ENRI

Ionospheric effects on GBAS and mitigation techniques

Susumu Saito
Electronic Navigation Research Institute, Japan

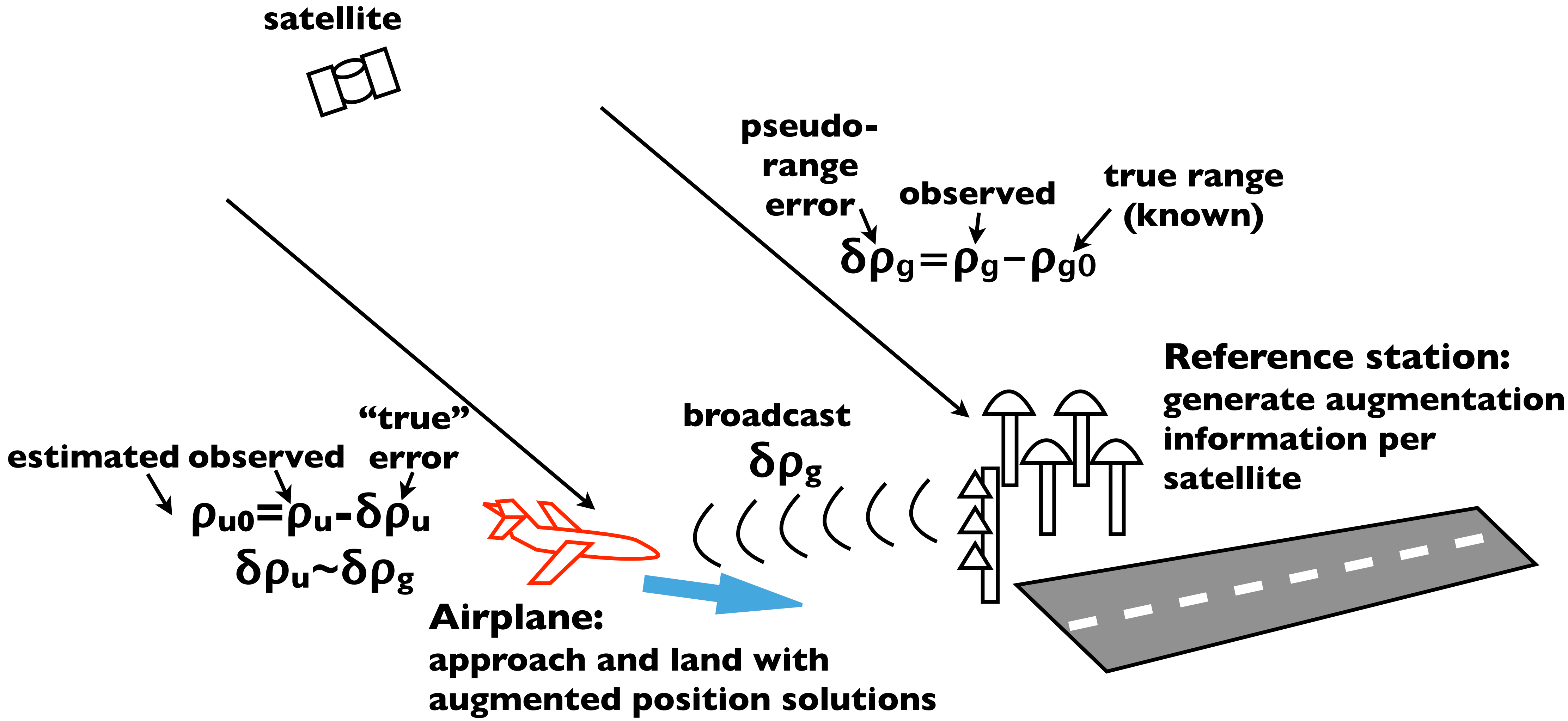
Workshop on Ionospheric data collection, analysis and sharing to support GNSS implementation, Bangkok, 5-6 May 2011

ENRI

Outline

* Outline of GBAS
* Ionospheric effects on GBAS
  - Ionospheric delay
  - Ionospheric scintillation
* Examples of Ionospheric anomalies that may impact GBAS
  - SED
  - Plasma bubble
  - Equatorial anomaly
* Mitigation of Ionospheric effects
  - Nominal ionosphere
  - Anomalous ionosphere
* Characterization of the Ionosphere
  - Ionospheric threat model
  - For better/optimized ionospheric characterization
* Summary

GBAS



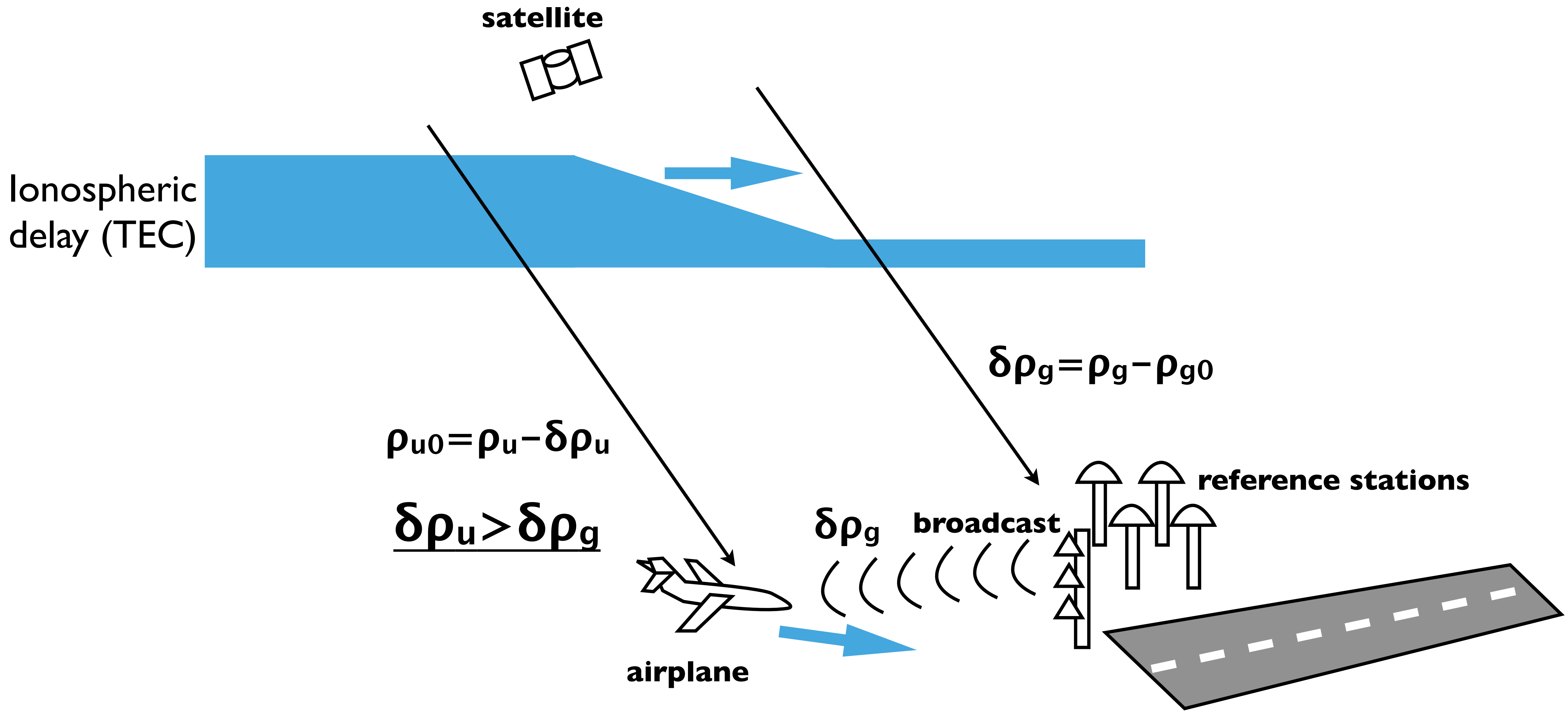
- Augmentation information is generated for each satellite based on observations at ground reference stations at an airport.
- Airplane perform positioning with the augmentation information.
- Service area is about 40 km around the airport

ENRI

Ionospheric anomalies preventing advanced use of GNSS

* Ionospheric delay gradient
  - Source of differential correction error
    - Undetectable by reference station: integrity risk
    - Make countermeasure to reduce the probability of the risk less than the limit. (Additional monitors, screening of potentially dangerous satellite geometry, etc.)
    - Availability may be degraded as a result of such countermeasures.
* Small-scale ionospheric irregularities
  - Scintillation resulting in degraded measurements and satellite lock-off
    - Integrity risk is unlikely, but degrades availability

Ionospheric delay gradient and GBAS



- Different errors between ground reference stations and airplanes result in differential correction error.
- Local spatial gradient in ionospheric delay can be an important error source.

Carrier-smoothing

- Noisy pseudo-range measurements are smoothed with an aid of carrier-phase variation.
- Error accumulates because of opposite polarity (pseudo-range delays in the ionosphere while carrier-phase advances) when ionospheric gradient exists.

Smoothed pseudo-range at time k

$$\rho_s^{(k)} = \frac{T_s}{\tau}\rho^{(k)} + \frac{\tau - T_s}{\tau}\left[\rho_s^{(k-1)} + \lambda\left(\phi^{(k)} - \phi^{(k-1)}\right)\right]$$

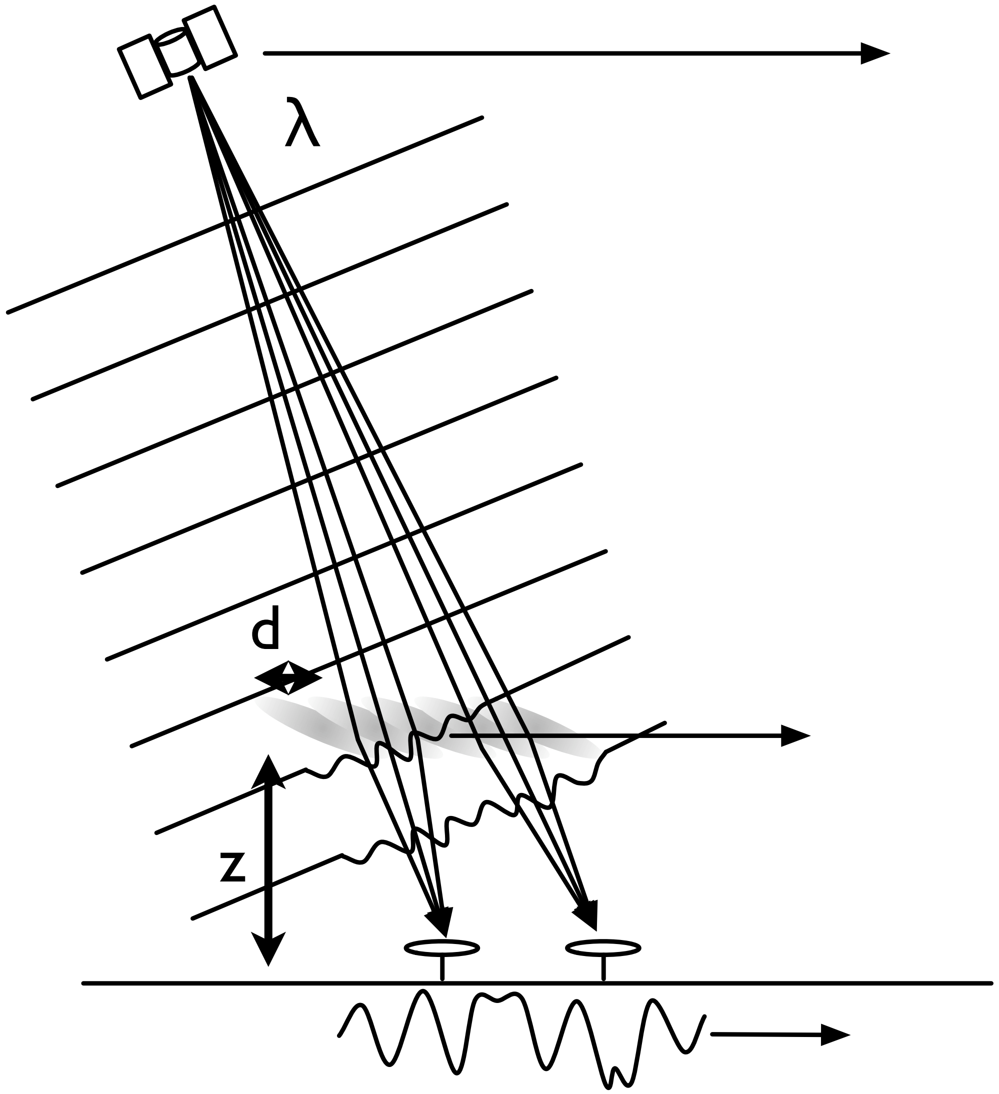
- **Sampling interval**: T_s
- **wavelength**: λ
- **Smoothing time constant**: τ
- **Raw pseudo-range measurements**: $\rho^{(k)}$, $\rho_s^{(k-1)}$
- **carrier-phase measurements**: $\phi^{(k)}$, $\phi^{(k-1)}$

Accumulated error

$$\delta I = (x + 2\tau v)\frac{dI}{dx}$$

- **Distance**: x
- **Aircraft velocity**: v
- **Smoothing time constant**: τ
- **Delay gradient**: $\frac{dI}{dx}$

Scintillation and GBAS

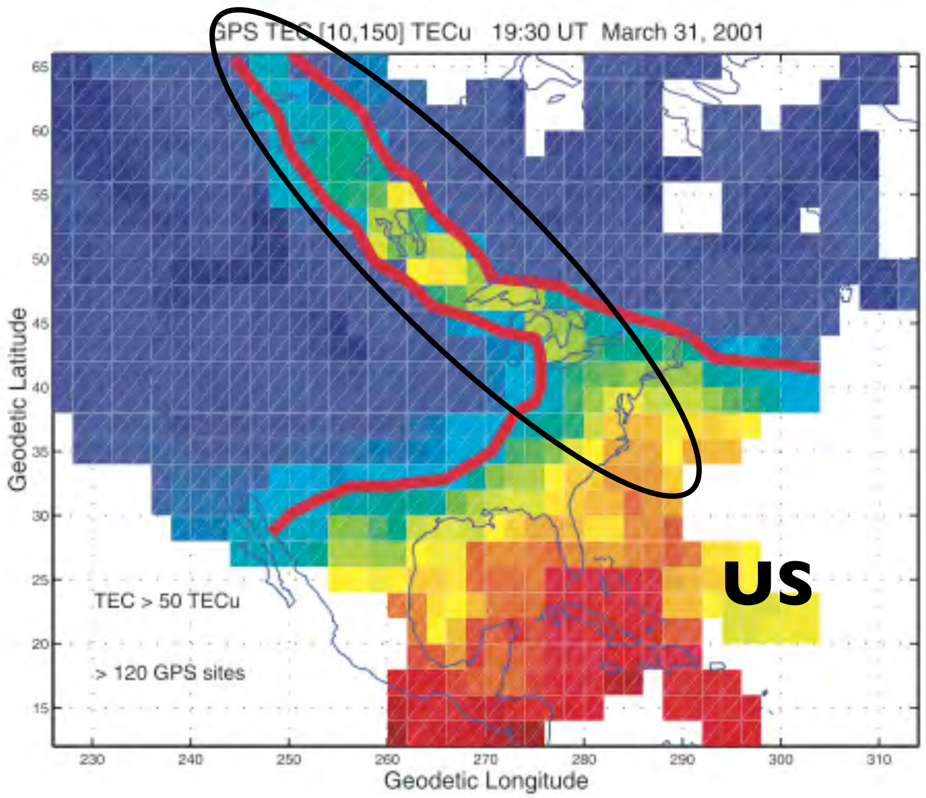


* Power and phase of received signals change rapidly.
* Degradation of measurements
  - enhanced error
* Loss-of-lock of satellite signals
  - degradation of geometry and enhanced error
* However, scintillation would not generate undetected error.
  - Less important for integrity risk, though availability would be affected.

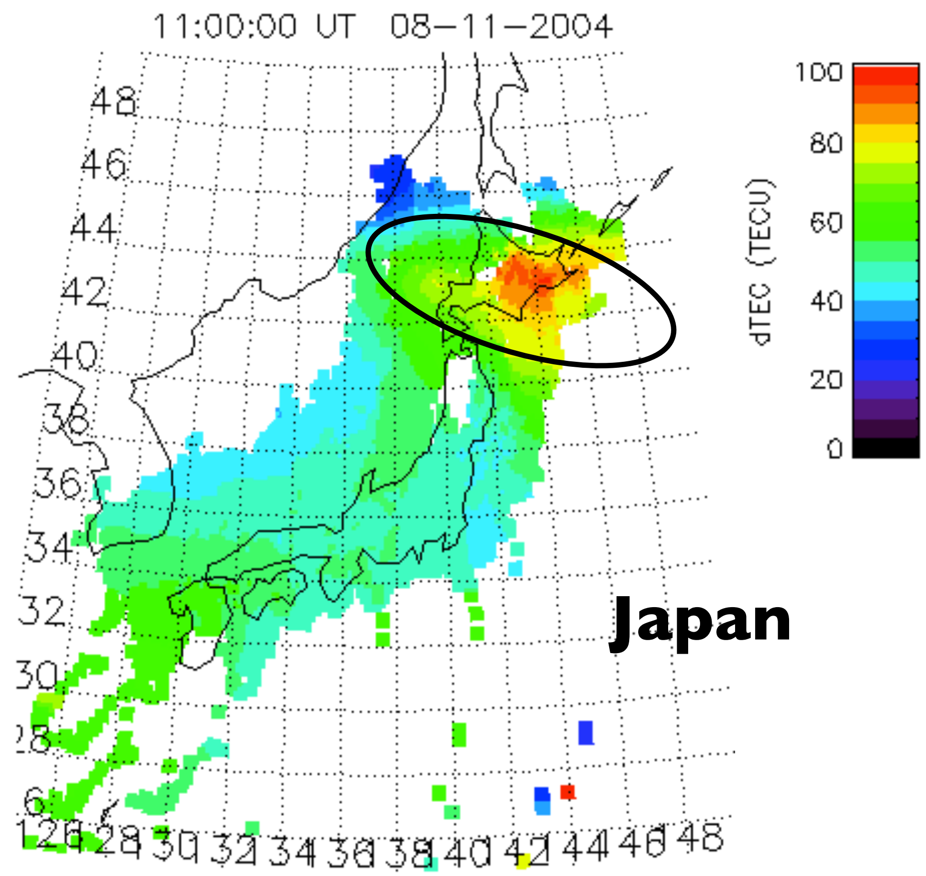
Ionospheric phenomena that may impact GBAS

* Storm enhanced density
* Plasma bubble
* Equatorial anomaly

Storm enhanced density

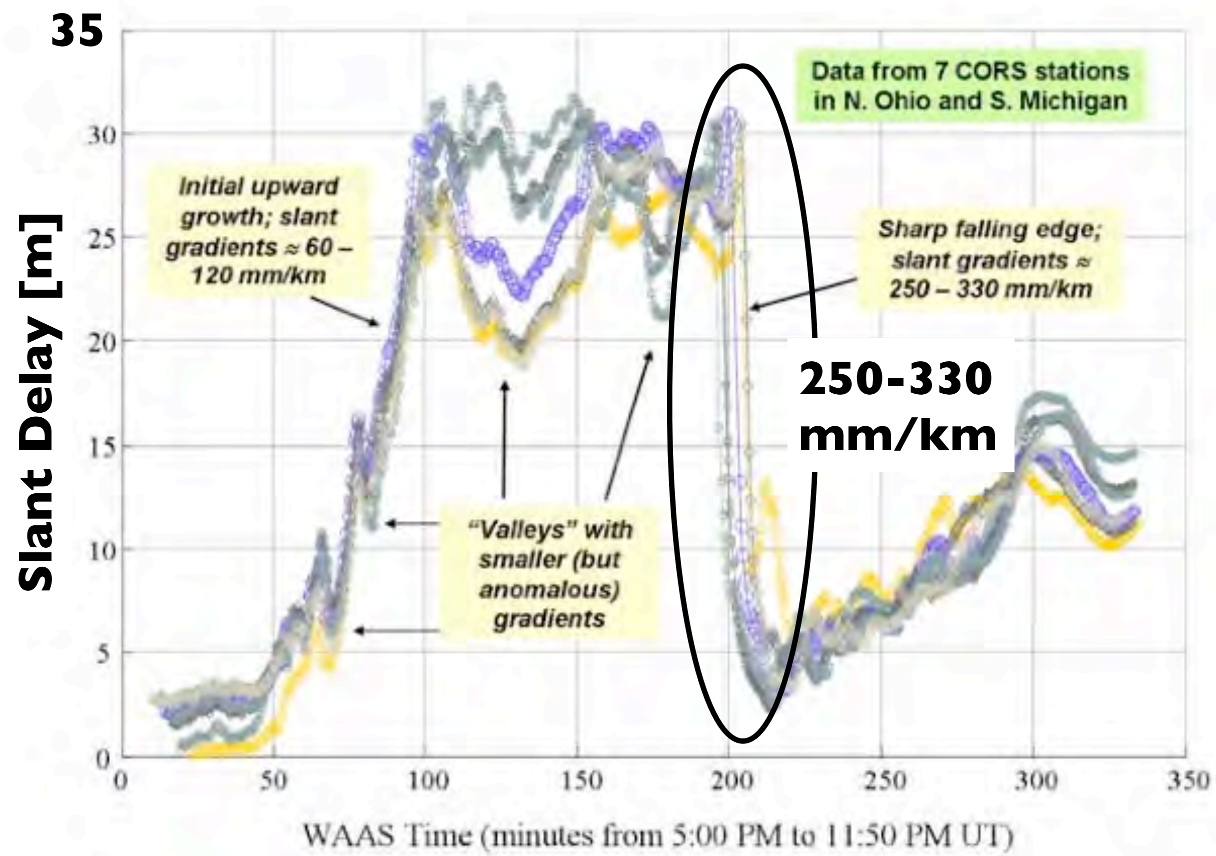


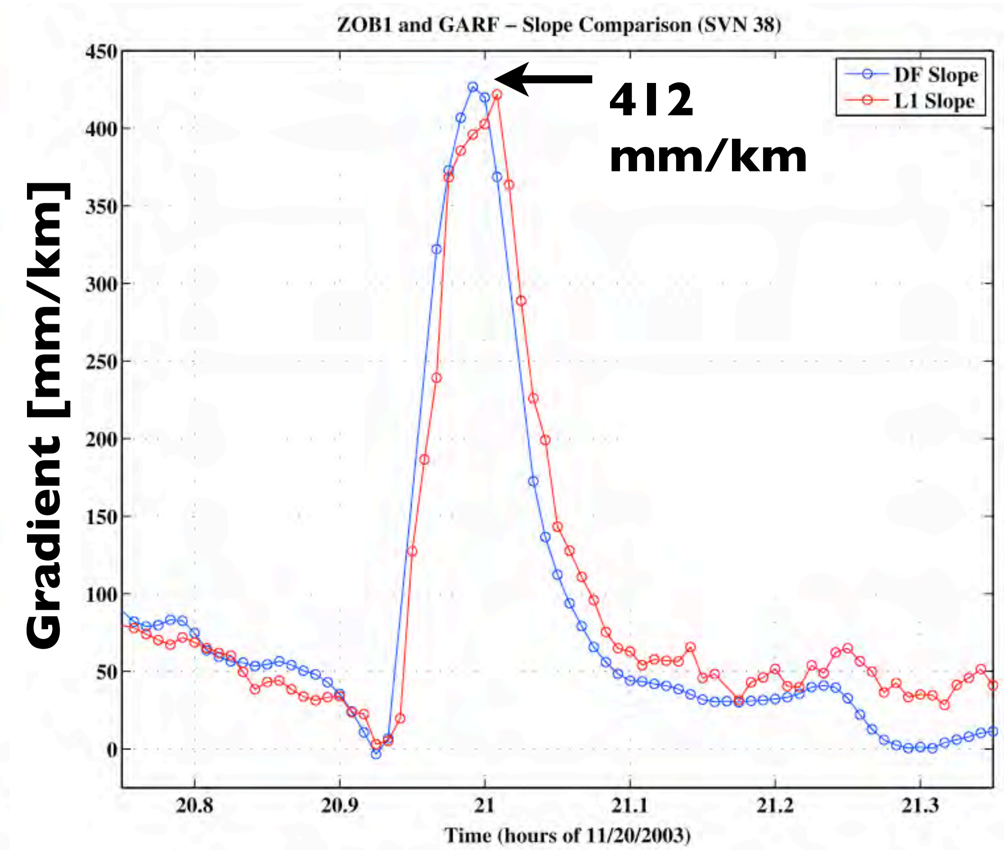
[Foster et al., 2002]



- Extreme ionospheric density enhancement asociated with severe magnetic storm
- Mid- to high latitude phenomenon
- Accompany very steep ionospheric gradient
- Relatively rare phenomenon

Impact of SED



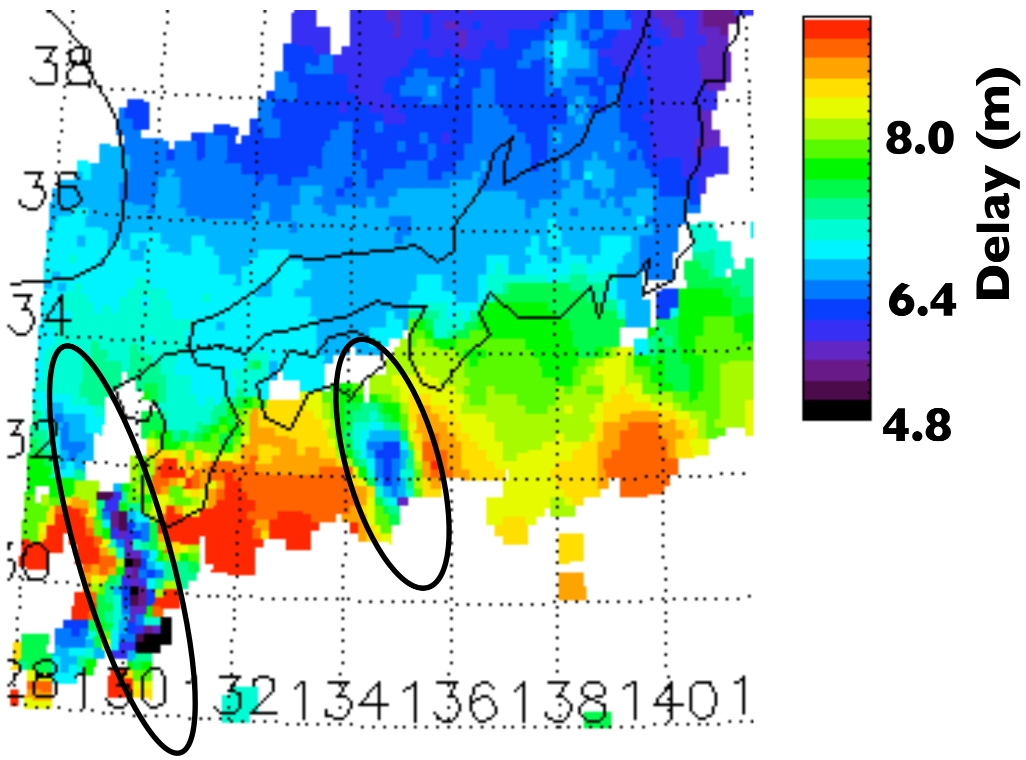


[Pullen et al., Radio Sci., 2008]

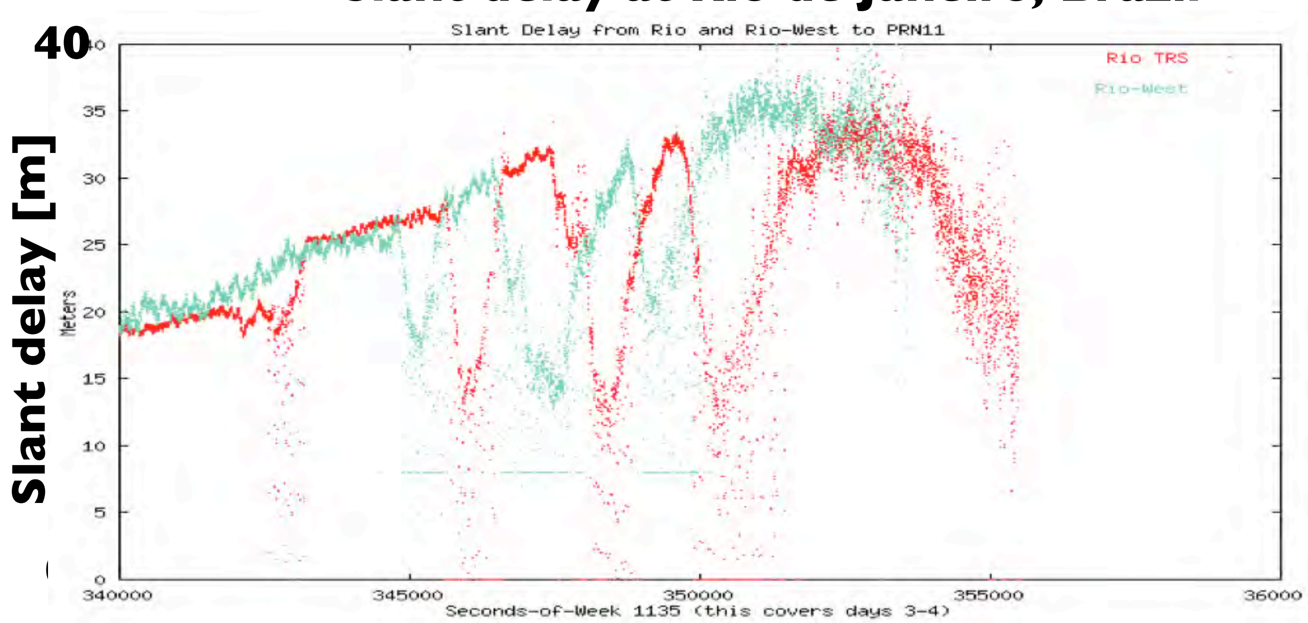
* Ionospheric delay gradient of 412 mm/km has been observed.
* Amplitude of the delay change is more than 20 m
* Miss-detection of SED would result in serious errors
* Since GBAS uses satellites with elevation angle down to 5°, SEDs should be considered even in low latitude region.

Plasma bubble

Vertical TEC variation over Japan
21:25:30 JST on 7 April 2002



Slant delay at Rio de Janeiro, Brazil

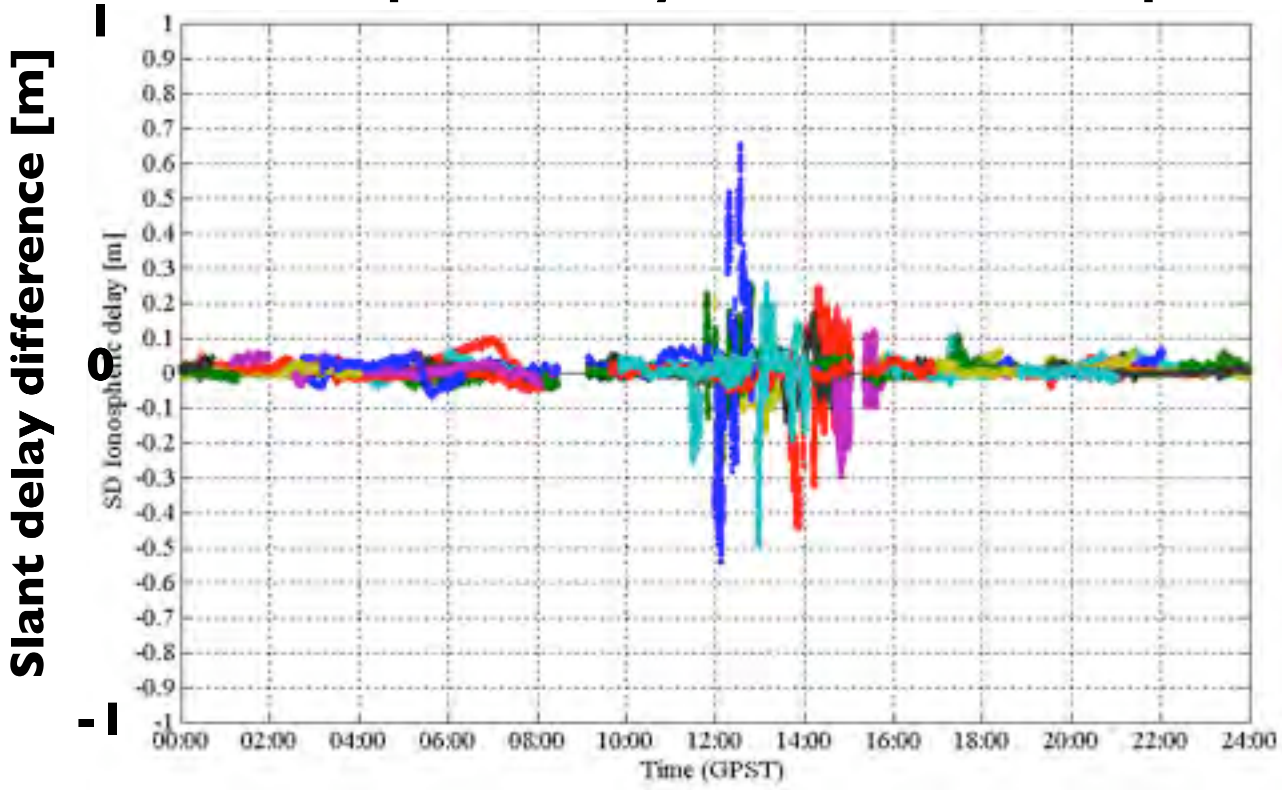


- Ionospheric density depletion elongated in the north-south direction
- Accompany very steep ionospheric gradient and scintillation
- Frequently occur after sunset in high solar activity periods
- In the Asia-Pacific region, higher occurrences are observed during equinox seasons (March-April and September-October)

[ICAO NSP Report on Ionospheric effects on GNSS,2006]

Impact of plasma bubbles

ionospheric delay difference on 03 April 2008



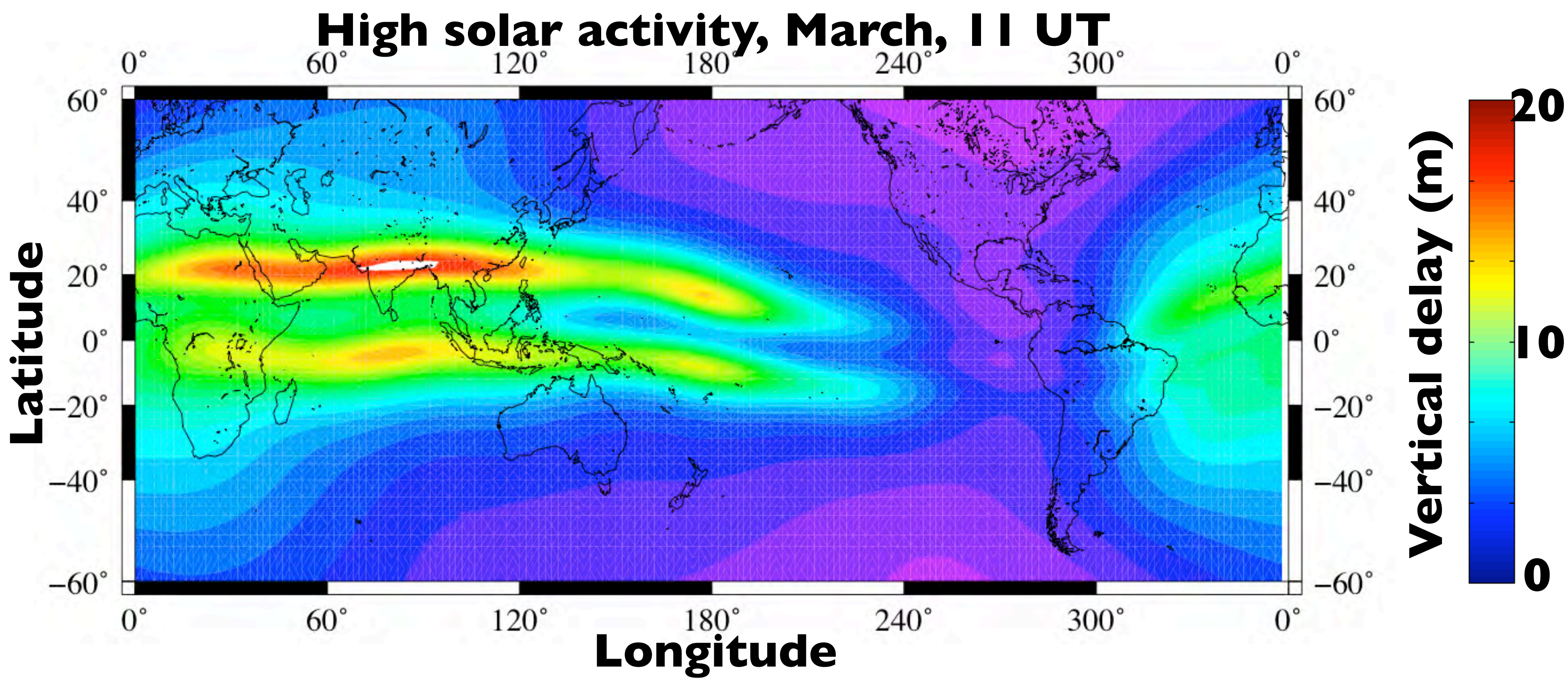
Ionospheric delay difference (single difference) between two GEONET stations separated by 6.3 km

[Fujita et al., JAAA, 2010]

- Gradients of 100 - 200 mm/km have been often observed.
- Miss-detection would results in serious errors.
- Scintillation would degrade GBAS performance.
- **Plasma bubbles have not been well studied in terms of gradient**.

Equatorial anomaly

- Large-scale ionospheric density enhancement around ±15° magnetic latitude
- Gradients are relatively small, but must be considered as a background ionospheric variability



Mitigation of ionospheric impacts

* Nominal ionosphere
  - Background ionospheric fluctuations, always exists
  - Covered by protection levels:
    - the signal-in-space upper confidence bounds on the error in the position relative to the GBAS reference point
* Anomalous ionosphere
  - Disturbed ionosphere, not always exists but potentially dangerous
  - Detected or prescreened, and excluded so that the aircraft will not use the misleading information

Protection level in normal condition

ENRI

$$\mathrm{VPL} = \max\left[\mathrm{VPL}_{H0}, \mathrm{VPL}_{H1}\right]$$

$$\mathrm{VPL}_{H0} = \mathrm{K}_{ffmd}\sigma_{vert}$$

$$\sigma_{vert} = \sqrt{\sum_{i=1}^{N} s\_vert_i^2 \times \sigma_i^2}$$

$$\sigma_i^2 = \sigma_{pr\_gnd,i}^2 + \sigma_{tropo,i}^2 + \sigma_{pr\_air,i}^2 + \sigma_{iono,i}^2$$

$$\sigma_{iono} = F_{pp}\sigma_{vig}(x_{air} + 2\tau v_{air})$$

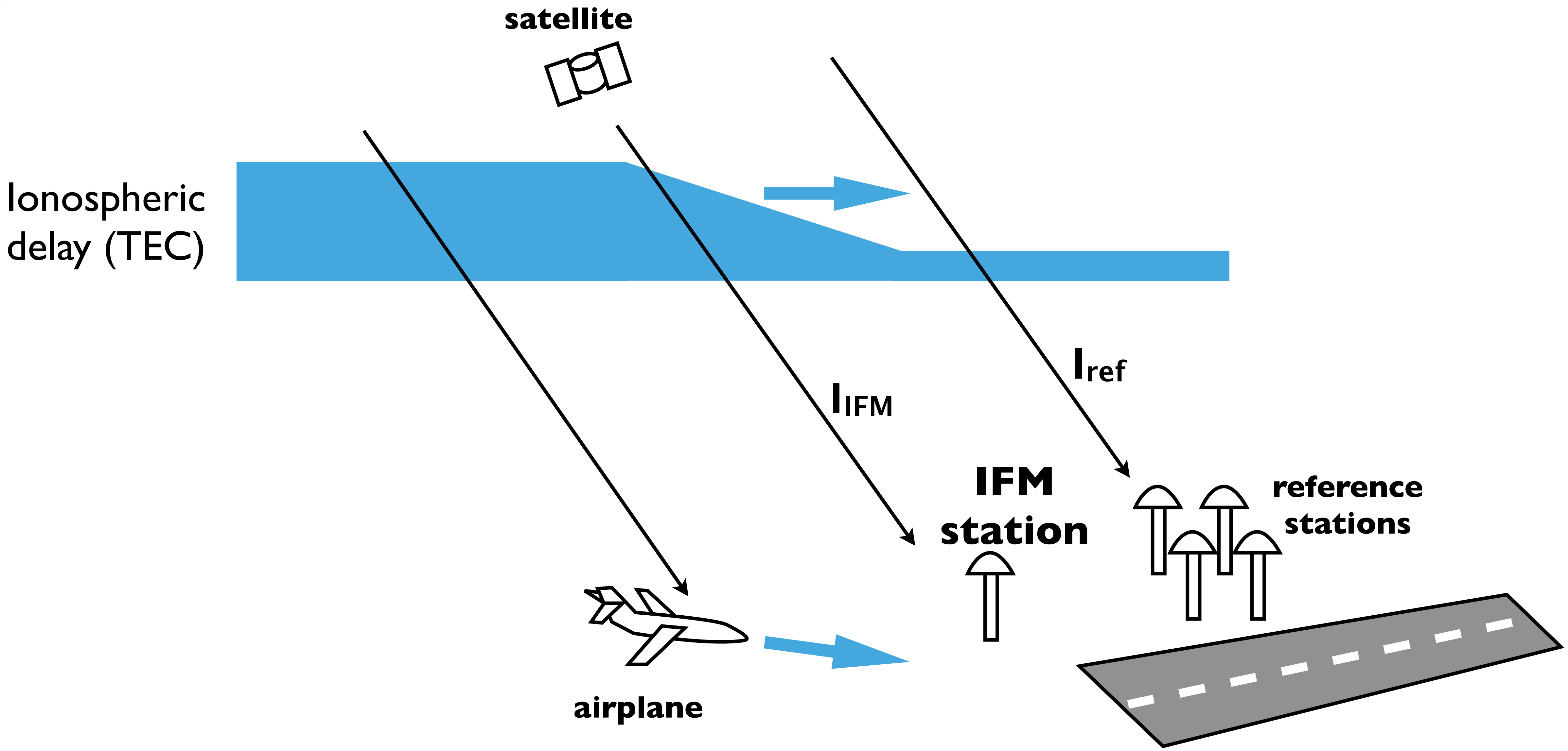
- VPL: vertical protection level
- H0: normal measurement
- H1: latent fault in one and only one receiver
- VPLH1 is not given here (See Ann. 10, Chap. 3, App. B, Sec. 3.6.5.5.1.2)

* K_{ffmd}: the multiplier derived from the probability of fault-free missed detection
* s_vert: the partial derivative of position error in the vertical direction with respect to pseudo-range error
* σ_{vig}: the standard deviation of a normal distribution associated with the residual ionospheric uncertainty (in vertical) due to spatial decorrelation (broadcast in the GBAS Type-2 message)
* F_{pp}: Slant factor

Anomalous ionosphere detection/ prescreening

* Code-carrier divergence (CCD)
  - Detect difference in variations in pseudo-range measurement and carrier-phase measurement
* Geometry screening
  - Screen out potentially dangerous satellite geometries by inflating GBAS correction parameters
* Ionospheric field monitor
  - Additional monitoring receiver near threshold to detect spatial gradient
* Absolute gradient monitor
  - Spatial gradient monitoring between reference stations (for GAST-D)
* Dual Solution Ionospheric Gradient Monitoring Algorithm (DSIGMA)
  - Airborne monitoring using two different smoothing time (for GAST-D)

Ionosphere field monitor (IFM)



- IFM station is placed closer to the threshold than ref. stations.
- IFM monitors spatial gradient and reduce a maximum potential range error.
- Prototype GBAS of ENRI at Osaka-Kansai airport adopts IFM.

Ionospheric monitors and characterization of the ionosphere

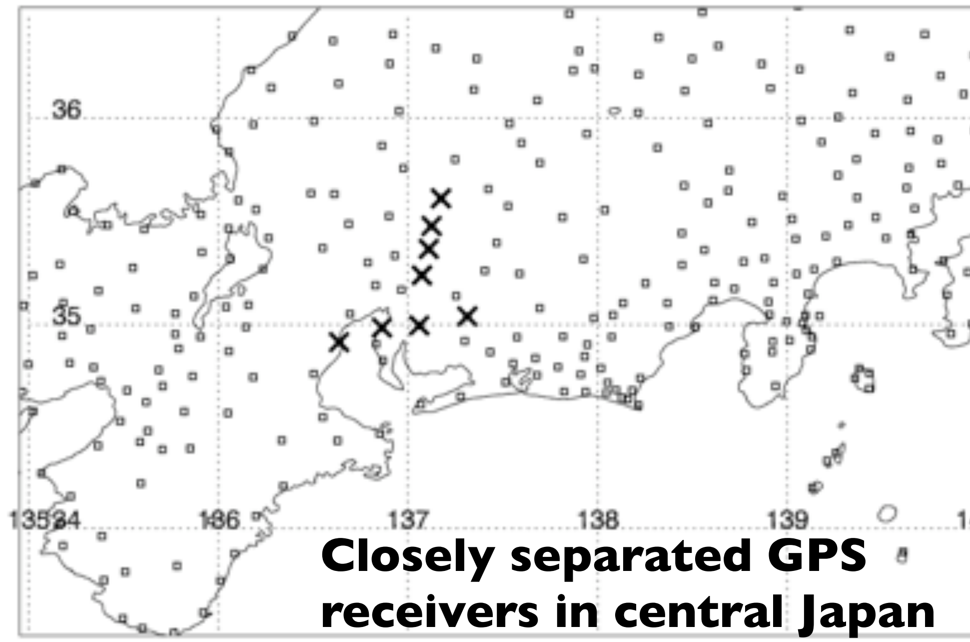
* Ionospheric monitors are necessary to protect the aircraft from hazardous conditions
* Too conservative detection criteria degrade availability
* In designing appropriate monitors that satisfy integrity and availability requirements, proper ionospheric characterization is necessary
  - How large the gradient can be
  - How large the total delay difference can be
  - How fast the gradient can move
  - How often such anomalies can occur

Characterization of the ionosphere

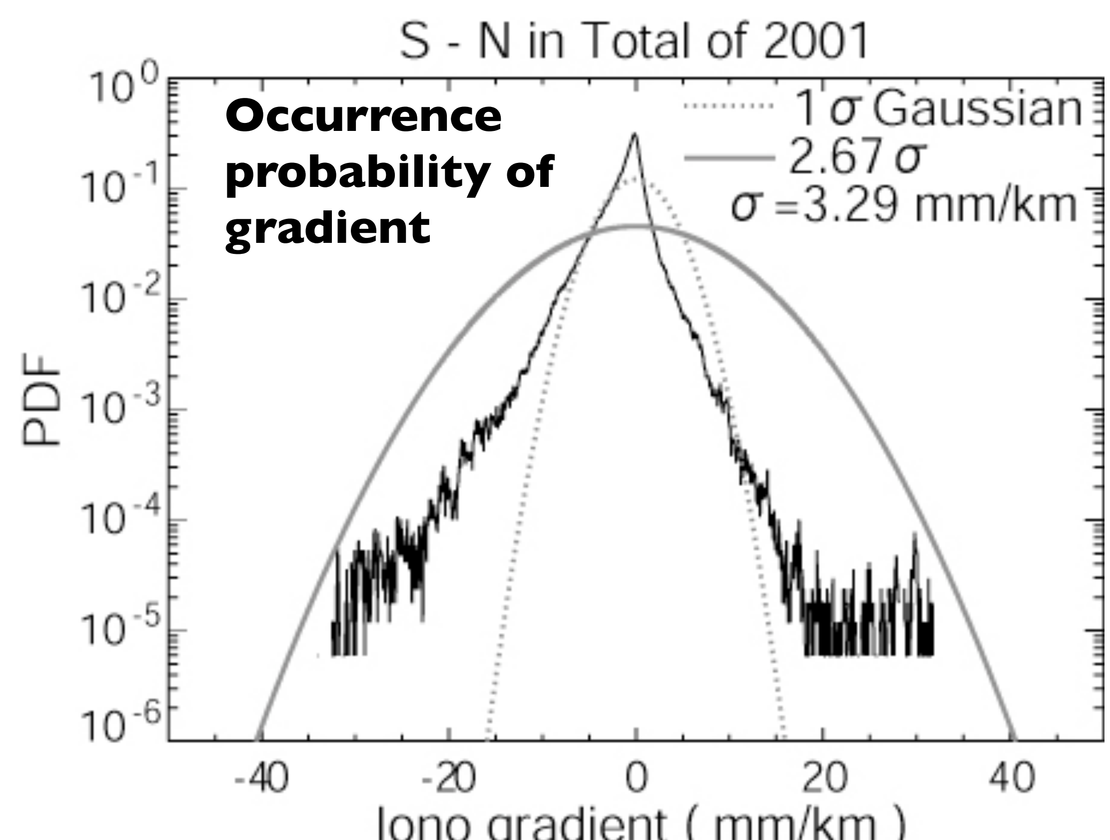
* Characterization of the ionosphere is necessary to design a system in such a way that the system is safe and available.
* Ionospheric threat model characterizes the behavior of the ionosphere and defines the range of parameters that should be taken into account in designing a GBAS.
* Two aspects, nominal and anomalous ionospheric conditions
* Nominal ionosphere
  - Background ionospheric fluctuations, always exists
* Anomalous ionosphere
  - Disturbed ionosphere, not always exists but potentially dangerous
* Defining the ionospheric threat is a responsibility of each State.

Nominal ionosphere

- σ_{iono} covers the ionospheric variability in nominal conditions.
- σ_{iono} should be determined to bound an observed occurrence distribution.
- Large number of observations with closely separated observing stations are necessary.



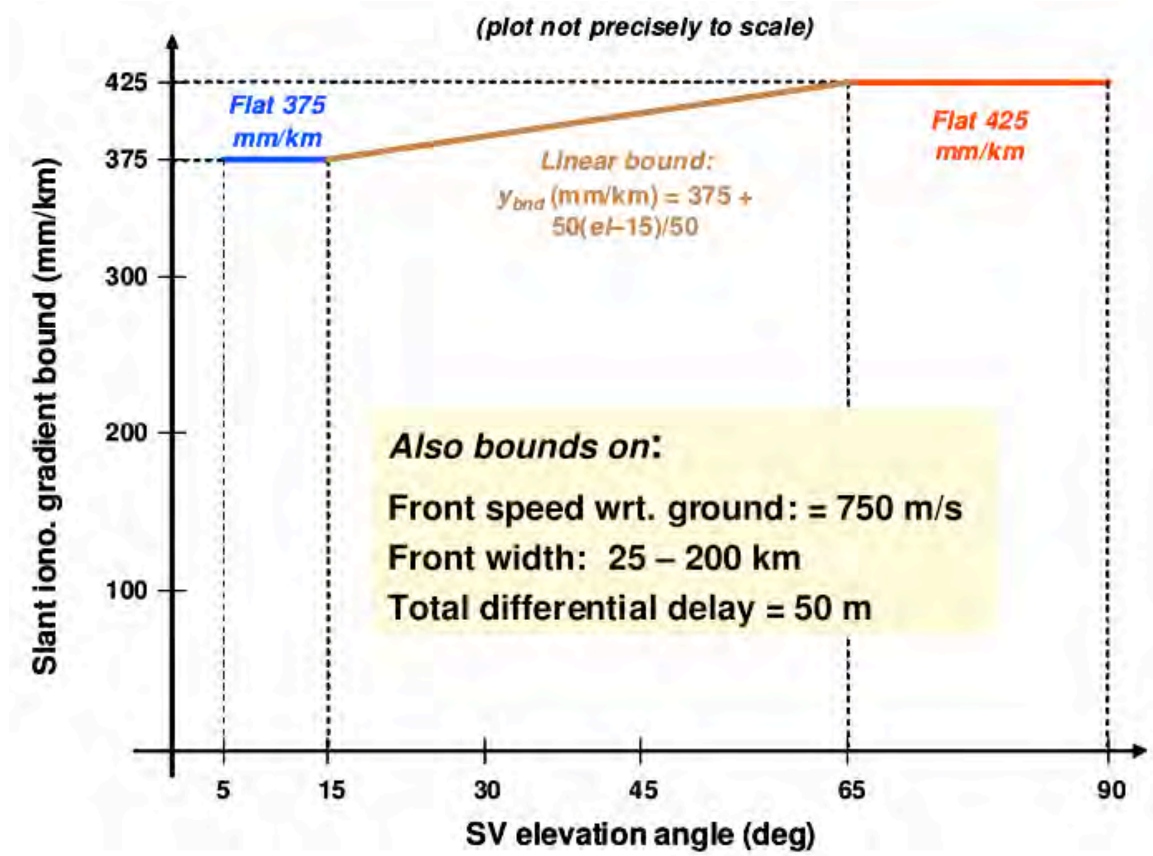
Closely separated GPS receivers in central Japan



Occurrence probability of gradient

[Yoshihara et al., Japan Inst. Nav., 2010]

Anomalous ionosphere

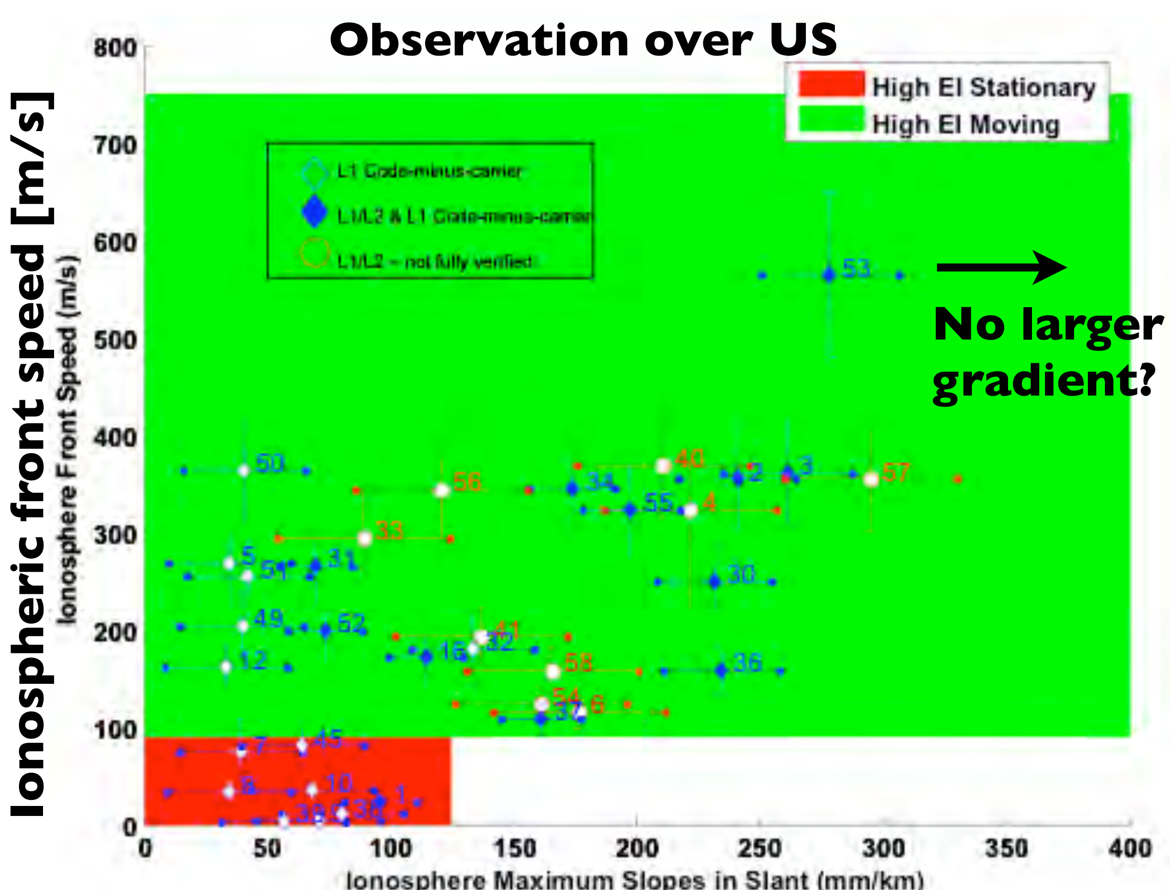


[Pullen et al., Radio Sci., 2008]

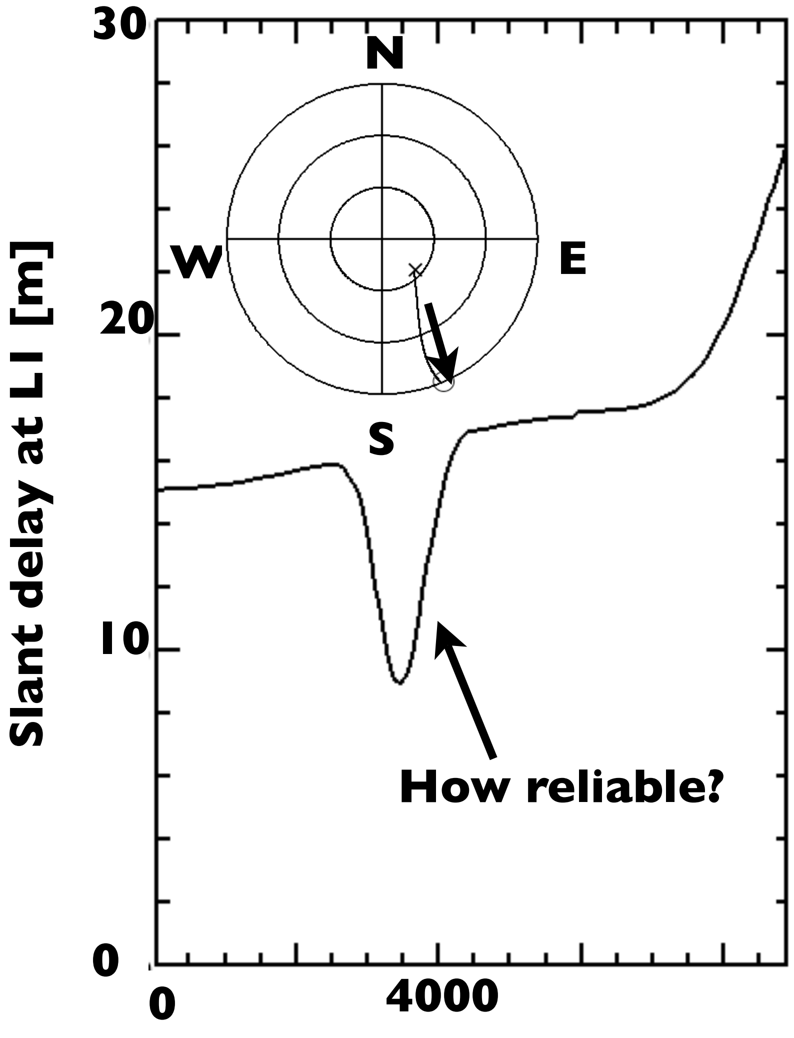
- Anomalous ionosphere is not bounded by σ_{iono} for nominal conditions.
- Anomalous ionosphere should be detected by monitors and excluded.
- Necessary parameters are:
  - Gradient
  - Total delay amplitude,
  - Ppropagation velocity

Approaches to threat model

* Observation-based approach
  - shows some aspects of reality, but a number of data is necessary.
* Simulation-based approach
  - Arbitrary situations can be tested, but validation is necessary based-on observations



Ionospheric slope [mm/km]
[Lee et al., ION GNSS 2006]



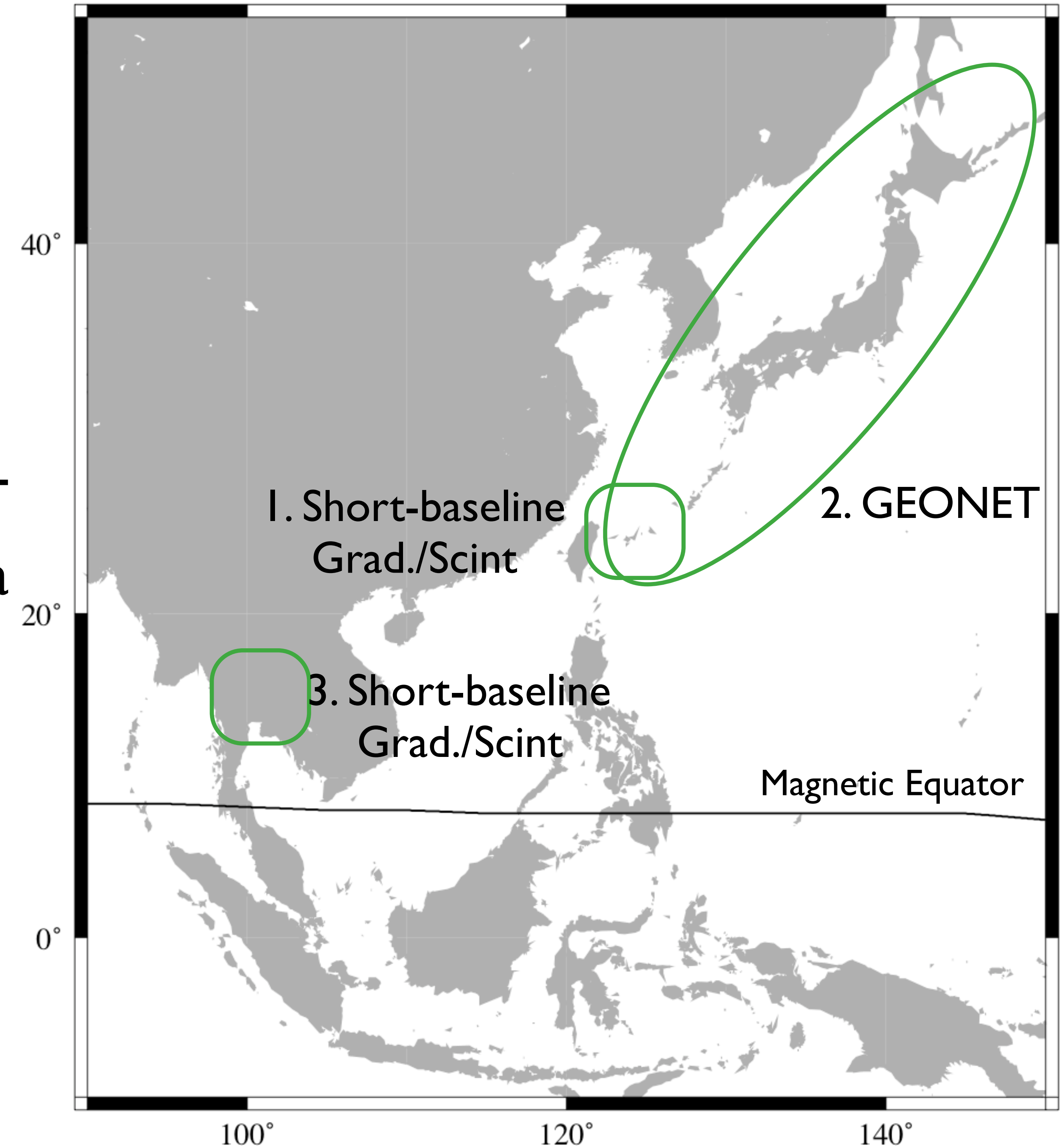
[Saito et al., ION ITM 2009]

Necessary observations for ionospheric characterization

* Local ionospheric gradient is one of the most important parameter in GBAS
  - Data of gradients associated with plasma bubbles are missing
  - Background ionospheric variability is also necessary in each region
* Short baseline (10-20 km, comparable to the scale size of plasma bubble wall) measurements are required.
* Wide-area (background) observations are necessary not only to characterize nominal ionosphere but also to understand the cause of the gradients.

ENRI's activities in ionospheric obsevation

1. Short baseline ionosphere gradient/scintillation system in Japan
2. 1 Hz realtime data collection from 200 GPS receivers selected from 1200+ GEONET stations operated by Geospatia Information Authority of Japan (former Geographical Survey Institute).
3. Short baseline ionosphere gradient/scintillation system in Thailand

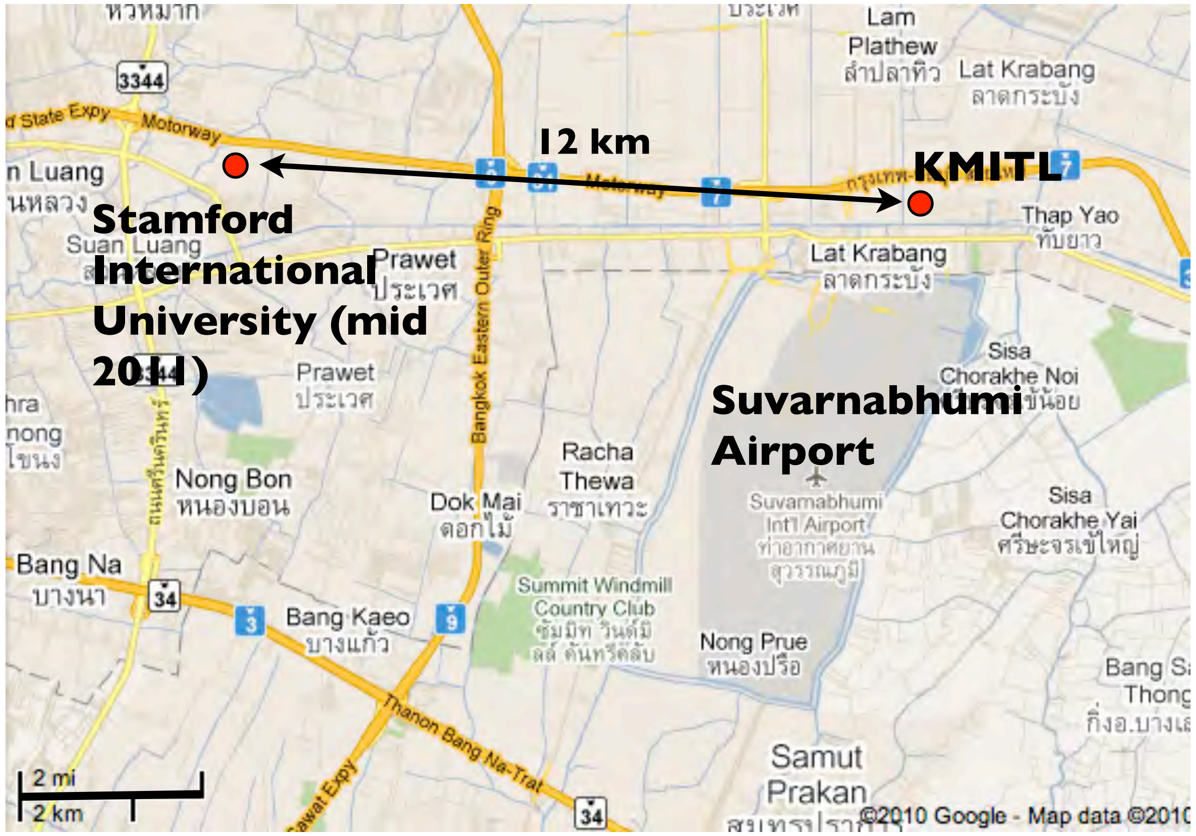


Short baseline ionospheric gradient/ scintillation measurement system in Japan

* Ionospheric gradient/scintillation measurements at Ishigaki Island (24.3°N, 124.2°E, 19.6° Mag. Lat) since 2008
* 4 stations with 0.4-1 km separation (Maximum separation 1.4 km)
* All the sites are equipped with dual-frequency GPS receivers and GPS scintillation receivers.
* 2 Hz sampling of Ionospheric delay

Short baseline ionosphere gradient/ scintillation system in Thailand

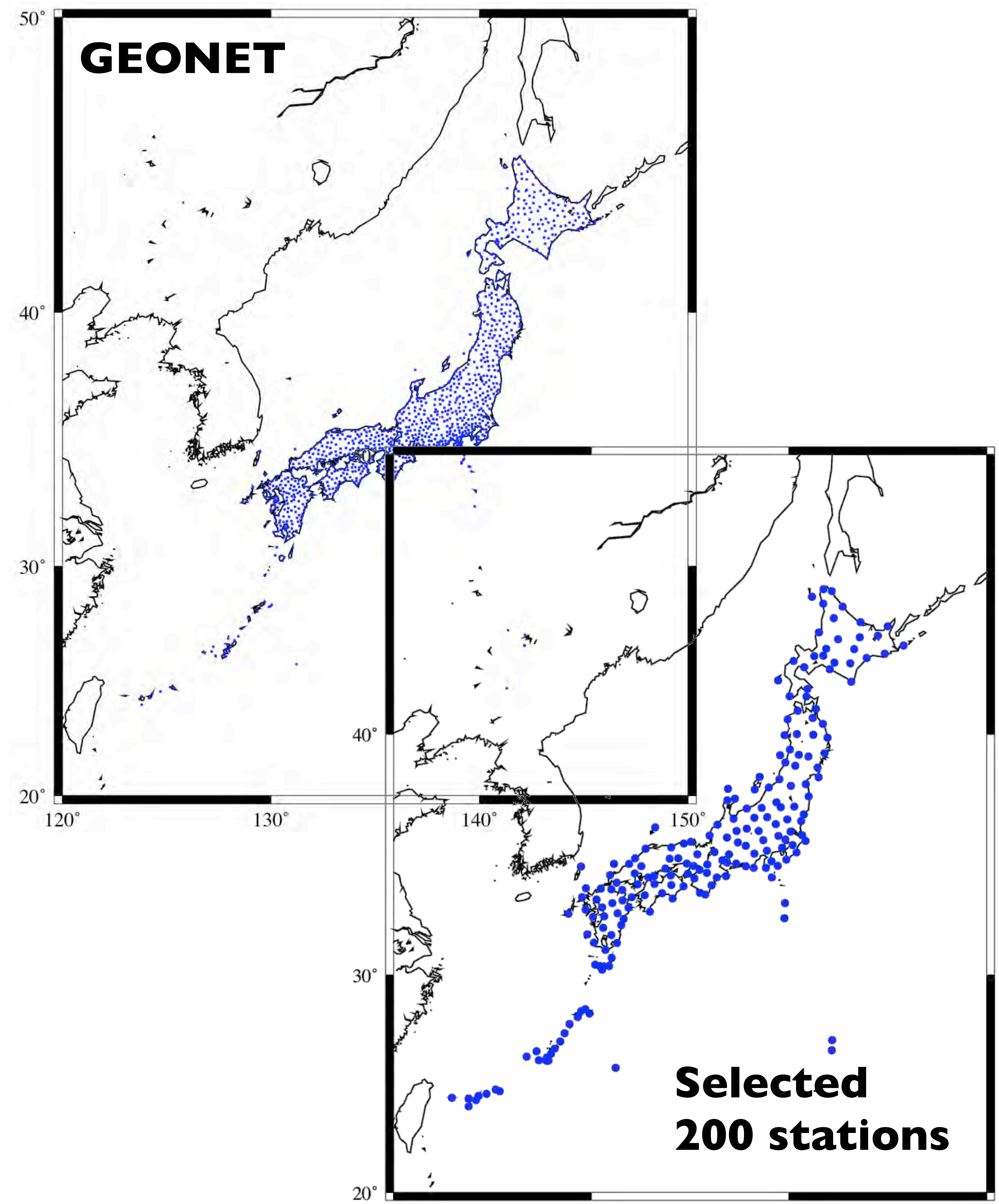
- Short baseline ionosphere gradient measurements near Bangkok airport.
  - Joint project of ENRI and King Mongkut's Institute of Technology Ladkrabang (KMITL)
  - Similar to the Ishigaki system
  - KMITL site is already in operation. Second receiver site will be started in mid 2011.



- More plasma bubble events are expected with increasing solar activity.

GEONET 1Hz data collection

- Realtime data collection from GPS Earth Observation Network (GEONET) at 1 Hz data rate.
- GEONET data were used to determine σ_{iono} value used in GBAS prototype [Yoshihara et al., ION GNSS 2010] and the ionospheric threat model used for ENRI's CAT-I GBAS prototype.



Summary

* Local ionospheric gradient is one of the most important parameter in GBAS.
* Characterization of the ionosphere is necessary to design a system in such a way that the system is safe and available.
* Data of gradient associated with low latitude ionospheric anomalies are missing.
* Short baseline (10-20 km, comparable to the scale size of plasma bubble wall) measurements are required to establish an ionospheric threat model for GBAS.
* Wide-area (background) observations are necessary not only to characterize nominal ionosphere but also to understand the cause of the gradients.
* ENRI has started observations in Japan and Southeast Asia collaborating with institutes and universities.