Impact of the low latitude ionosphere disturbances on GNSS studied with a three-dimensional ionosphere model

Susumu Saito and Naoki Fujii
Communication, Navigation, and Surveillance Department,
Electronic Navigation Research Institute, Japan

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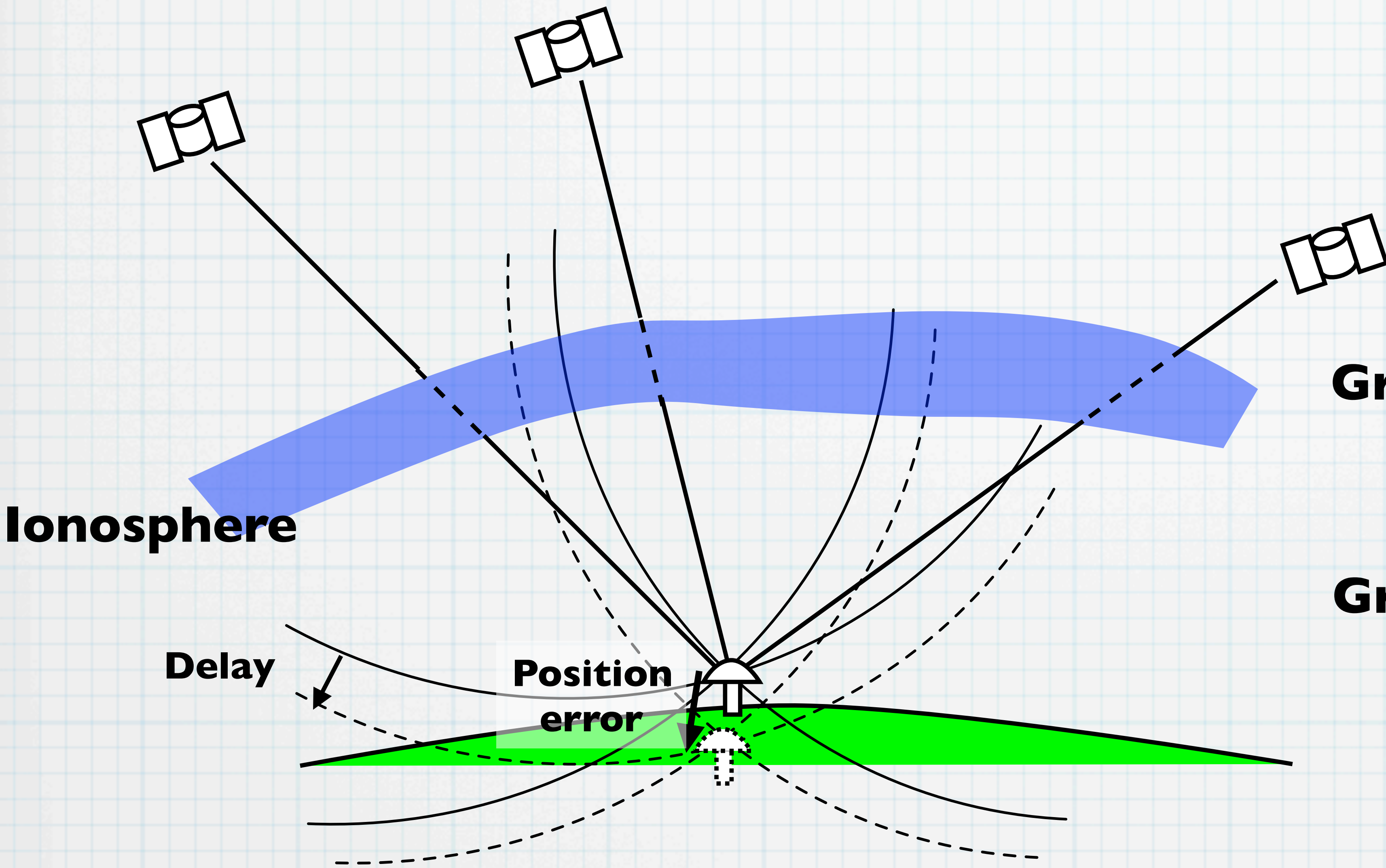
Satellite positioning and the ionosphere



Group refractive index

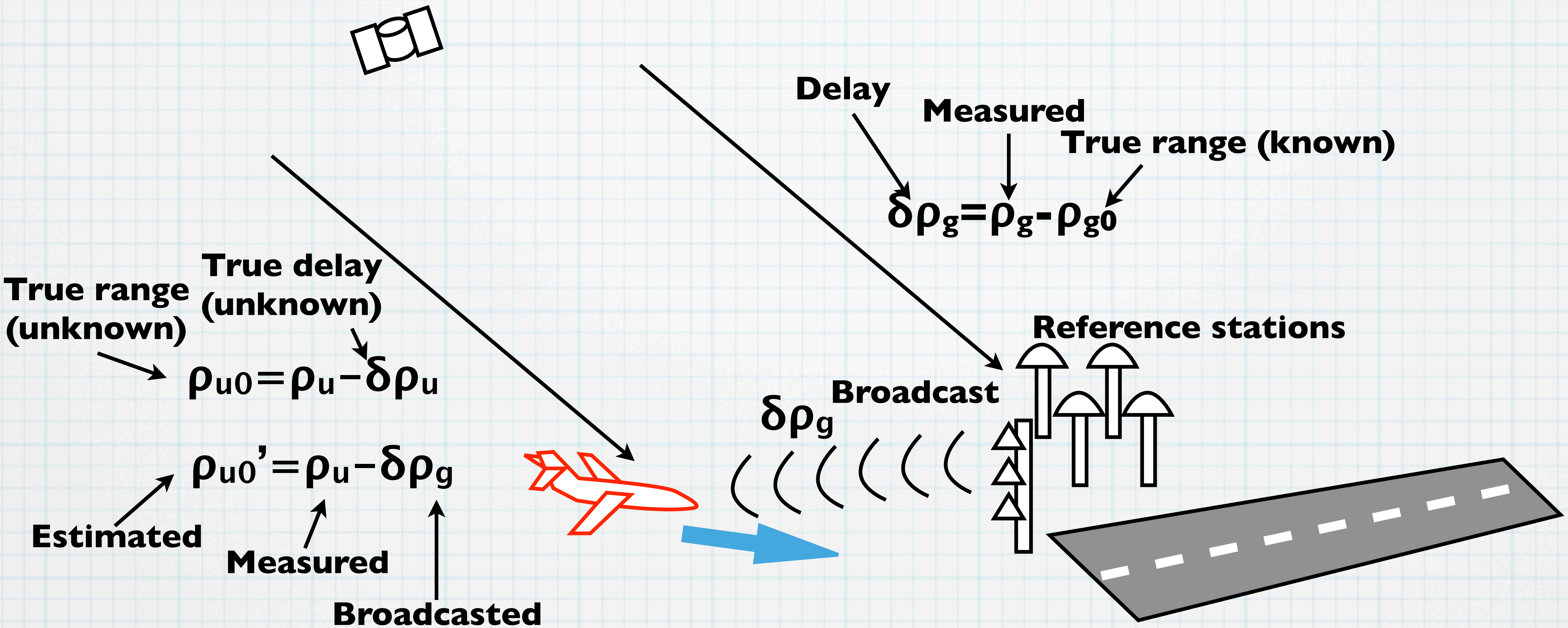
$$\mu' = 1 + \frac{e^2 n_e}{8\pi^2 m_e \epsilon_0 f^2}$$

Group delay

$$I_\rho = \frac{40.3}{f^2} \int_{sat}^{rec} n_e(l) dl$$

- Radio wave propagation is delayed by ionospheric plasma that change the refractive index
- At 1.57542 GHz (GPS L1), 16 cm delay per 1 TECU ($10^{16} m^{-2}$).

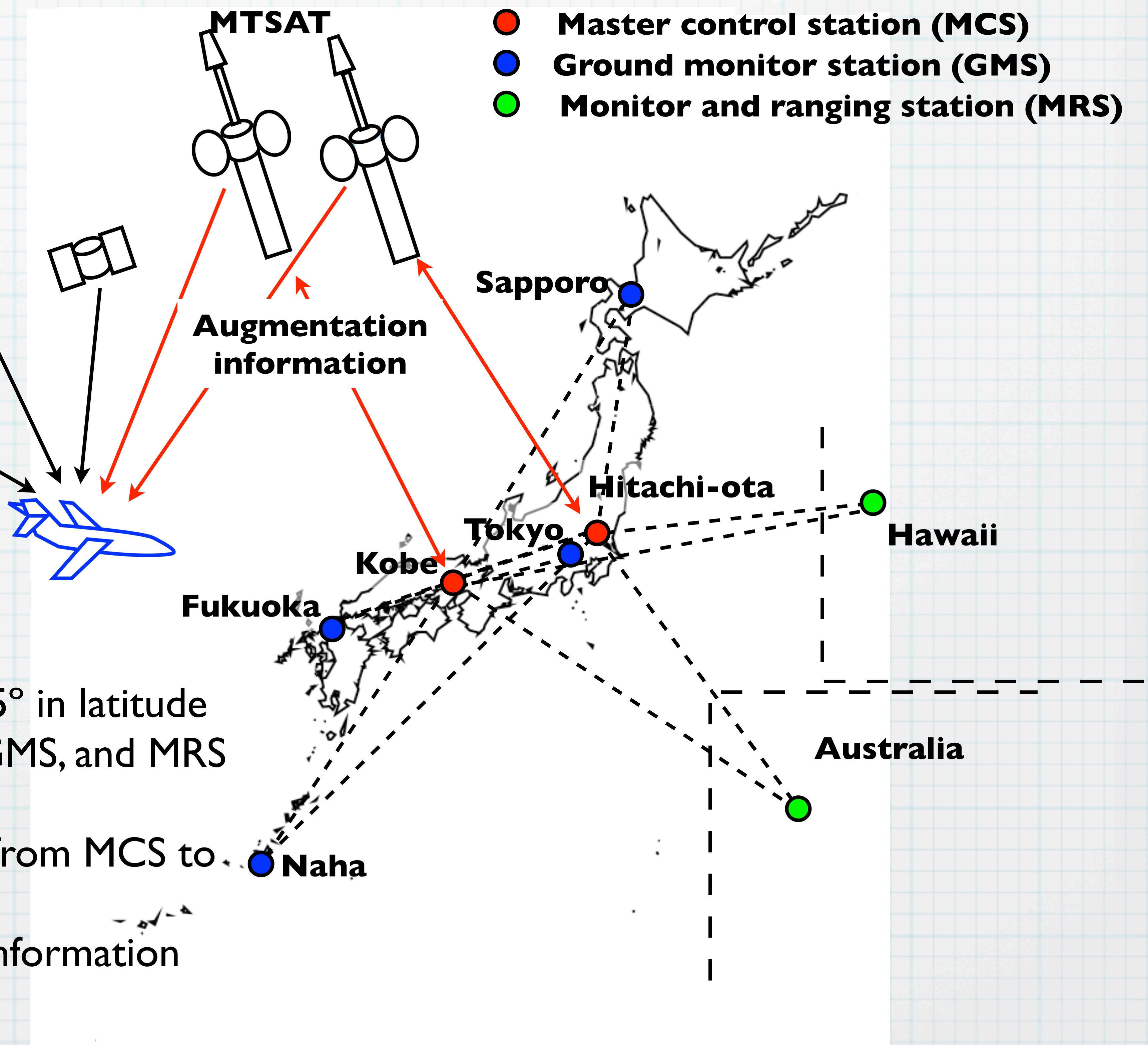
GBAS and ionospheric inhomogetuity



- Ionospheric delay is one of the largest error source.
- Inhomogeneous ionosphere ($\delta\rho_g \neq \delta\rho_u$) results in differential correction errors.

SBAS (Satellite-based augmentation system)

MSAS (MTSAT Satellite Based Augmentation System)



* Correction information (every 5° in latitude and longitude) based on MCS, GMS, and MRS observations.
* Correction information is sent from MCS to MTSAT
* MTSAT broadcasts correction information

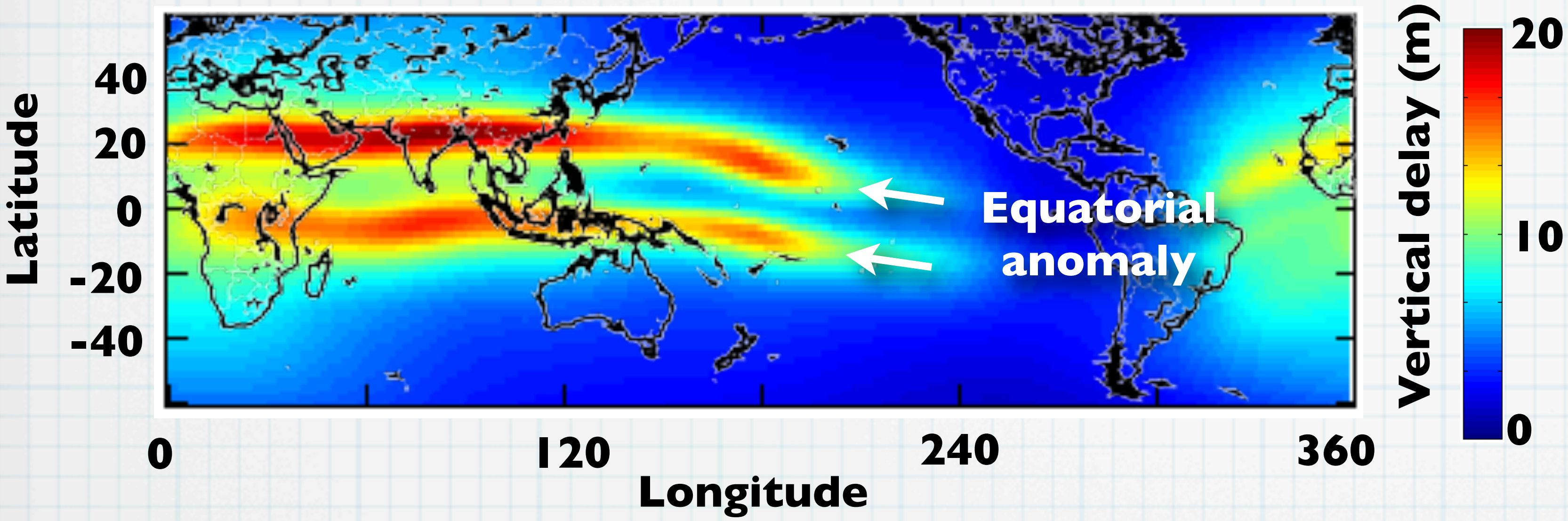
Ionospheric Anomaly and SBAS/GBAS

* GBAS
  - Local sharp ionospheric delay gradients results in error.
* SBAS
  - Small-scale Ionospheric irregularities may be miss-detected.
  - Ionospheric irregularities smaller than the grid size (5°x5°) cannot be well corrected.
* Both
  - Scintillation associated with ionospheric irregularities may degrade availability of GNSS.

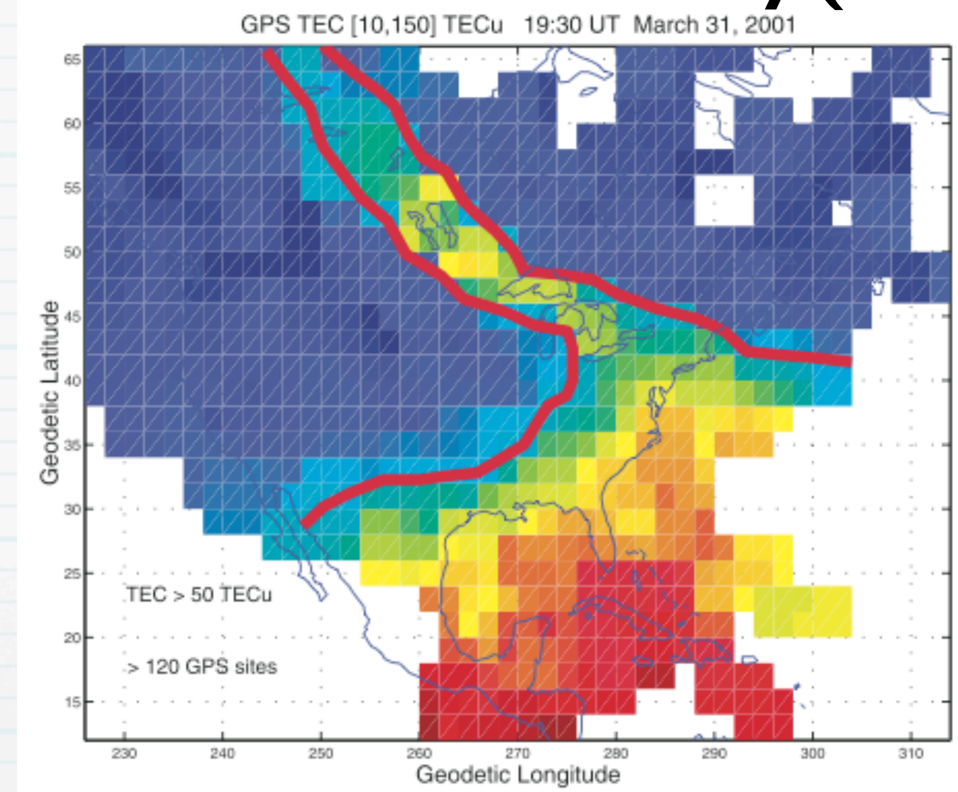
Ionospheric anomalies in low latitudes

* Equatorial Anomaly

Solar max., March, 11 UT



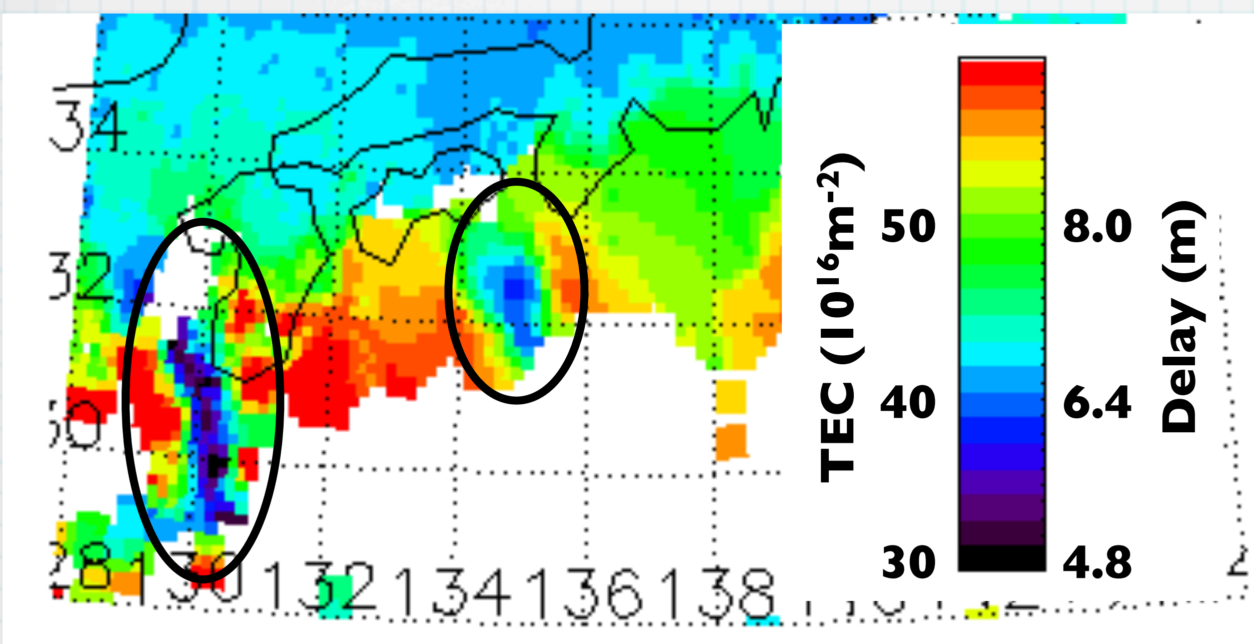
* Storm Enhanced Density (SED)



[Foster et al., 2002]

* Plasma Bubble

Vertical delay over Japan on 7 April 2002

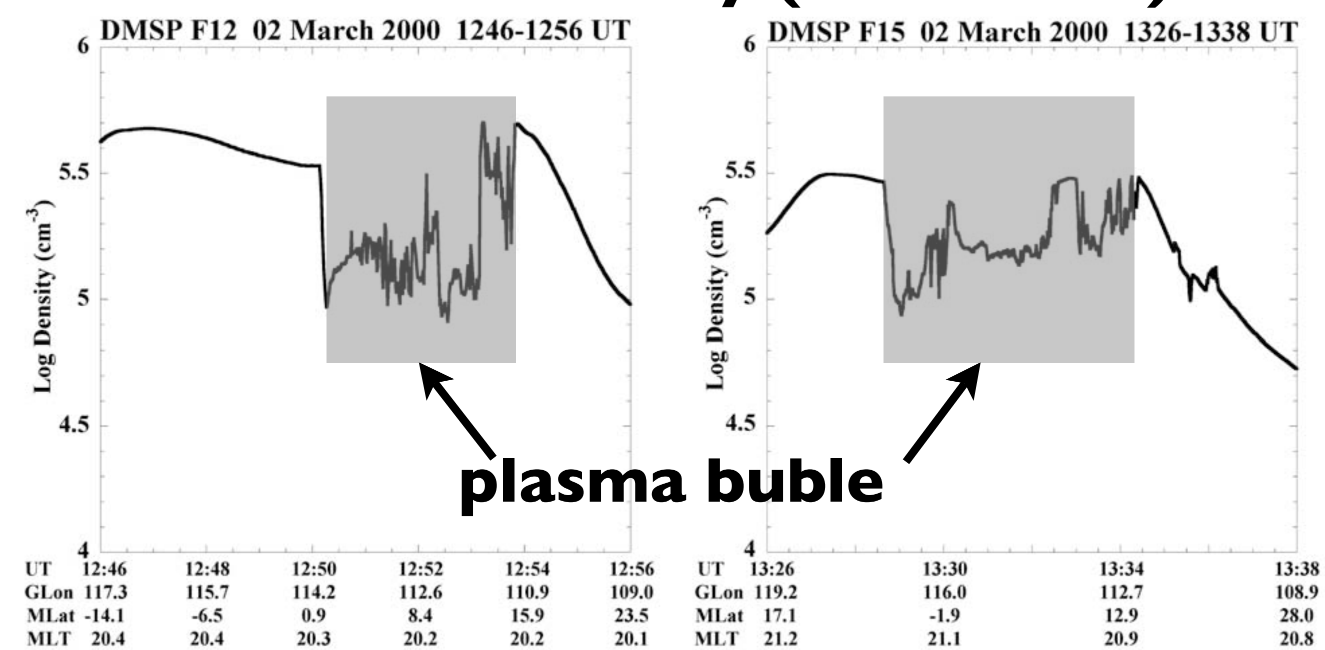


* Equatorial anomaly (Always)
  - Enhanced ionospheric plasma density around ±15° magnetic latitude
* Plasma bubble (low latitude, frequent)
  - Local plasma density depletion
* SED (mid-latitude, rare)
  - Increased ionospheric density associated with severe magnetic storms

Plasma bubbles and ionospheric density variation

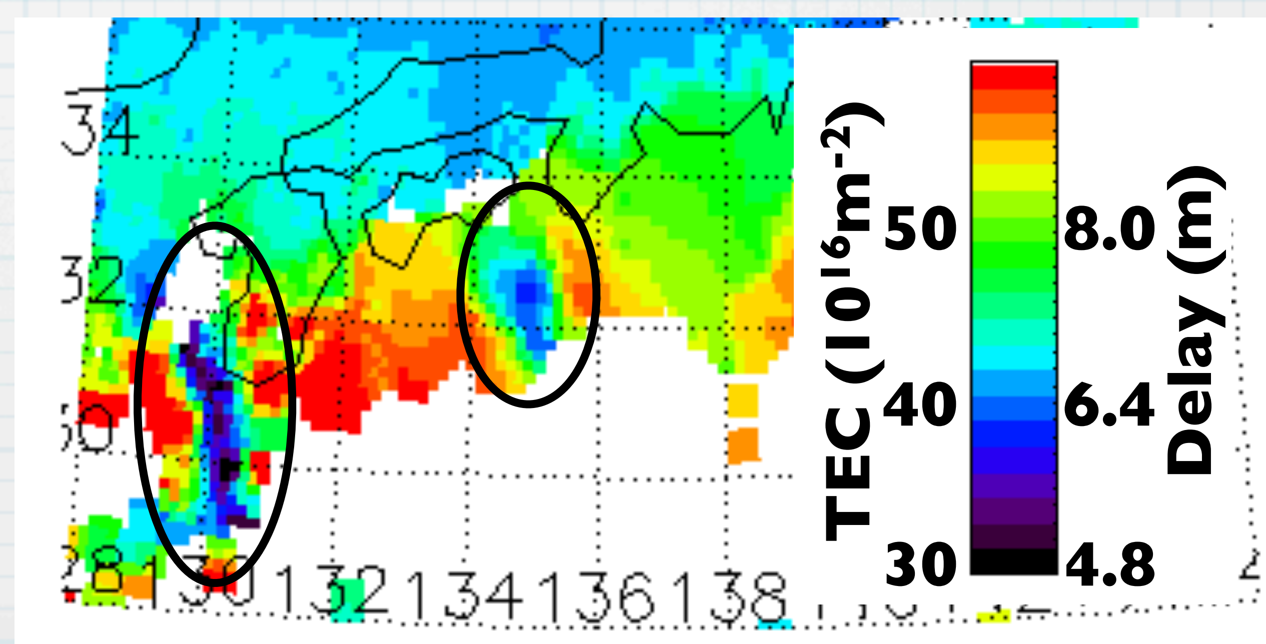
- Unique phenomenon in low latitude.
- Extreme depletion in plasma density inside of a bubble.
- Very sharp edges (15-30 km).
- Sharp spatial gradient in ionospheric delay.
- Frequent occurrence after sunset in solar maximum period.

Plasma density (ROCSAT-1)



[Burke et al., 2004a]

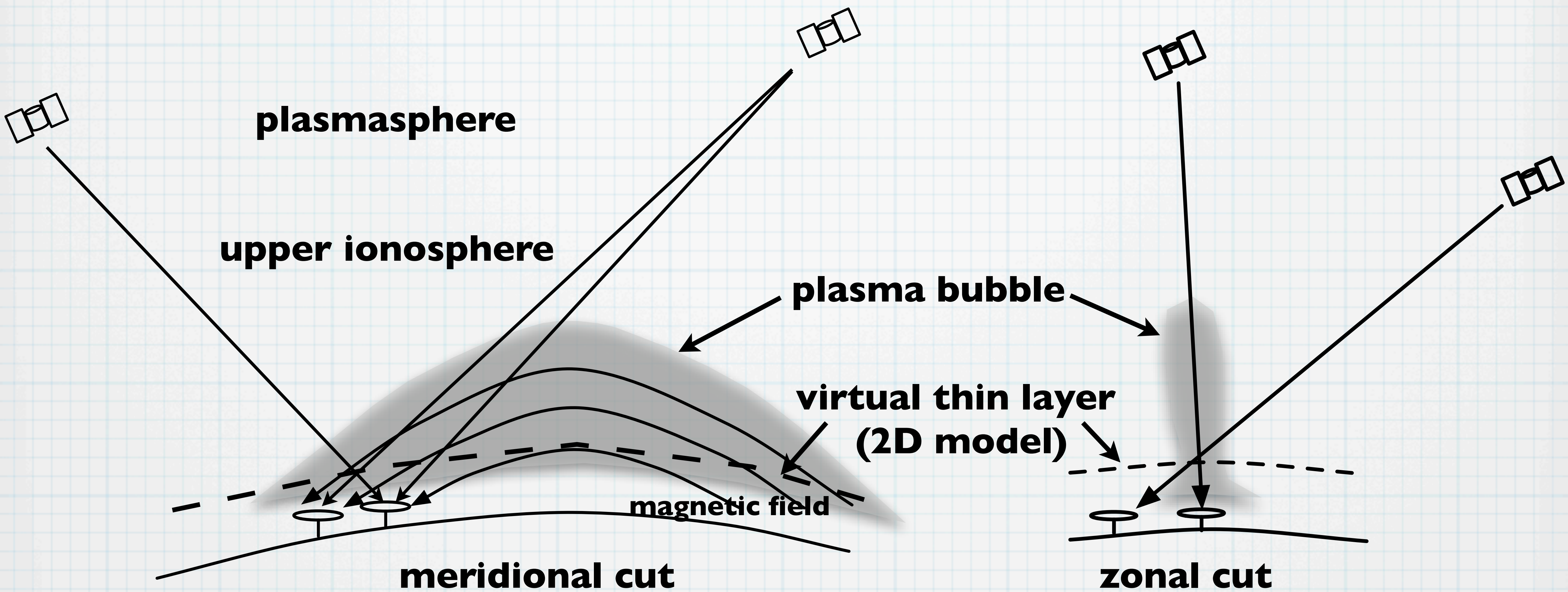
Vertical delay over Japan on 7 April 2002



Need of modeling

* General characteristics of the plasma bubble is rather well known unlike storm-enhanced density (SED).
* Number of observations of ionospheric gradients with short baselines are limited: "worst case" may not have been recorded yet.
* Modeling study based on the large amount of past studies on plasma bubble should be effective.

3-D plasma bubble shape and ionospheric delay

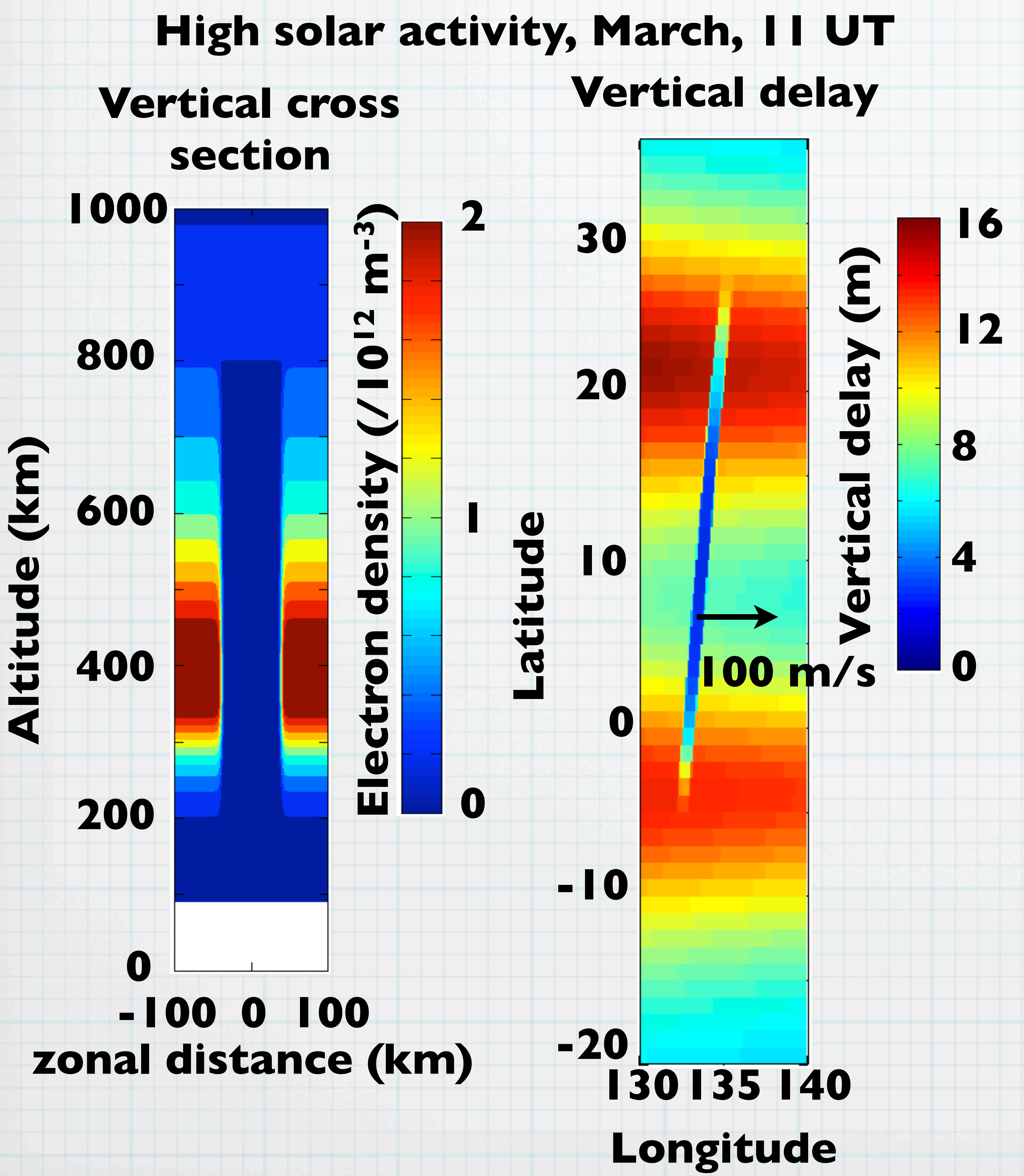


- Plasma bubble impacts on satellites at west/east low elevation angles or high elevation were not significant.
- Plasma bubble develops along the magnetic field line.
- Total delays may be different for the same ionospheric pierce points, which cannot be described by 2-D models.

3-D ionospheric delay model with plasma bubbles

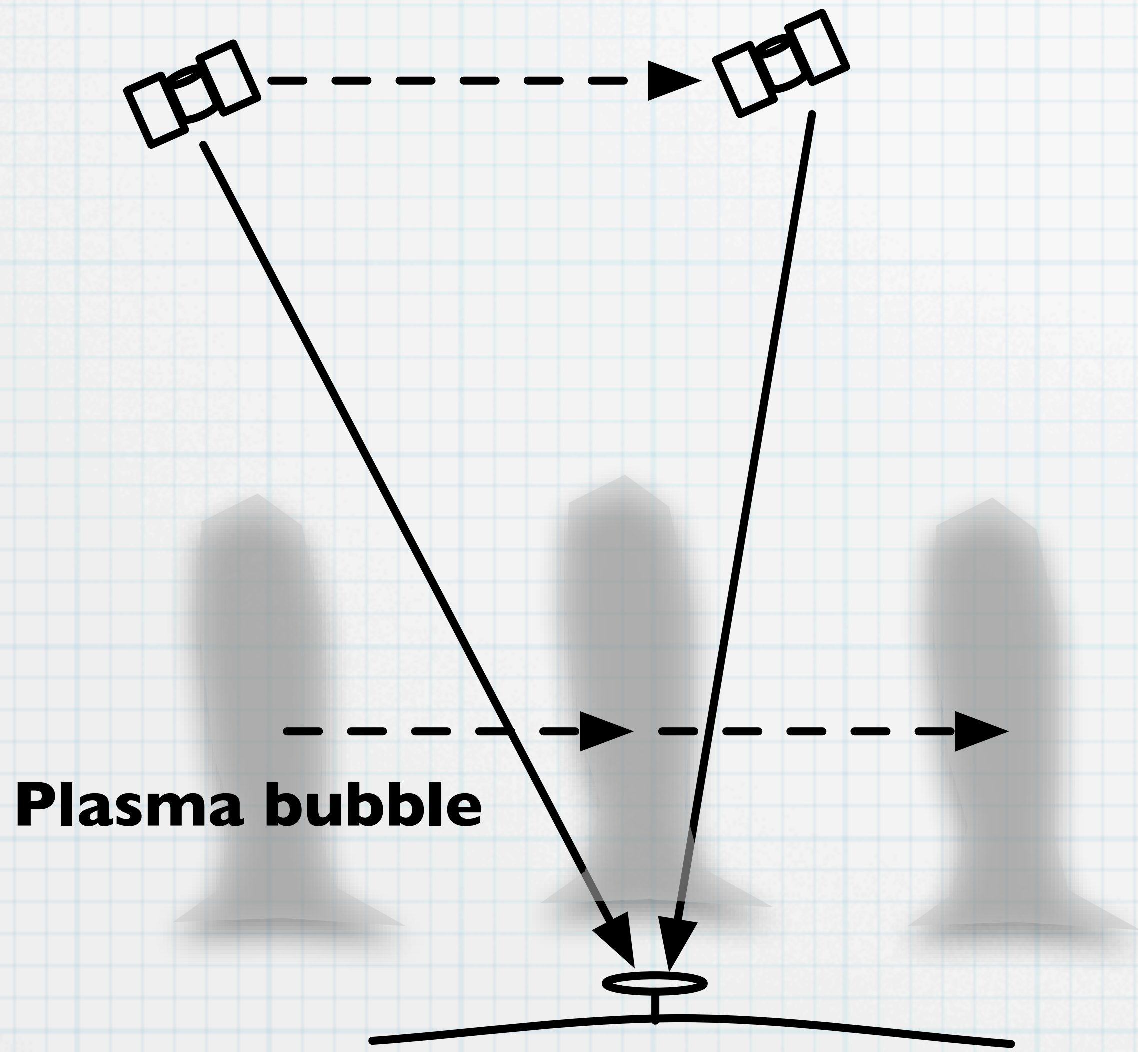
- Background plasma distribution * plasma bubble
- Background plasma distribution:
  - NeQuick [Giovannni and Radicella, 1990; Radicella and Zhang, 1995]
- Plasma bubble:
  - defined on the equatorial vertical plane with equivalent longitude and altitude
  - represented as depletion normalized by background (no plasma bubble) density
- Written in FORTRAN (Platform independent).

Plasma bubble model



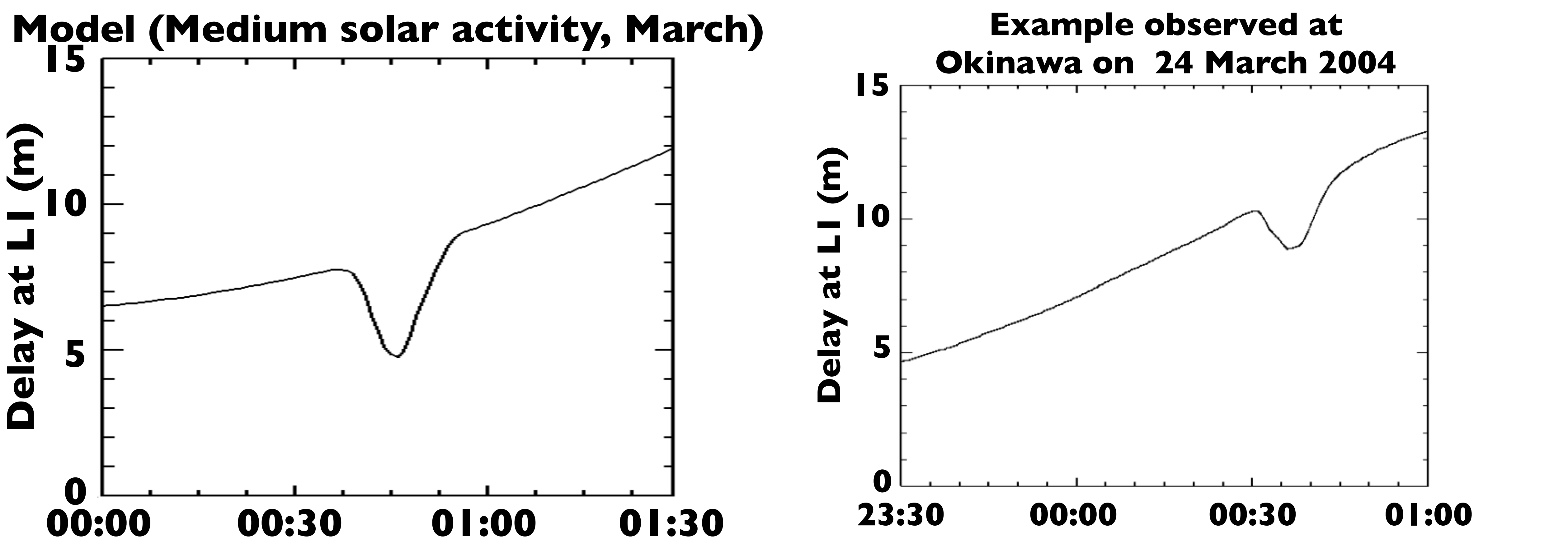
* Plasma bubble parameters
  - Width: 100 km
  - Top altitude 800 km
  - Depletion: 100 %
  - Scale of wall: 20 km
  - Eastward velocity: 100 m/s
  - Rectangular cross section
  - Tilted-dipole magnetic field

Test : Slant ionospheric delay variation



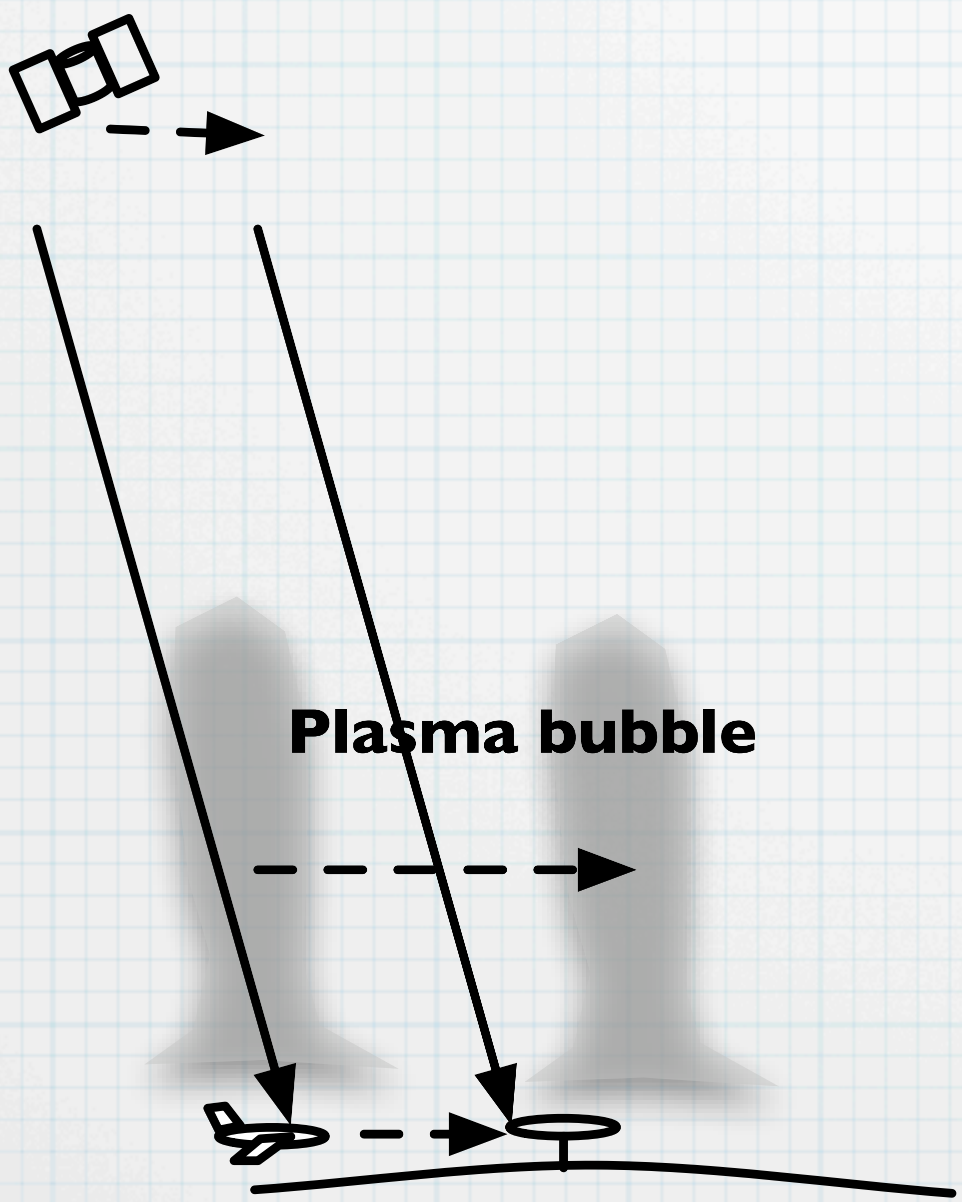
* Plasma bubble drifts at a constant zonal velocity.
* Receiver is fixed on a ground.
* A satellite is picked up from standard 24 satellite constellation.
* Delay changes as local time goes by (background changes), as a satellites moves, and as a plasma bubble passes over.

Test: Slant ionospheric delay variation



- Slant ionospheric delay at (135°E, 25°N) with a plasma bubble in March with medium solar activity is modeled.
- Delay depletion due to a plasma bubble is reproduced.
- The result looks similar to observed delay variation.

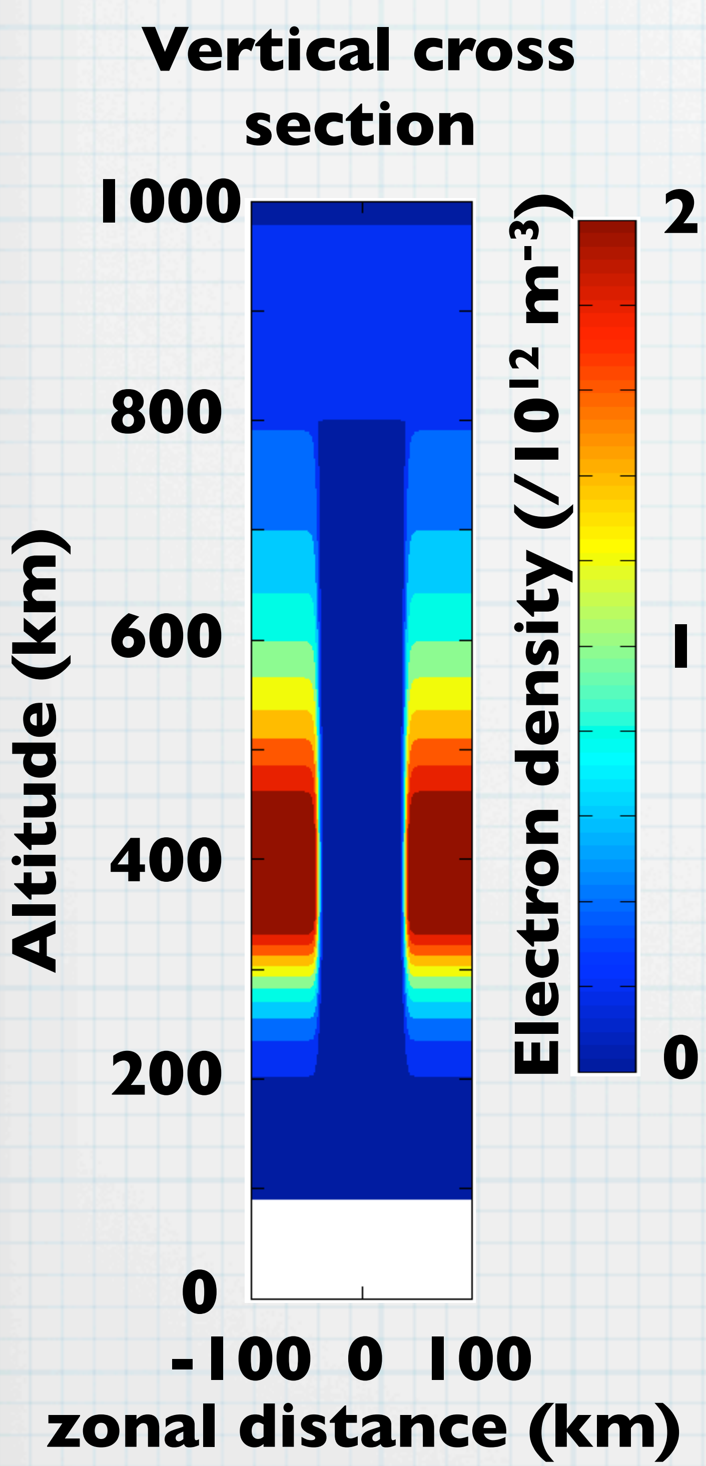
GBAS simulation

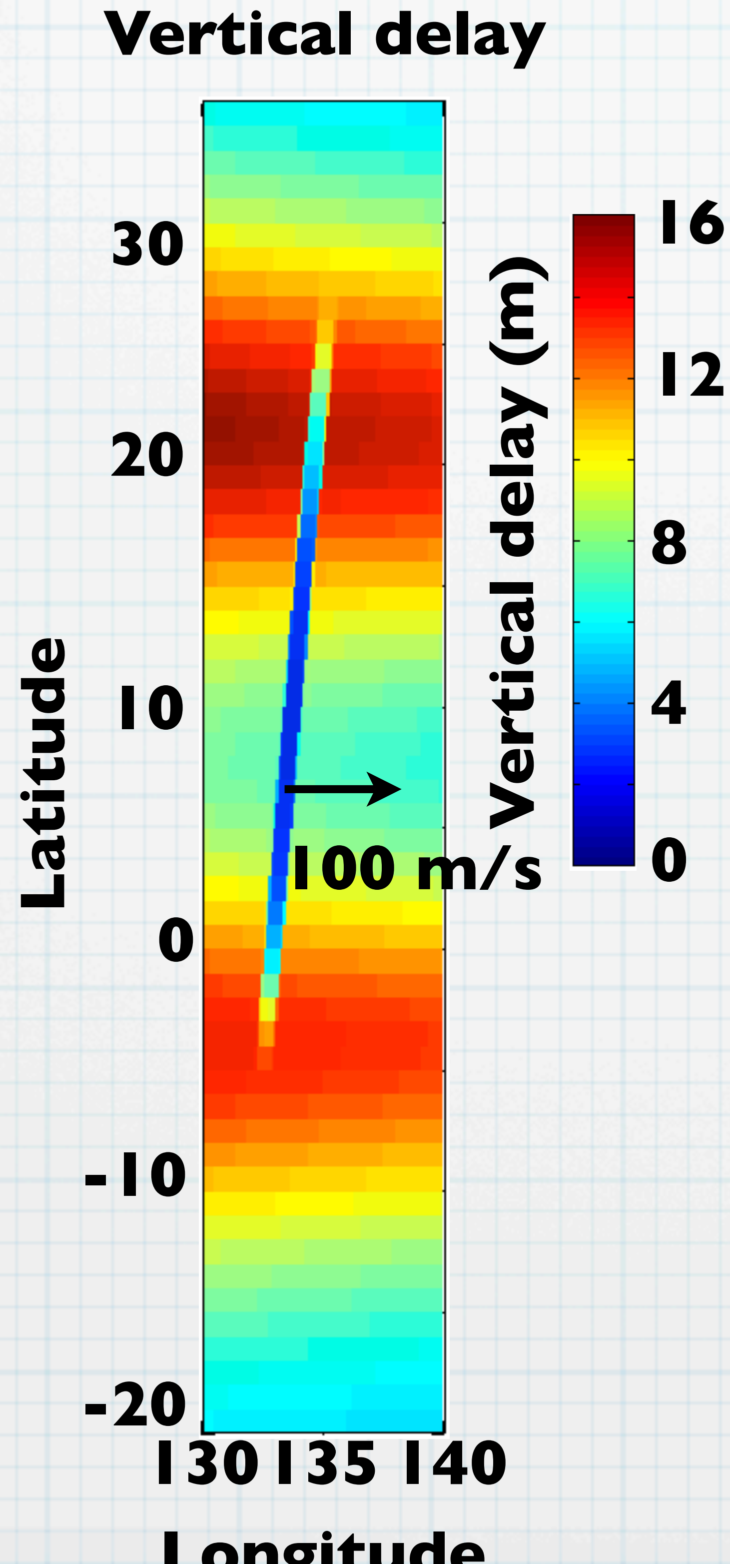


- Plasma bubble drifts at a constant zonal velocity.
- Airborne receiver moves toward the reference station at a constant velocity.
- A satellite is picked up from standard 24 satellite constellation.
- Positioning errors calculated with the delays of the reference and airborne receivers.
- No monitor neither on the ground nor airborne.

Plasma bubble model

High solar activity, March, 11 UT





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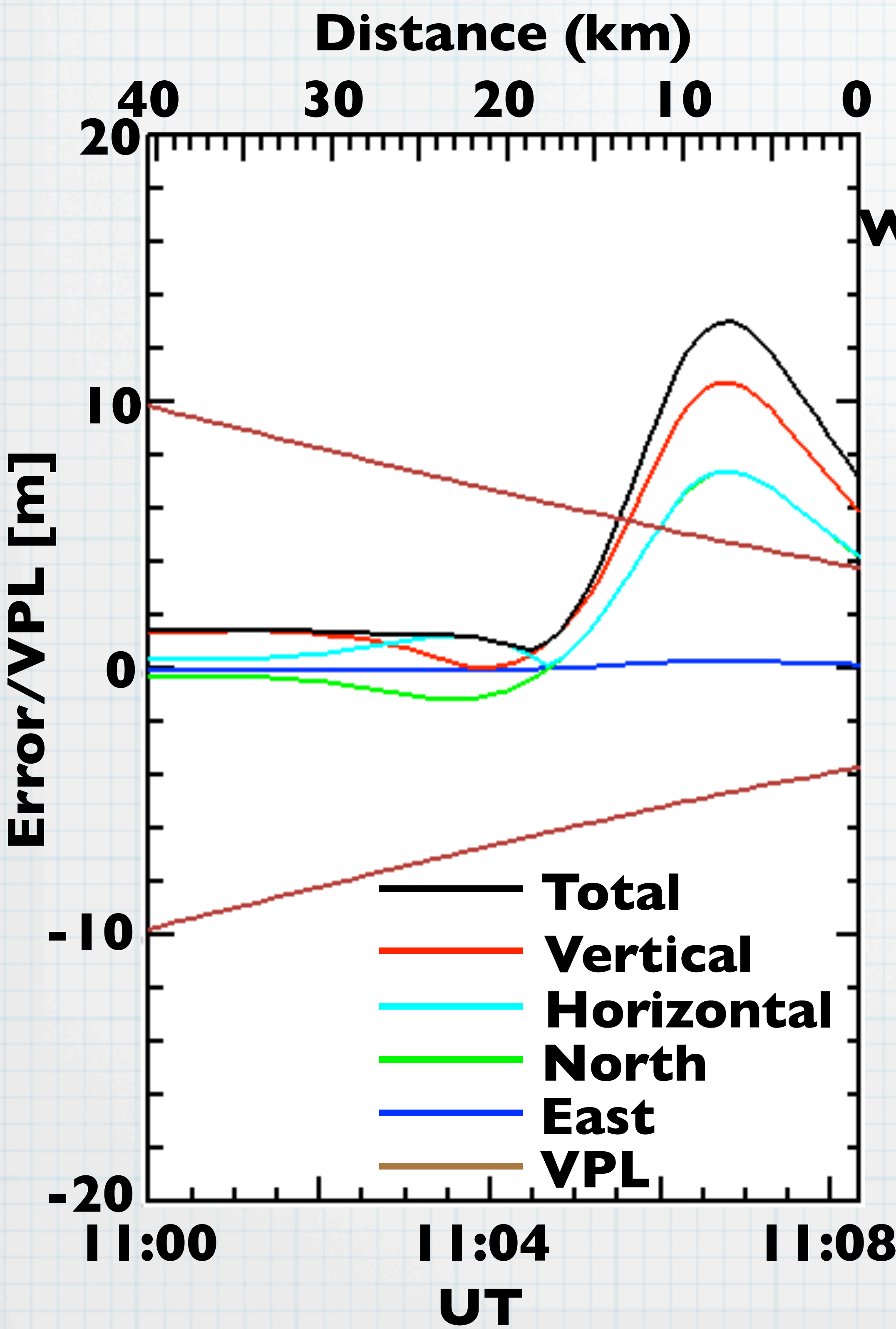
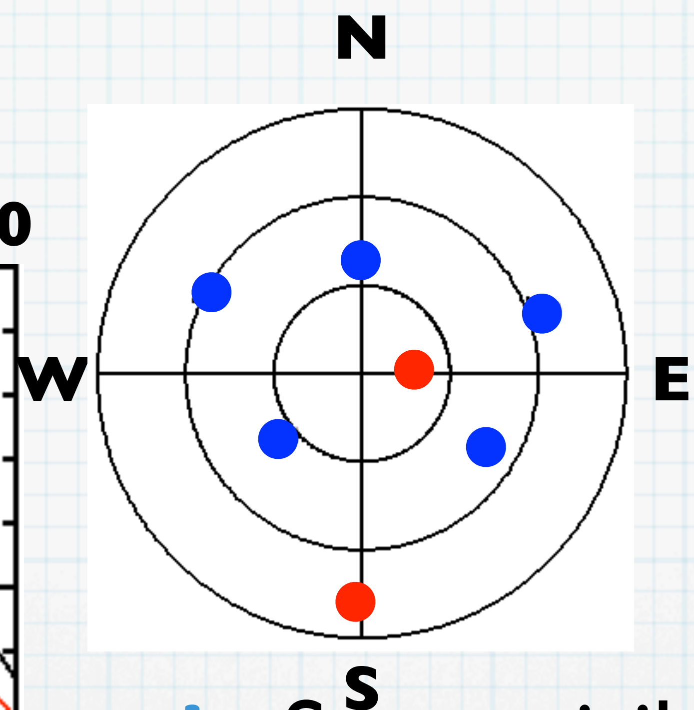
Simulation: Satellite geometry and plasma bubble location (2)

- Background parameters
  - season: March
  - solar activity: high
  - UT = 11 at t = 0
- Receiver
  - ground: 135°E, 25°N
  - air: 134.6°E, 25°N, 80 m/s. (Approach to RW09)
- Satellite geometry
  - The worst case geometry of (1)
- Run simulations by changing the plasma bubble initial location from 130 to 140°E.

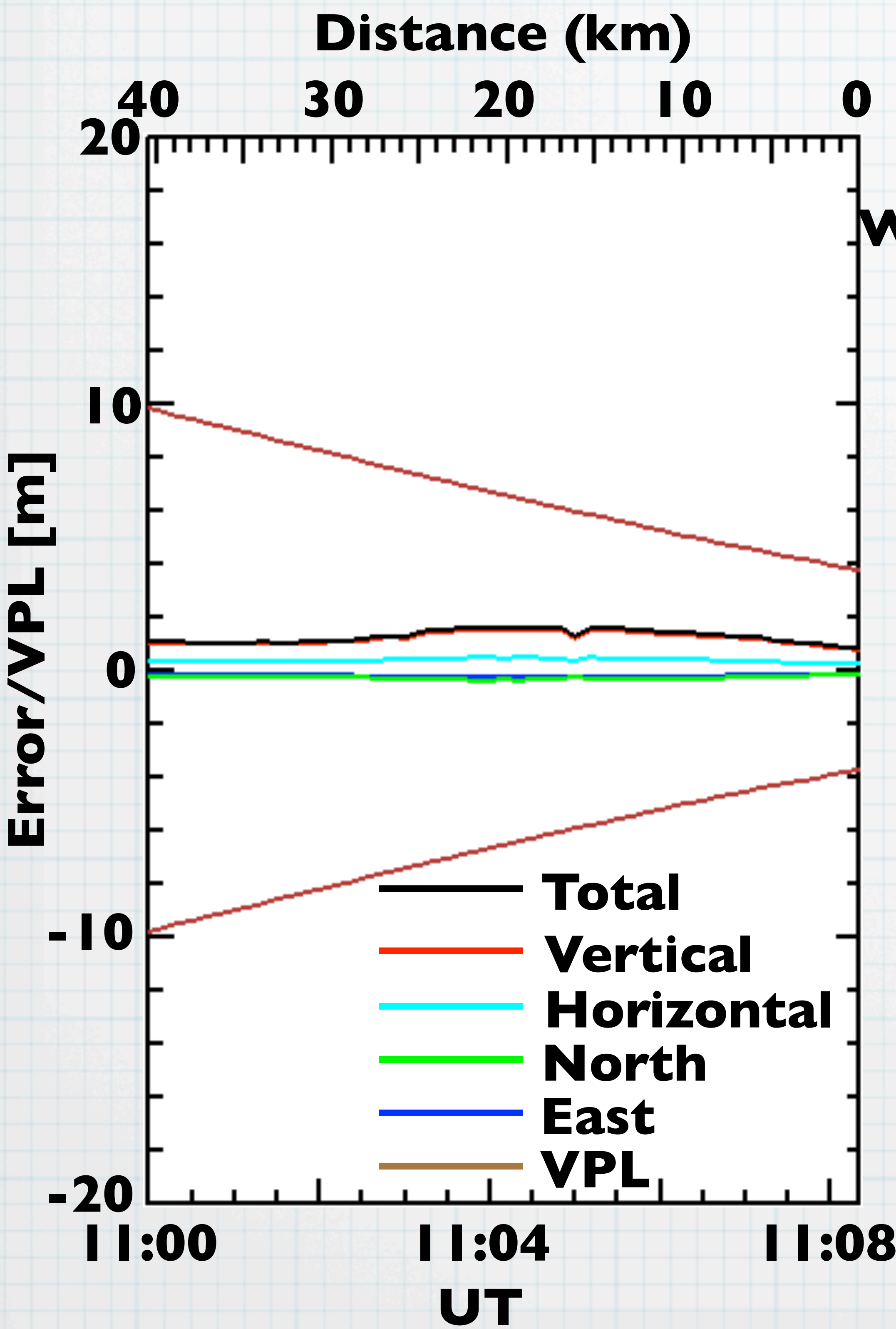
Satellite geometry and plasma bubble location: Result with the worst vertical error

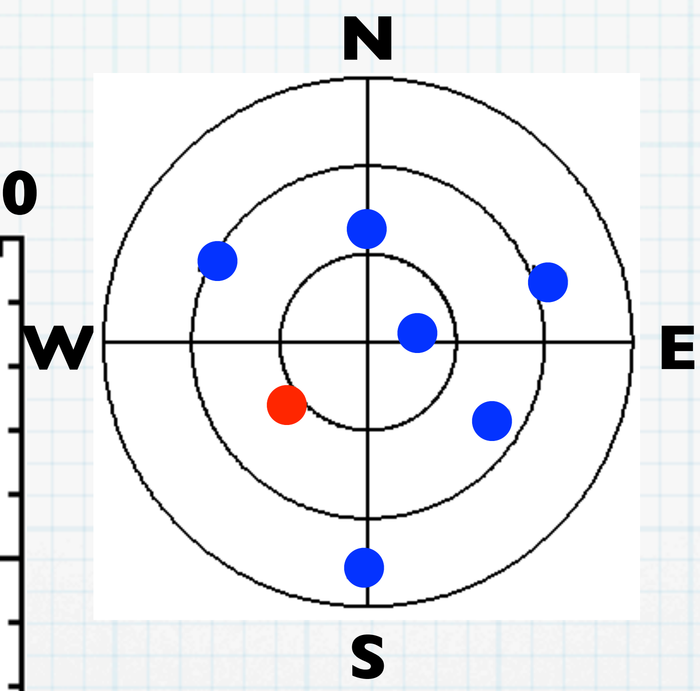




- Seven visible satellites.
- 10.2 m vertical error at 6 km from the reference station.
- Two satellites were impacted.
- The southward low elevation satellite was mainly impacted.
- The impact on the high elevation satellite was not significant.

Satellite geometry and plasma bubble location: Result with the worst vertical error





- Seven visible satellites.
- 1.2 m vertical error at 6 km from the reference station.
- One satellites was impacted.
- Small error mainly due to small delay difference.

Low latitude ionosphere effects on SBAS
(ENAC-ENRI Internship project)

* Impacts of the low latitude ionosphere on SBAS has been studied with simulations using the 3-D ionosphere model.
  - Strong ionospheric gradient associated with the equatorial anomaly makes it difficult to derive ionospheric correction term.
  - Plasma bubbles are hardly detected by SBAS ground monitor stations and result in large user error.

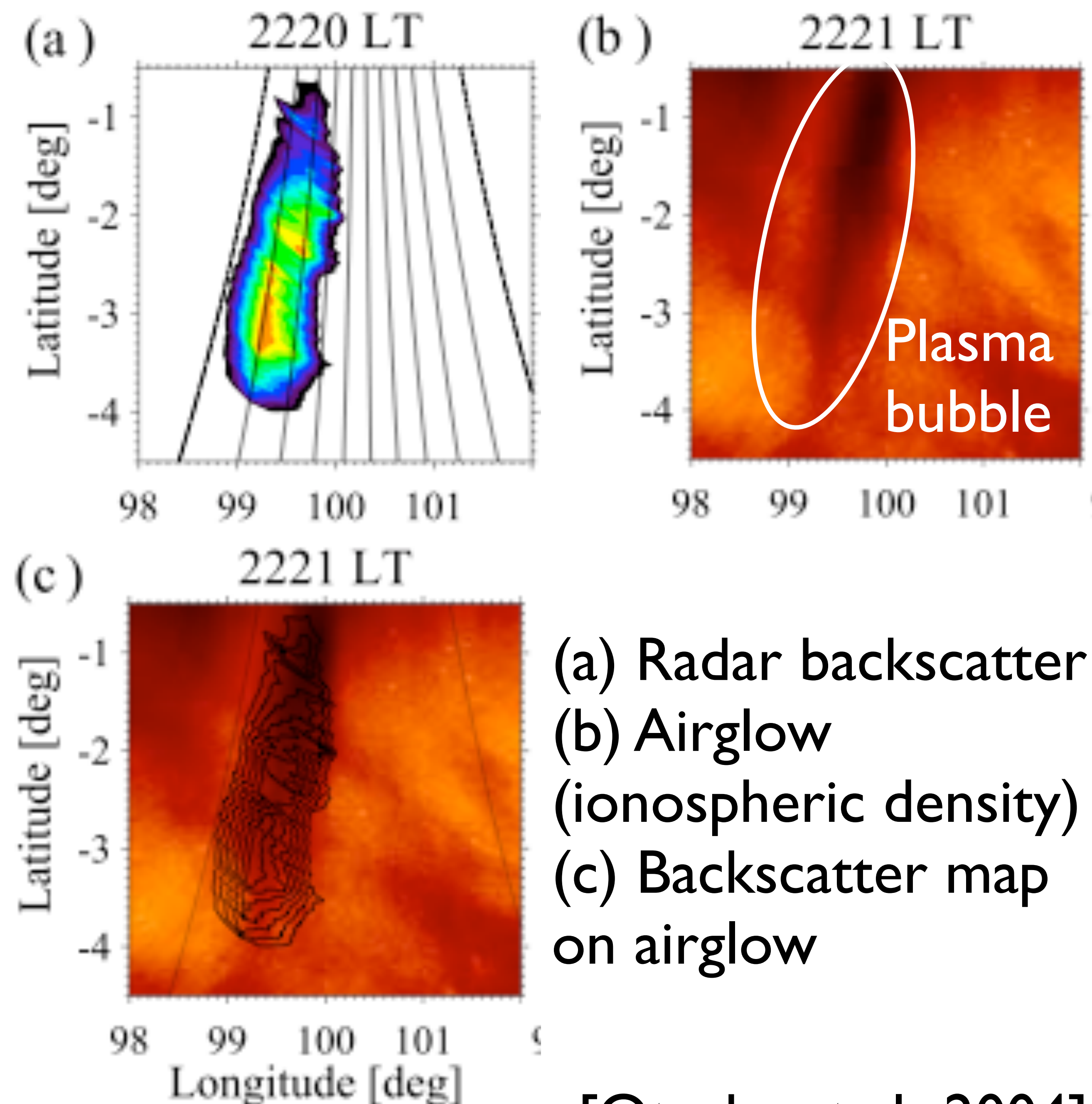
* Further studies are planned to be conducted.
  - More simulations with different conditions
  - Optimal distribution of ground reference staitons
  - Backscatter radar monitoring of plasma bubbles for SBAS

External monitors

* GNSS measurements are "point measurements".
  - There are a lot of "blank" area.
  - GNSS measurement are used both for navigation and monitoring: not independent
* A technique to monitor ionopsheric anomalies effectively in a wide area would be useful.
  - It should be independent of GNSS signals: external monitor
* There are a number of techniques that have been used to study the ionosphere.

Plasma bubble detection by radar

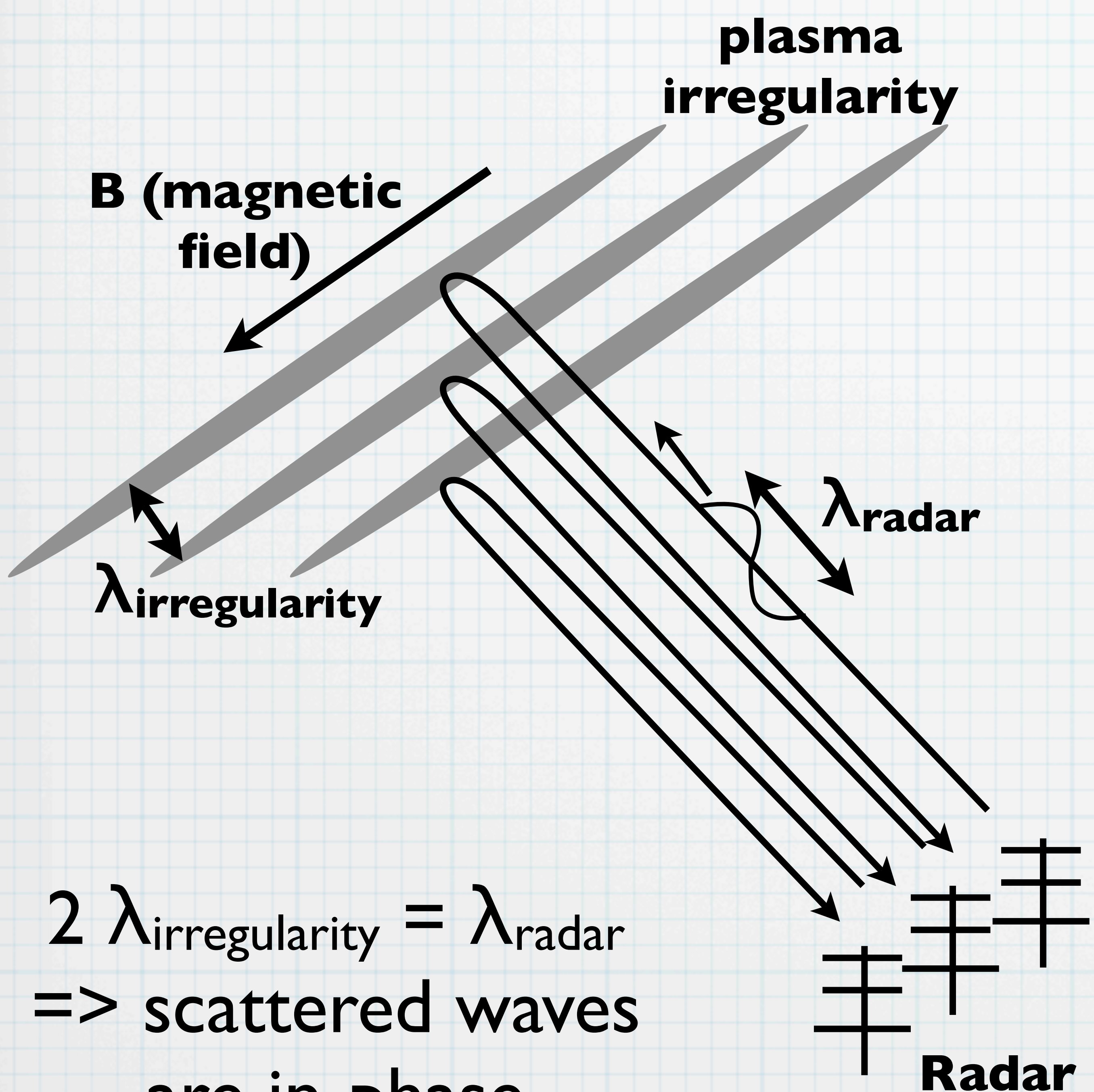
* Plasma bubble accompany plasma irregularities of various scale sizes from kilometer down to meter.
* Irregularities can be detected effectively by a **backscatter radar** using VHF band.
* Backscatter radar can detect plasma bubbles.



(a) Radar backscatter
(b) Airglow (ionospheric density)
(c) Backscatter map on airglow

[Otsuka et al., 2004]

Backscatter radar

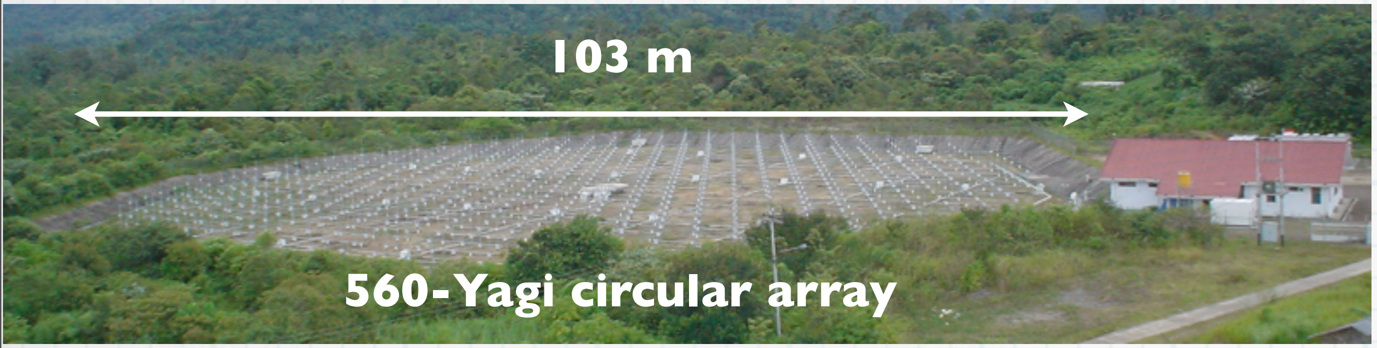


2 $\lambda_{irregularity} = \lambda_{radar}$
=> scattered waves are in-phase

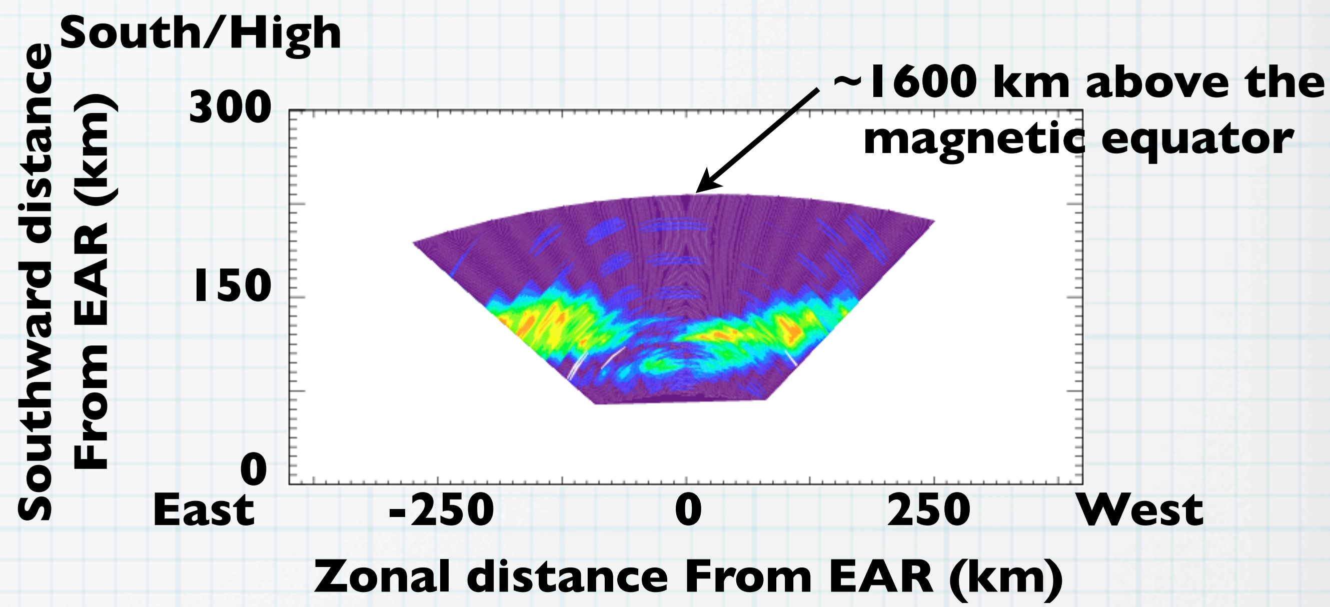
* Detects echoes scattered by plasma irregularities
* Intensified echo when radar wave vector is twice the irregularity wavelength (Bragg scattering)
  - $2\,\mathbf{k}_{radar} = \mathbf{k}_{irregularity}$
* Irregularities aligned with magnetic field => radar beam perpendicular to magnetic field for strong echo
  - $\mathbf{k}_{radar} \cdot \mathbf{B} = 0$
* VHF band (typically 30-50 MHz) is often used.

Backscatter radars

Equatorial Atmosphere Radar (47 MHz, Indonesia)

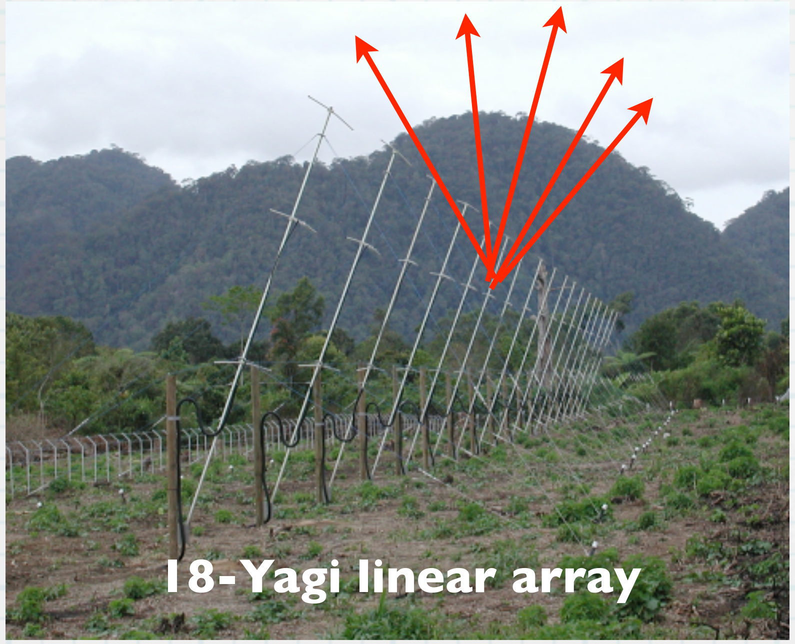


Echo power on 28 March 2006

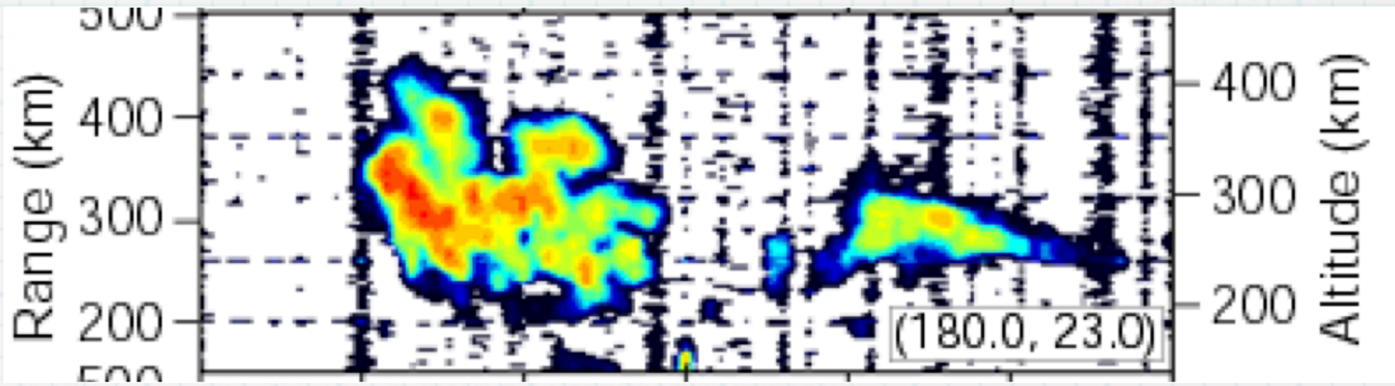


[Saito et al., 2008]

Nagoya Univ. VHF radar (30.8 MHz, Indonesia)



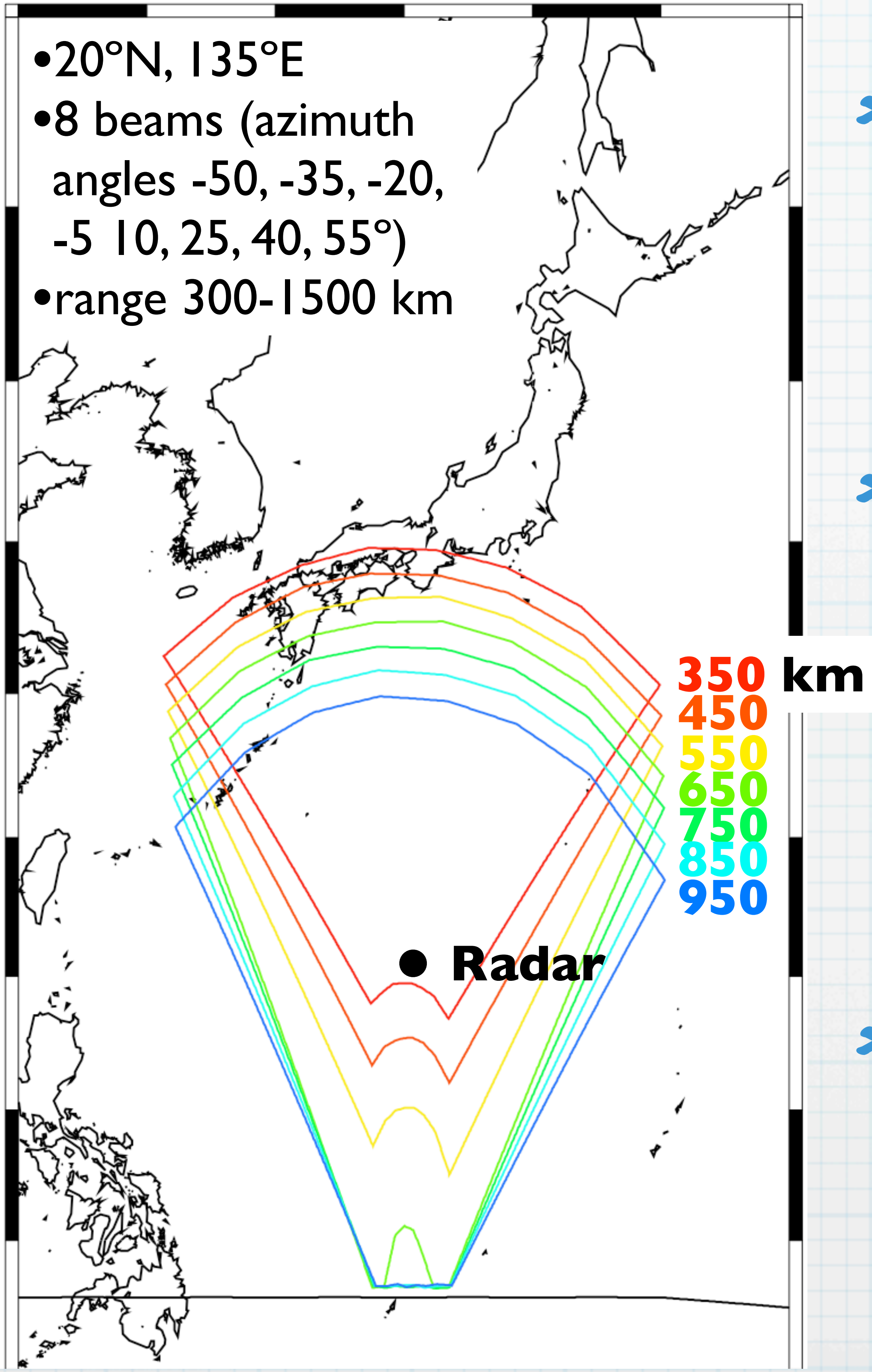
Echo power in one of the beams on 31 March 2006



[Courtesy of Y. Otsuka]

- 2-D image of plasma bubbles by electronic beam swinging
- Wide coverage area
- Cost effective (Nagoya Univ. Radar: ~ 200,000 USD)

Backscatter radar coverage

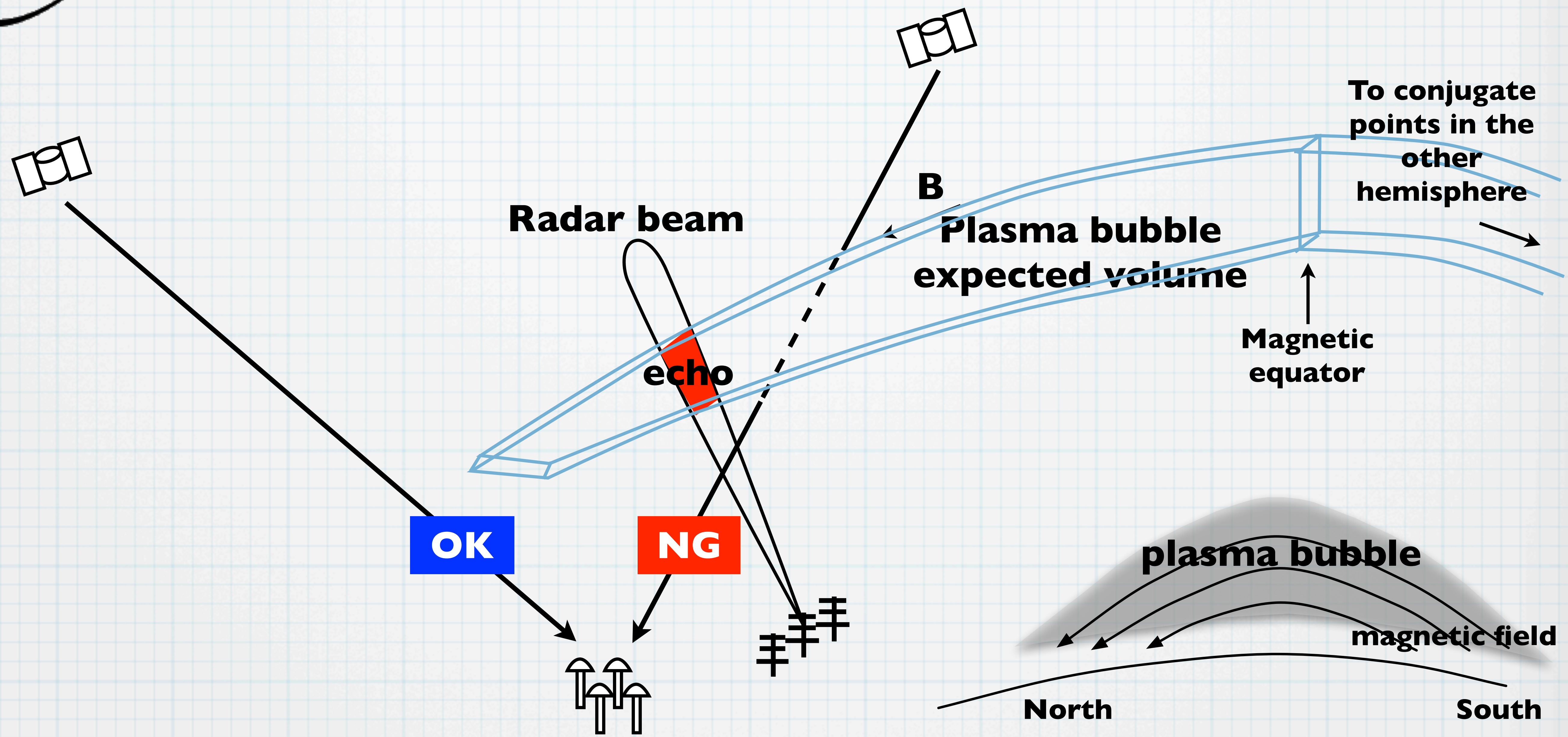


- Radar coverage is determined by the geometry of radar beams and the Earth's magnetic field.
- Plasma bubble develops along the magnetic field
  - Radar monitors "magnetic field line".
  - Different covered area for different altitudes.
- Magnetic conjugate area in the other hemisphere is also covered.

Simulation Study of Backscatter Radar for GBAS

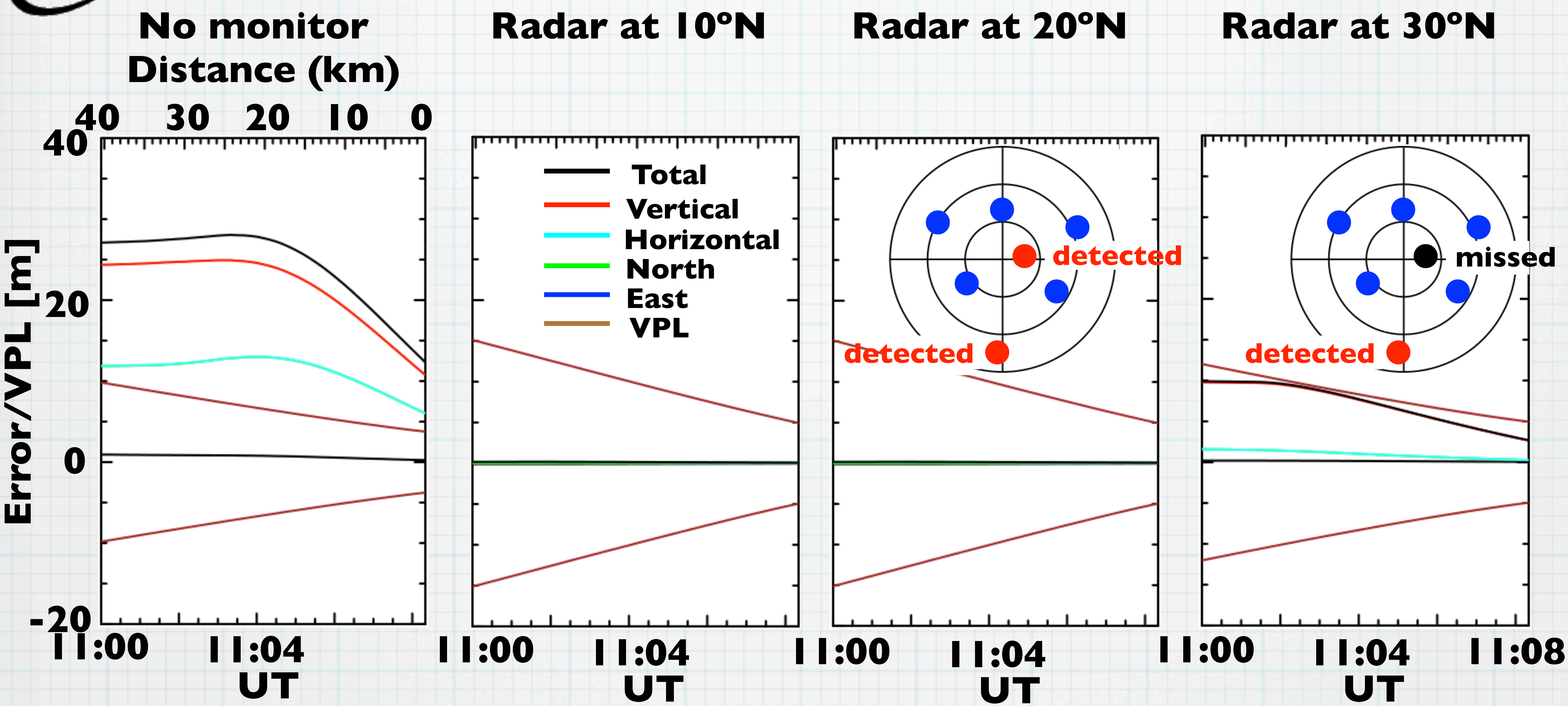
* Three major blocks:
  1. Ionosphere delay model
     - 3-D model with plasma bubbles [Saito et al., ION GNSS 2009]
  2. Backscatter radar observation model
     - Multi-beam radar
     - Reject satellites of which ray-paths seen from the ground reference pass through plasma bubbles
  3. GBAS simulation
     - Range correction and positioning error estimation for an approaching airplane
     - Based on the information from the blocks 1 and 2

Backscatter radar observation model



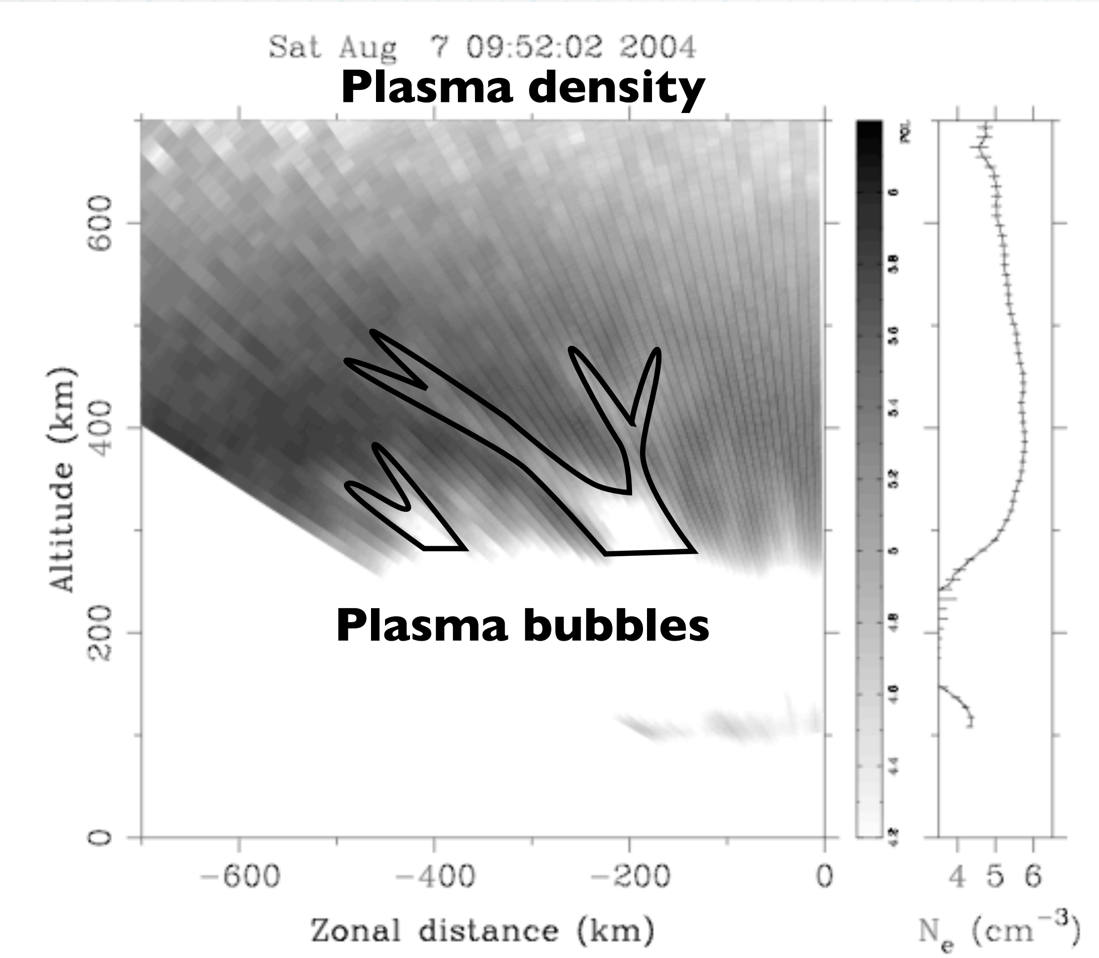
* Backscatter radar detects plasma bubbles in the radar beams
* Satellite ray-paths crossing the same magnetic field lines as the detected plasma bubbles are rejected.

Radar location and effects



* Radar at too high latitudes may miss-detect plasma bubbles and error may remain.
* Closer to the magnetic equator, the more effective.

Incoherent scatter (IS) radar



[Hysell et al., 2006]

	Frequency (MHz)	Peak Power (MW)
MU	46.5	1
Jicamarca	50	3
ALTAIR	422/160	2.5
Arecibo	430	2.5
Poker Flat	450	1.3
EISCAT Svalbard	500	1
EISCAT	933/224	1.5/5
Millstone Hill	**1290/440**	**2.5/5**
Sondrestrom	**1290**	**3.5**
ARSR	**1300**	**2**

* Electron density (and basic plasma parameters) can be measured directly.
* The most powerful tool to monitor the ionosphere.
* ARSRs that are being decommissioned can be converted to IS radar.

Summary (1)

* A 3-D ionospheric delay model that account for the low latitude ionosphere including the equatorial anomaly and the plasma bubble has been developed.
* The model is a very useful tool to examine the impacts of the low latitude ionospheric anomalies on GNSS applications.
* GBAS
  - 3-D ionosphere delay model can be used to study the effect of ionospheric anomalies in more realistic manner.
  - The model was used to validate the baseline SARPs of GAST-D (single-frequency CAT-III GBAS).

Summary (2)

- SBAS
  - Strong ionospheric gradient associated with the equatorial anomaly makes it difficult to derive ionospheric correction term.
  - Plasma bubbles are hardly detected by SBAS ground monitor stations and result in large user error.
- An external plasma bubble monitor by a backscatter radar is proposed and its effects are investigated with the 3-D ionosphere model.
  - Backscatter radar monitor can significantly reduce the potential error caused by the plasma bubble.
- ARSRs that are going to be decommissioned could be converted to IS radars to monitor the ionospheric density directly, because the frequency and power is suitable for IS measurements.