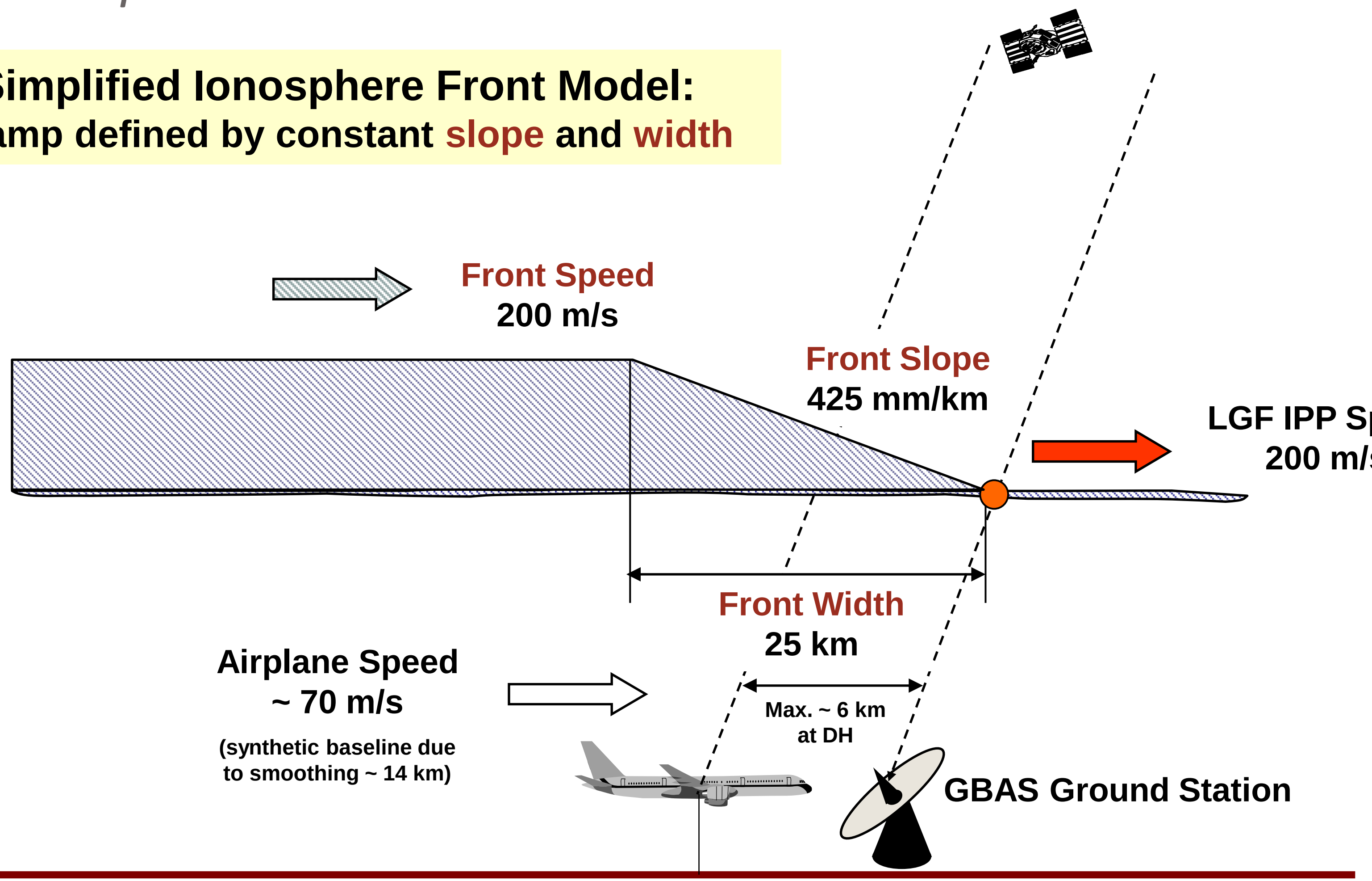
***Source*: S. Datta-Baura, *et al*, "Ionospheric Threats to SBAS" ION GNSS 2004**



Ionosphere Anomaly Front Model:

Potential Impact on a GBAS User

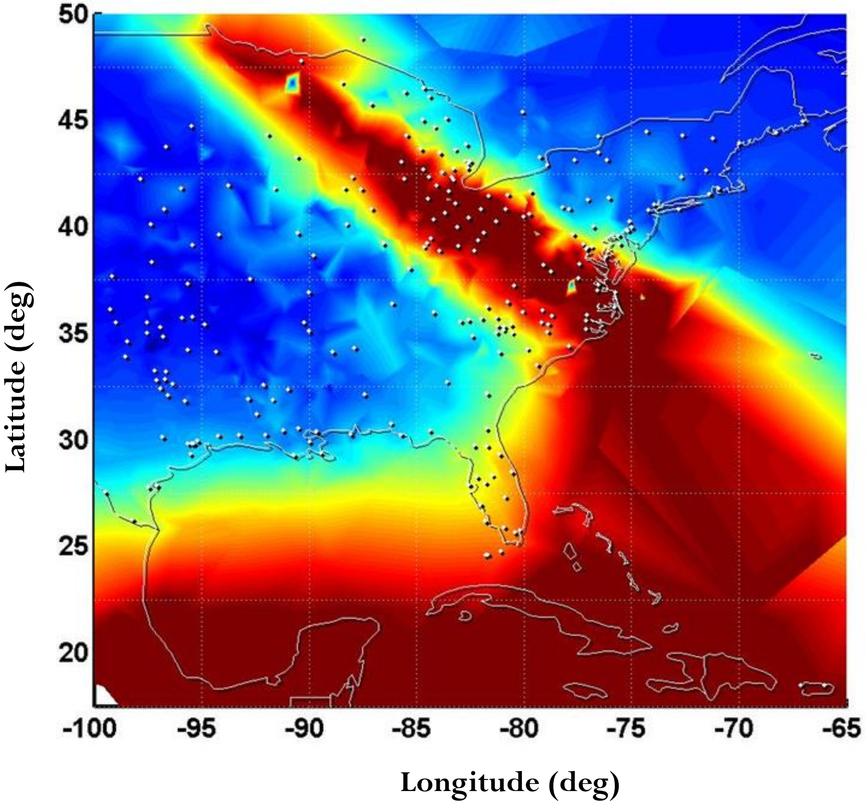
Simplified Ionosphere Front Model:
a ramp defined by constant slope and width



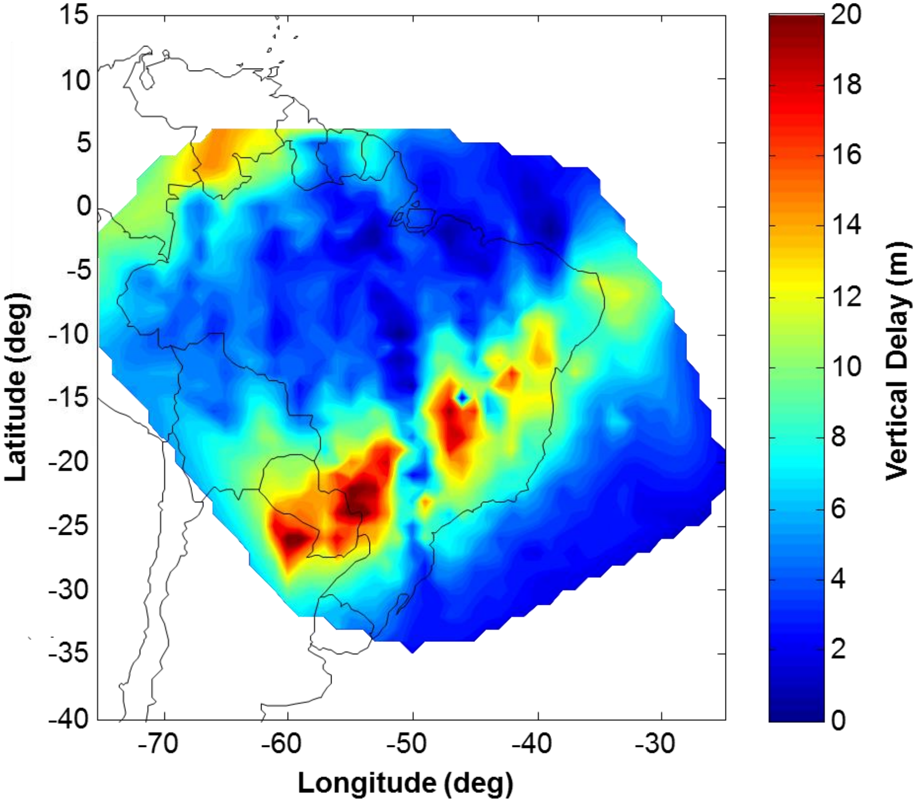
***Stationary Ionosphere Front Scenario*:**
Ionosphere front and IPP of ground station IPP move with same velocity.
Maximum Range Error at DH: 425 mm/km × 20 km = 8.5 meters

Abnormal Gradients:
Mid-Latitudes vs. Low-Latitudes

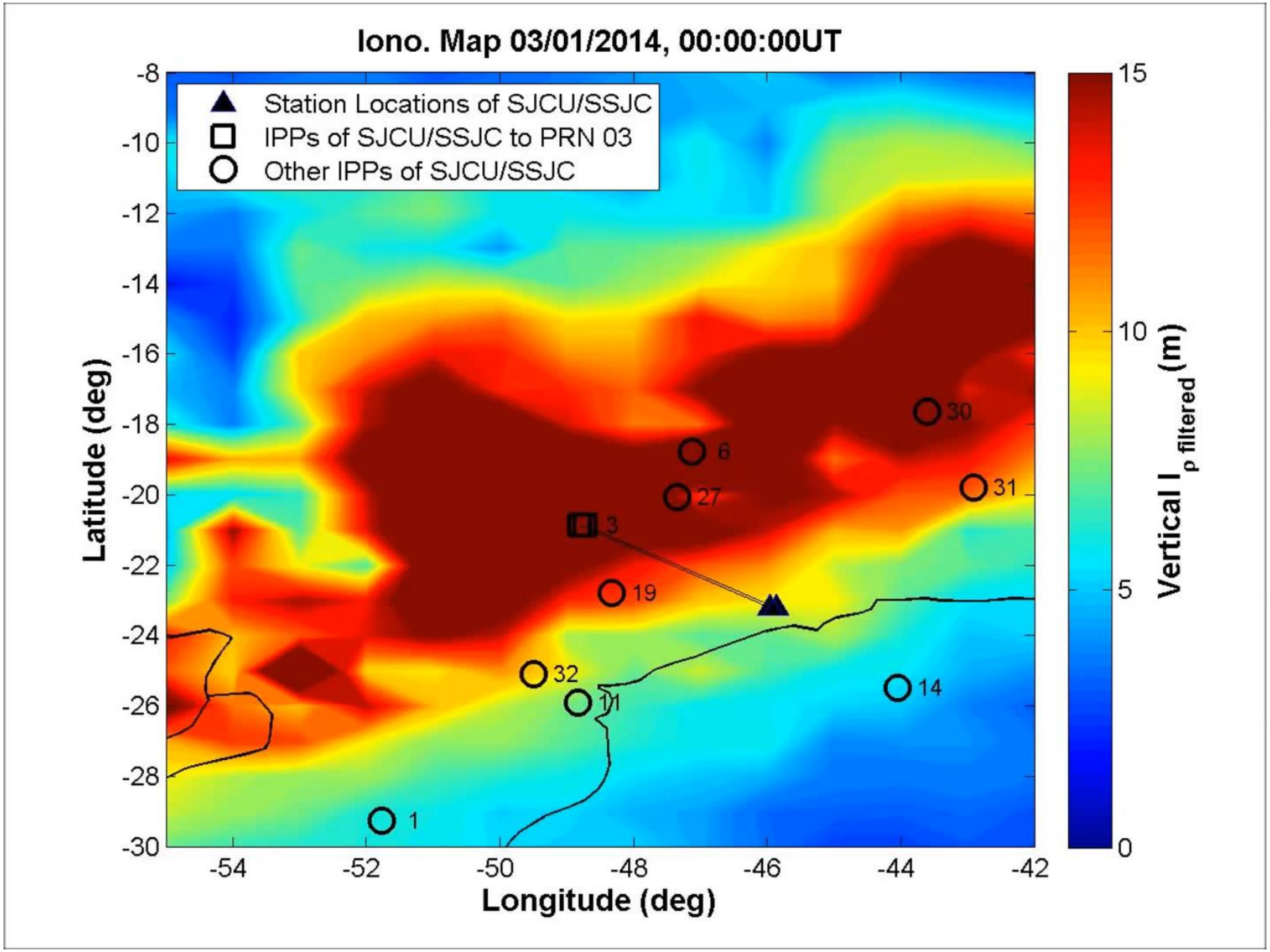
Over CONUS
(11/20/2003, 20:15 UT)
425 mm/km max.



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



Regional Ionospheric Delay Map (Video)



Solutions

- **Understanding space weather**
  - Continue to advance present understanding of space weather and its impacts on satellite-based navigation systems and other critical infrastructure.
  - Develop better space weather predictions.

- **Strengthen international collaboration**
  - Improve spatial coverage of ionospheric and space weather measurements.
  - Reduce vulnerability of safety-critical systems to space weather

Thank You

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