Imaging the Ionosphere Using Spaceborne Synthetic Aperture Radar

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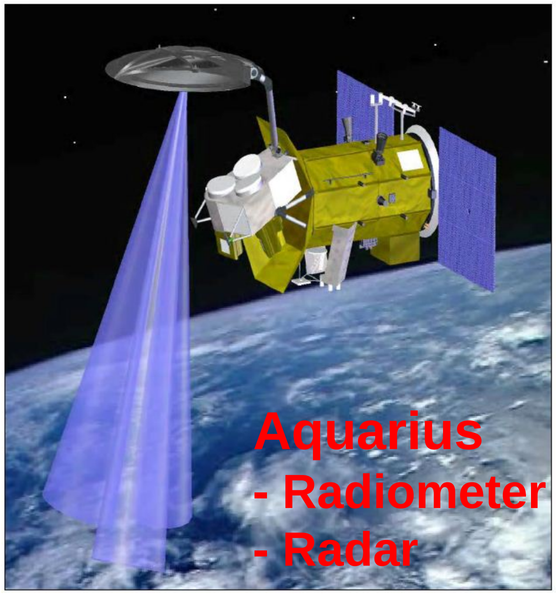
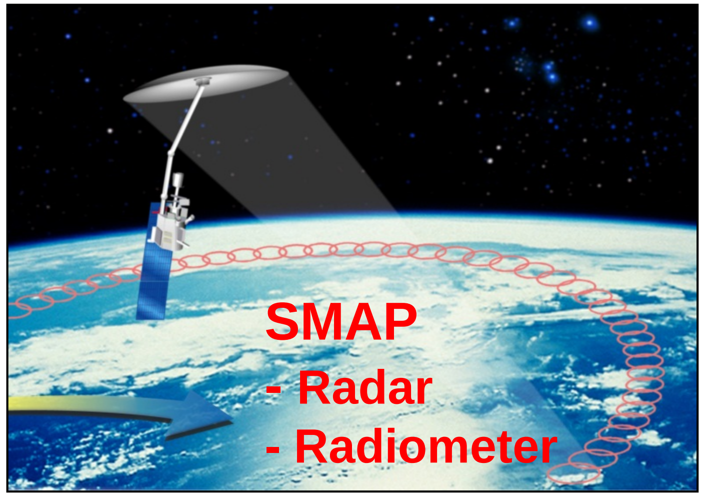
Earth Science Radar Missions



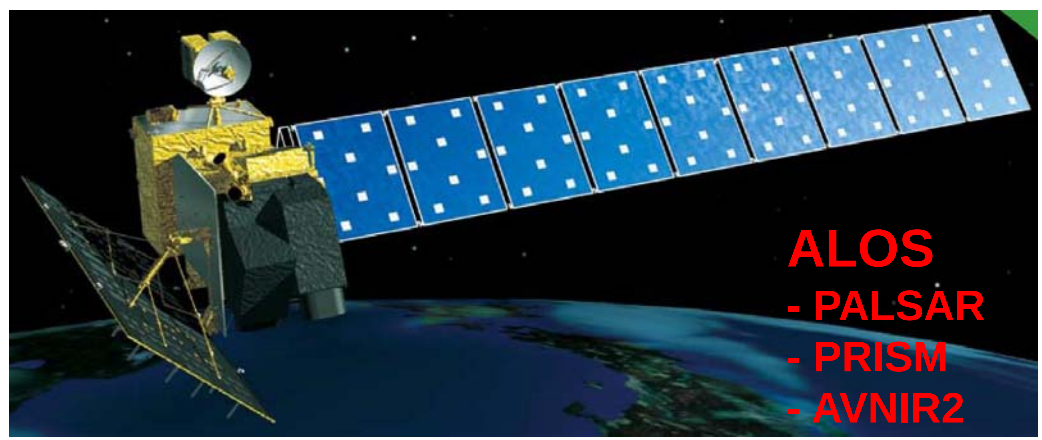
Global Sea Surface Salinity
Launched in June 2011



Global Soil Moisture
To be launched in 2015

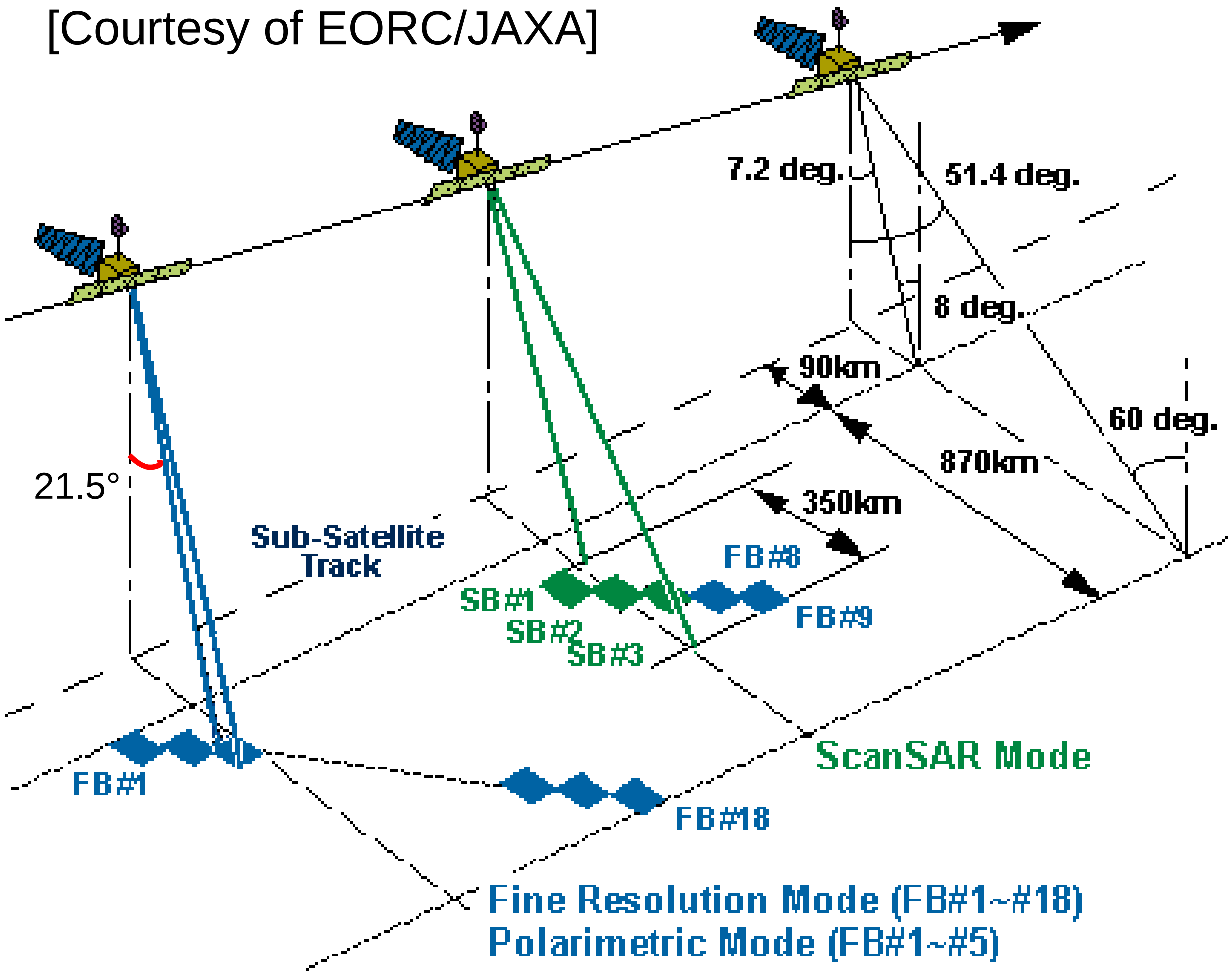
ALOS
Advanced Land Observing Satellite, JAXA's InSAR mission launched in Jan 2006.
(ALOS-2 will follow.)

DESDynI
Deformation, Ecosystem Structure, and Dynamics of Ice
NASA InSAR Mission
Under study



Advanced Land Observing Satellite Phase Array type L-band SAR

[Courtesy of EORC/JAXA]



ALOS (JAXA) Orbit

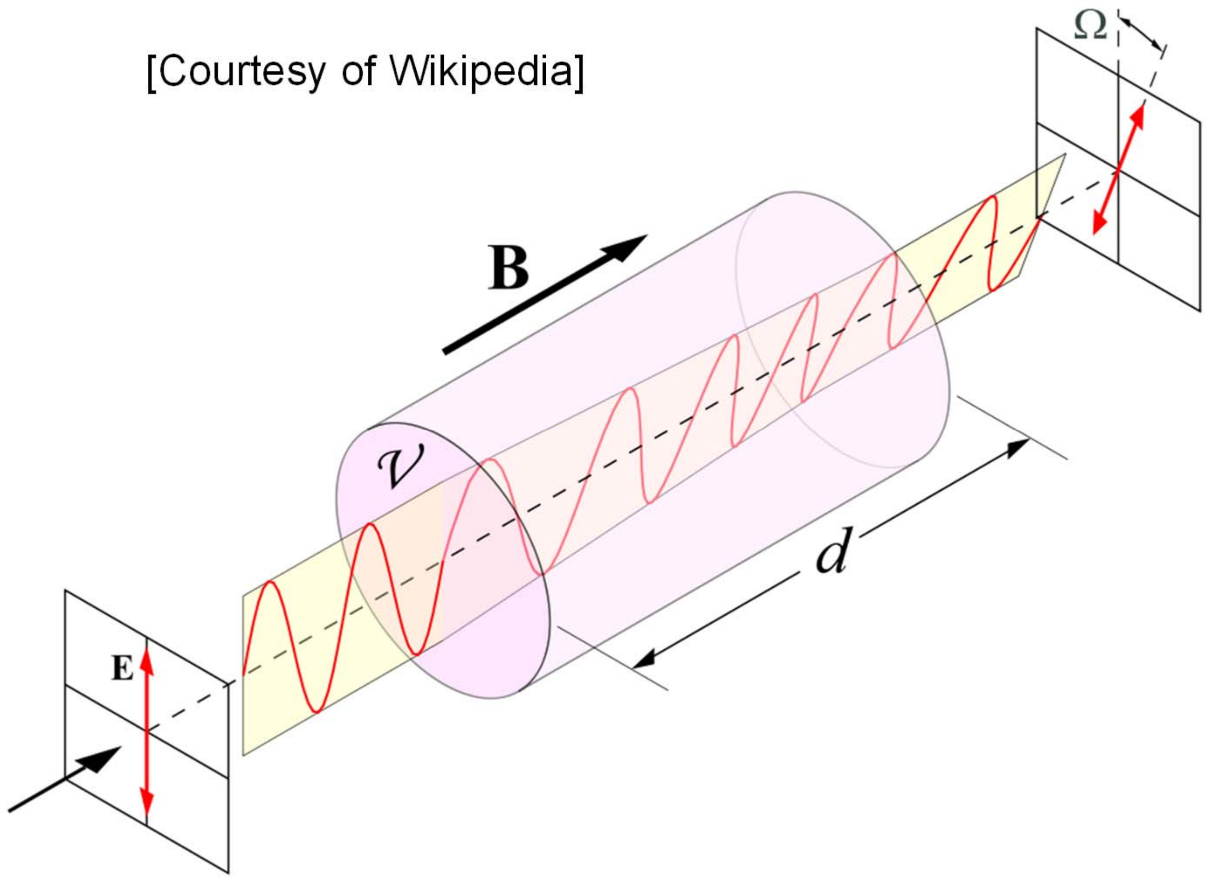
- ~690 km ALT
- I = 98° (Sun-synchronous 10 AM/10 PM)
- Repeat period: 46 days

PALSAR

- L-band: 1.27 GHz
- Signal chirp bandwidth: 28 MHz or 14 MHz for single-pol or multi-pol obs modes
- Experimental quad-pol mode among other observation modes
  - HH, HV, VH, and VV
- Polarimetric image pixel spacings (resolutions)
  - Along track (azimuth) = 3.6 m
  - Cross track (range) = 9.4 m
  - Cross track (ground) = 23.3 m

Faraday Rotation and TEC

[Courtesy of Wikipedia]



$$\Omega = \frac{K}{f^2}\int_{\mathbf{r}_t}^{\mathbf{r}_r} n_e B_0 \cos\theta \, ds$$

$$= \frac{K}{f^2}\langle B_0 \cos\theta \rangle \mathrm{TEC}$$

$$\mathrm{TEC} = \Omega \frac{f^2}{K\langle B_0 \cos\theta \rangle}$$

(for each radio link)

The effect is less sensitive near or at the magnetic equator for a nominal SAR system as θ approaches 90° and $\cos\theta$ becomes very small.

Faraday Rotation Measurements Using PolSAR

- **Polarimetric measurements (scattering matrix):**

$$\begin{pmatrix} M_{hh} & M_{vh} \\ M_{hv} & M_{vv} \end{pmatrix} = A(r,\theta)e^{j\phi}\begin{pmatrix} 1 & \delta_2 \\ \delta_1 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 \\ 0 & f_1 \end{pmatrix}\begin{pmatrix} \cos\Omega & \sin\Omega \\ -\sin\Omega & \cos\Omega \end{pmatrix}\begin{pmatrix} S_{hh} & S_{vh} \\ S_{hv} & S_{vv} \end{pmatrix}$$

$$\cdot\begin{pmatrix} \cos\Omega & \sin\Omega \\ -\sin\Omega & \cos\Omega \end{pmatrix}\begin{pmatrix} 1 & 0 \\ 0 & f_2 \end{pmatrix}\begin{pmatrix} 1 & \delta_3 \\ \delta_4 & 1 \end{pmatrix} + \begin{pmatrix} N_{hh} & N_{vh} \\ N_{hv} & N_{vv} \end{pmatrix}$$

Or $$\mathbf{M} = Ae^{j\phi}\mathbf{R}^{\mathbf{T}}\mathbf{R}_{\mathbf{F}}\mathbf{S}\mathbf{R}_{\mathbf{F}}\mathbf{T} + \mathbf{N}$$

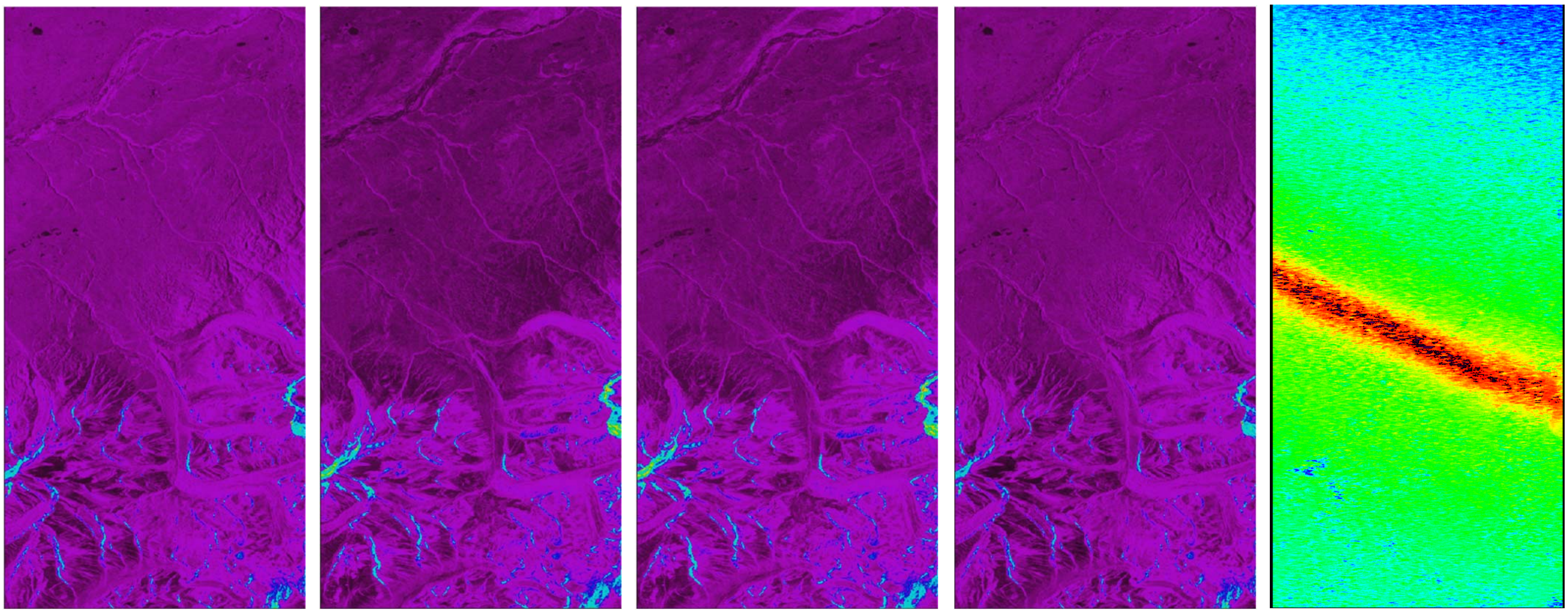
- **System calibration [Freeman, 2004; Freeman et al., 2008; Shimada et al., 2009]:**
  - ➢ Calibration without or with Faraday rotation

- **Deriving Faraday rotation image using Bickel and Bates' approach [1965]:**

$$\begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} = \begin{bmatrix} 1 & j \\ j & 1 \end{bmatrix}\begin{bmatrix} M_{hh} & M_{hv} \\ M_{vh} & M_{vv} \end{bmatrix}\begin{bmatrix} 1 & j \\ j & 1 \end{bmatrix}, \qquad \Omega = \frac{1}{4}\arg\left(Z_{12}Z_{21}^{*}\right)$$

Polarimetric SAR Images

PALSAR Observation
04-01-2007, Alaska: GLAT = ~62.2°, GLON = ~214.5°
during a geomagnetic storm



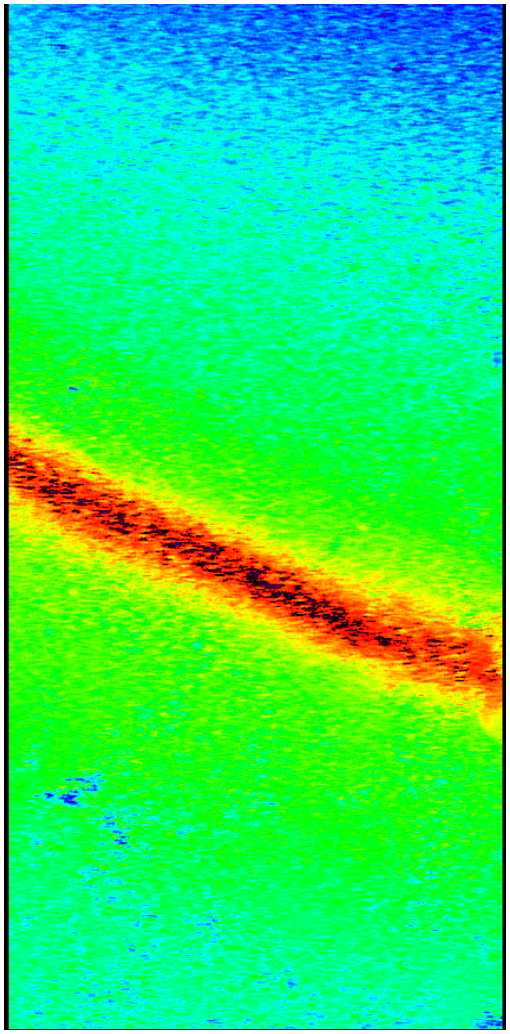
HH HV VH VV FR

Size of individual images: 18432 x 1248 pixels, ~ 66 km x 29 km.

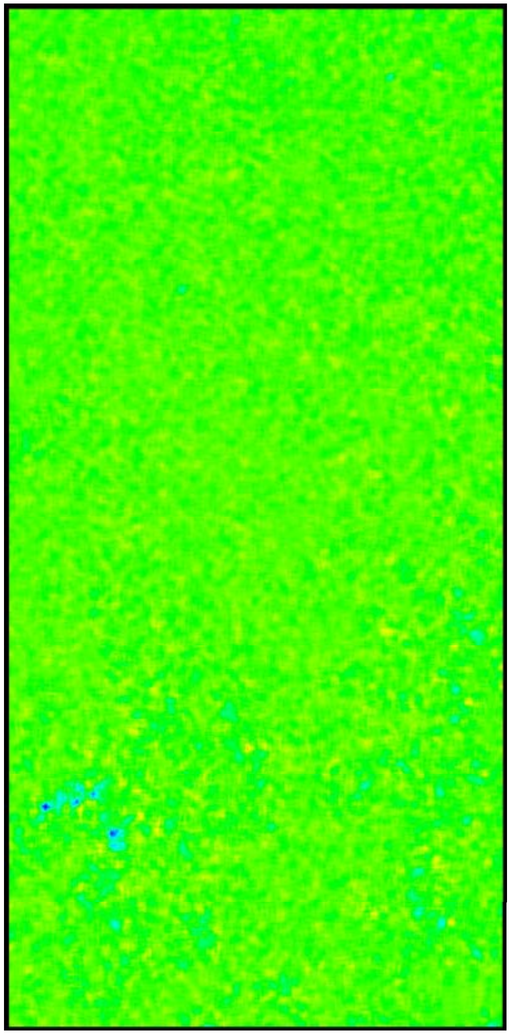
SAR Polar Ionospheric Images during Storm and Quiet Days

- Faraday rotation images on two days
  - 04-01-2007 (storm)
  - 05-17-2007 (quiet)

  (repeat orbit, 46 days) when PALSAR illuminated the same area.
- Significant ionospheric difference between the two days.
- The ionospheric arc seen in the 4-1-2007 data is associated with an auroral arc when a geomagnetic storm occurred on 4/1/2007.

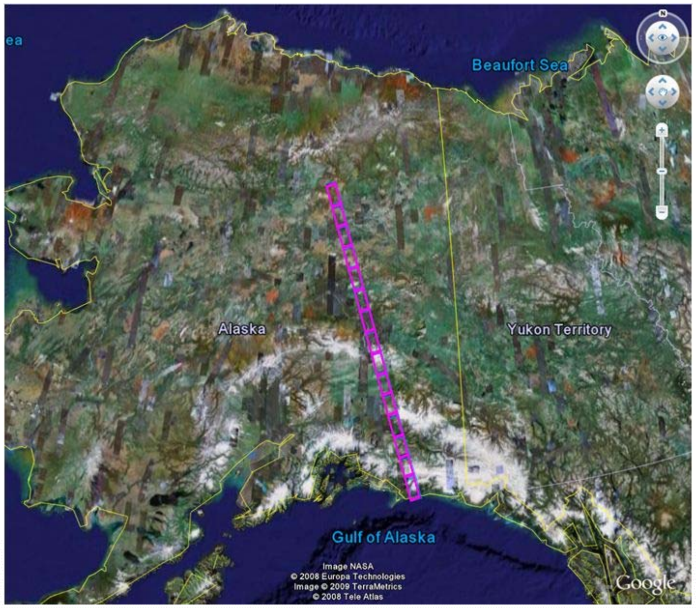


FR



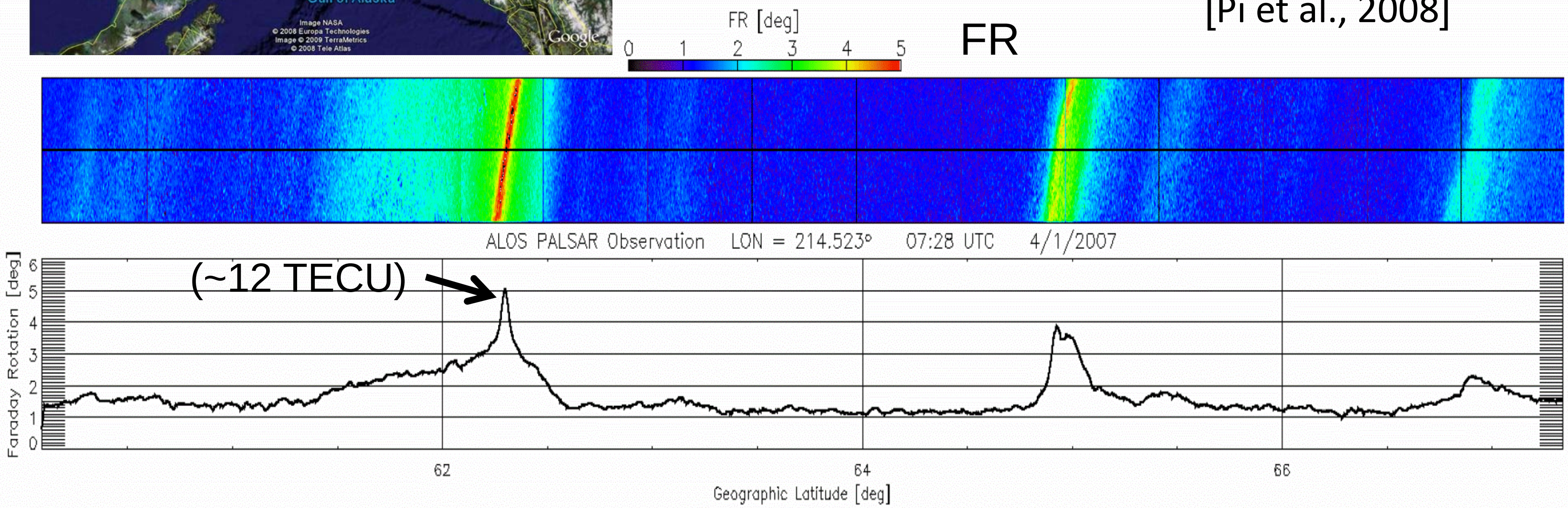
FR

Polar Ionospheric Arcs
Captured in Polarimetric SAR images



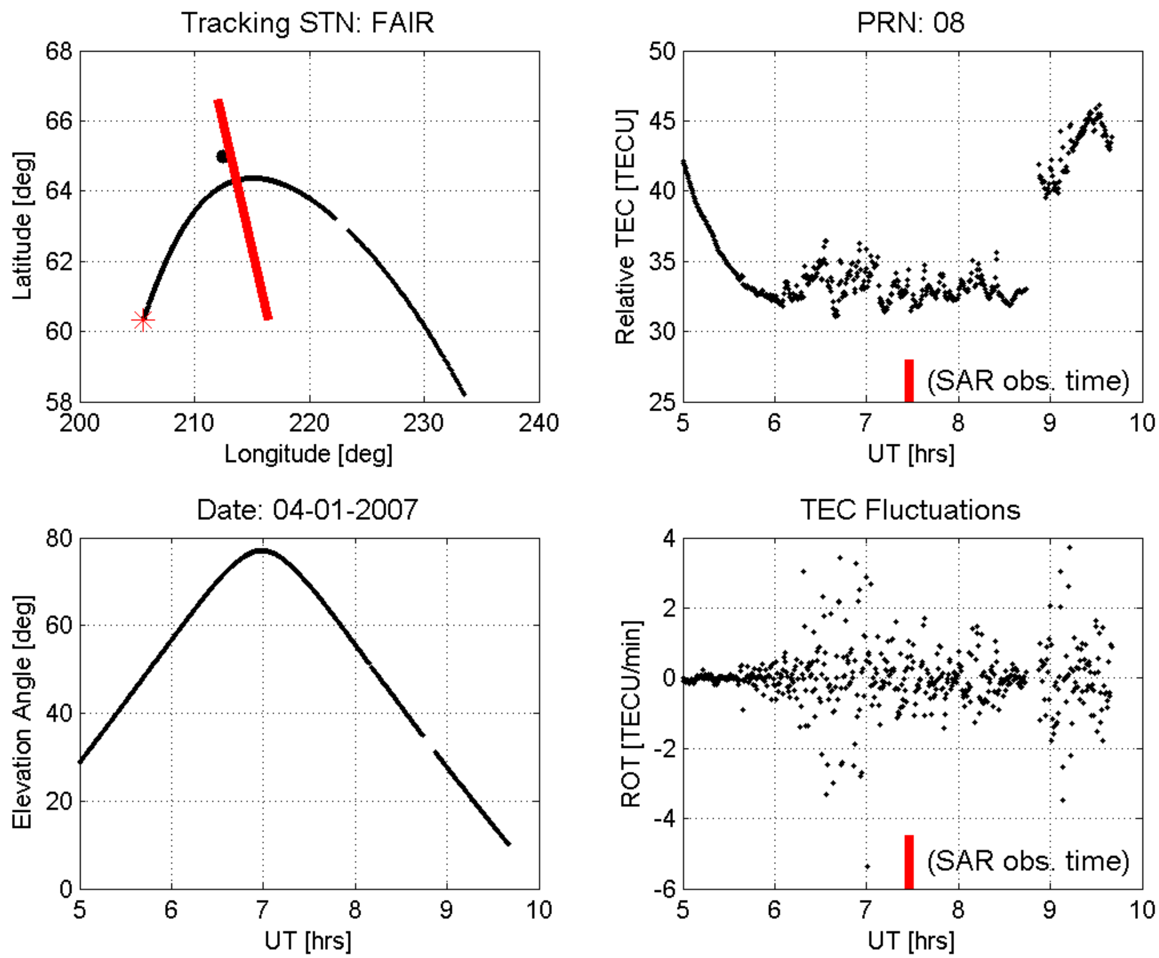
- 15 PALSAR image frames are used to compose the Faraday rotation (FR) image strip (~900 x 30 km²).
- Enhanced FR/TEC arcs over the polar region.
- FR structures as small as ~0.2 degrees (< 0.5 TECU) are identified after reducing noise.
- Extended enhancements with different gradients surrounding sharp peaks at both edges of the arcs

[Pi et al., 2008]



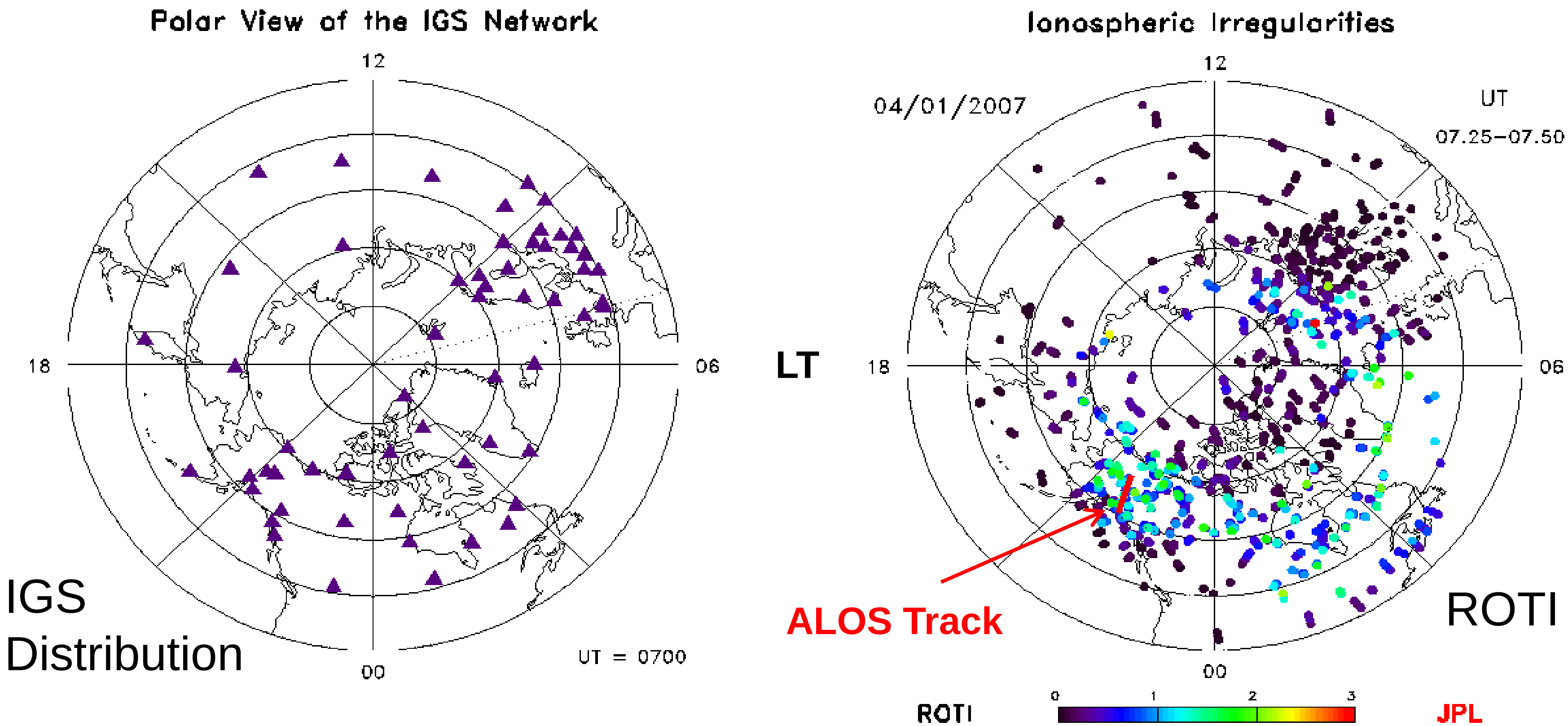
Ionospheric Irregularities Measured Using GPS in and near the ALOS Path

Red Track: ALOS-PALSAR Path



- Ionospheric irregularities were captured by a GPS receiver at Fairbanks, Alaska, tracking L1 and L2 signals transmitted from PRN-08 satellite.
- At ~07:28 UT, GPS data show TEC perturbations in and near the regions of an ALOS-PALSAR path.

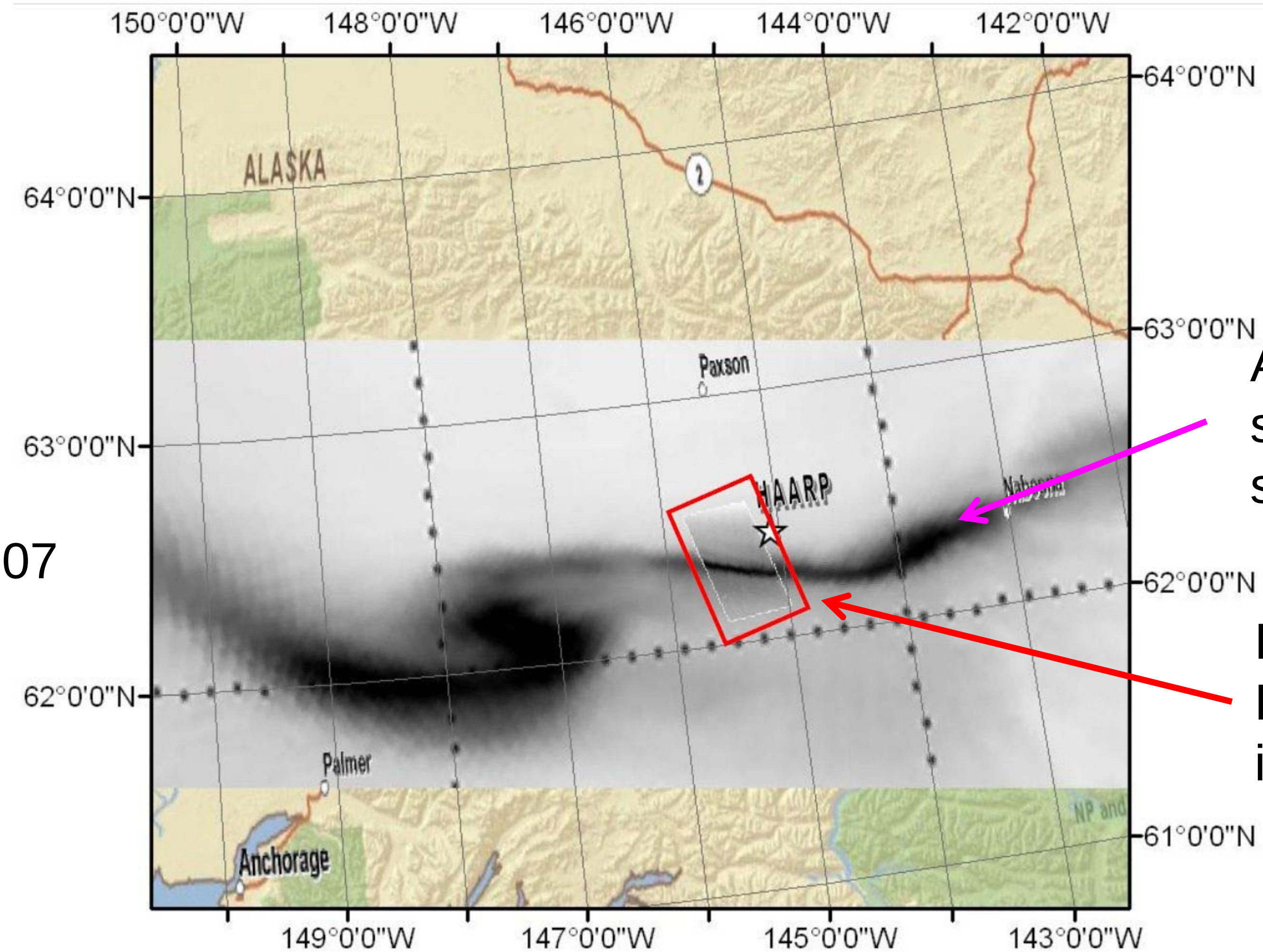
Snapshot of Ionospheric Irregularities Measured Using GPS



- Dual-frequency GPS observations from 58 stations in the polar region (LAT ≥ 50°) are processed to produce rate of TEC (ROT) and rate of TEC index (ROTI) measurements
- Increased ROTI values indicate ionospheric irregularities during the storm
- The ALOS-PALSAR passed through a perturbed ionospheric region

Comparison of SAR and Auroral Images

04-01-2007

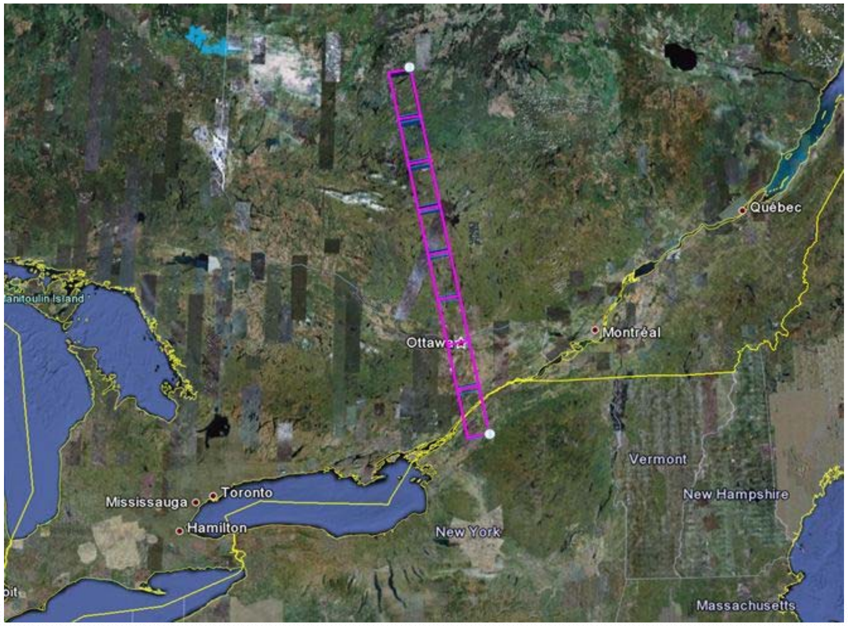


Auroral arc seen in all-sky imager

PALSAR FR image

Comparison between PALSAR and ground-based all-sky auroral images [Meyer et al., 2009].

Mid-Latitude Ionospheric Gradient Captured in PolSAR Images

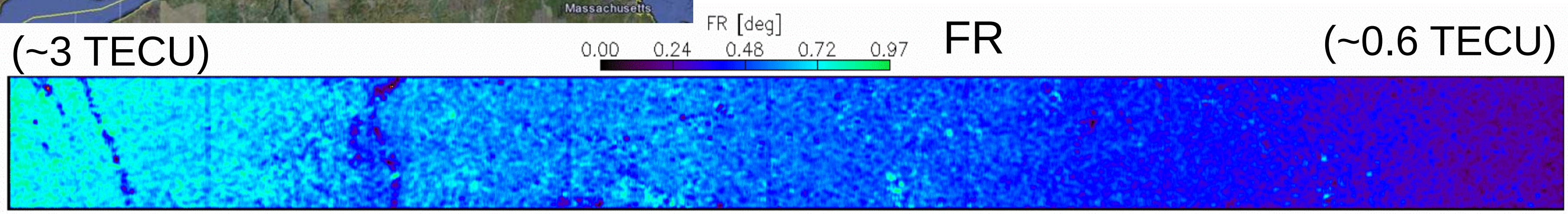


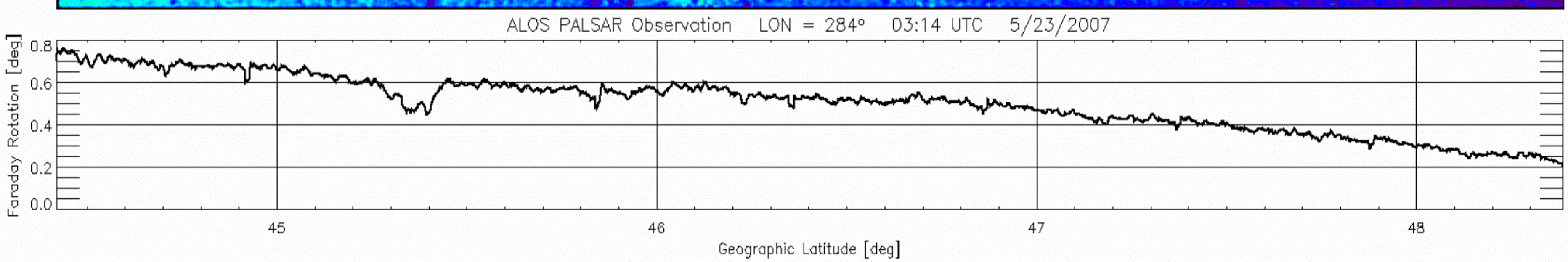
- ALOS-PALSAR was making polarimetric observations when passing by at ~03:14 UT on 5/23/2007
- PolSAR data for 8 radar scenes/frames are used to compose the 2D FR image
- Large FR/TEC gradient is observed along the ALOS path near the “mid-latitude trough”.

(~3 TECU)

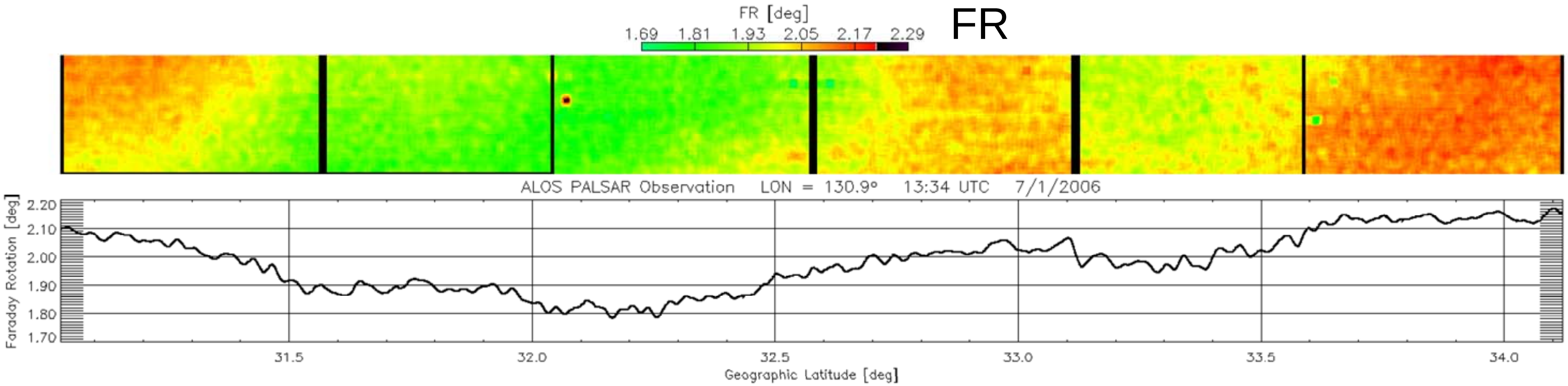
FR

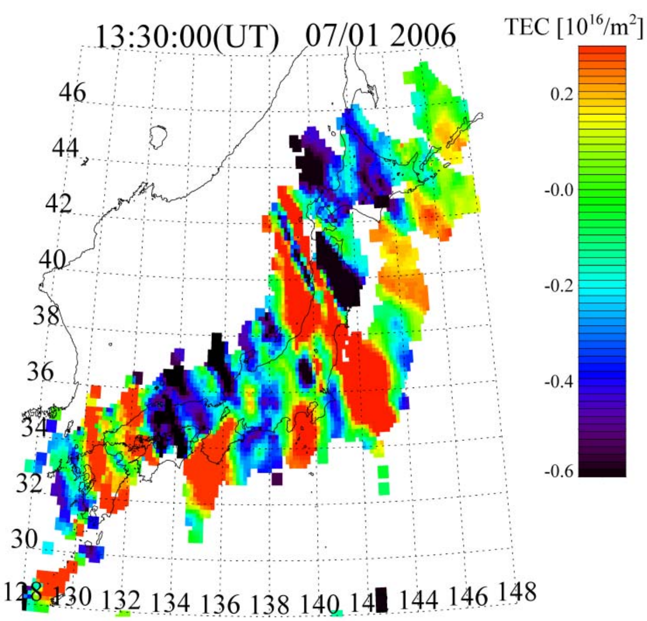
(~0.6 TECU)

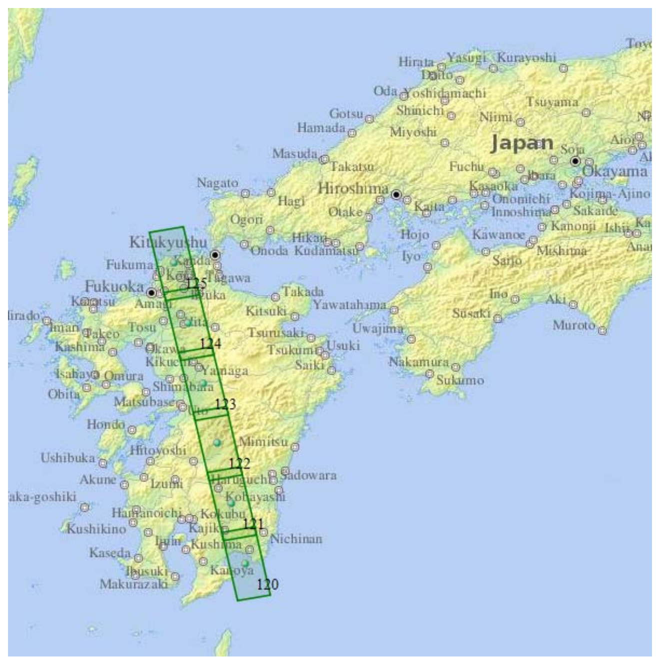


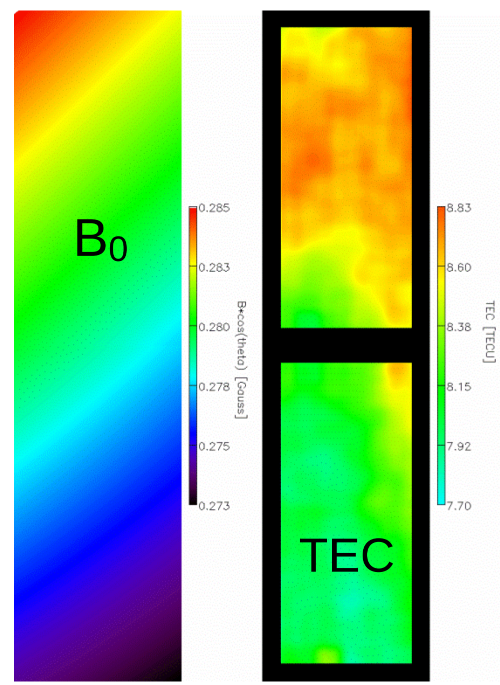


Imaging TID's at Middle Latitudes







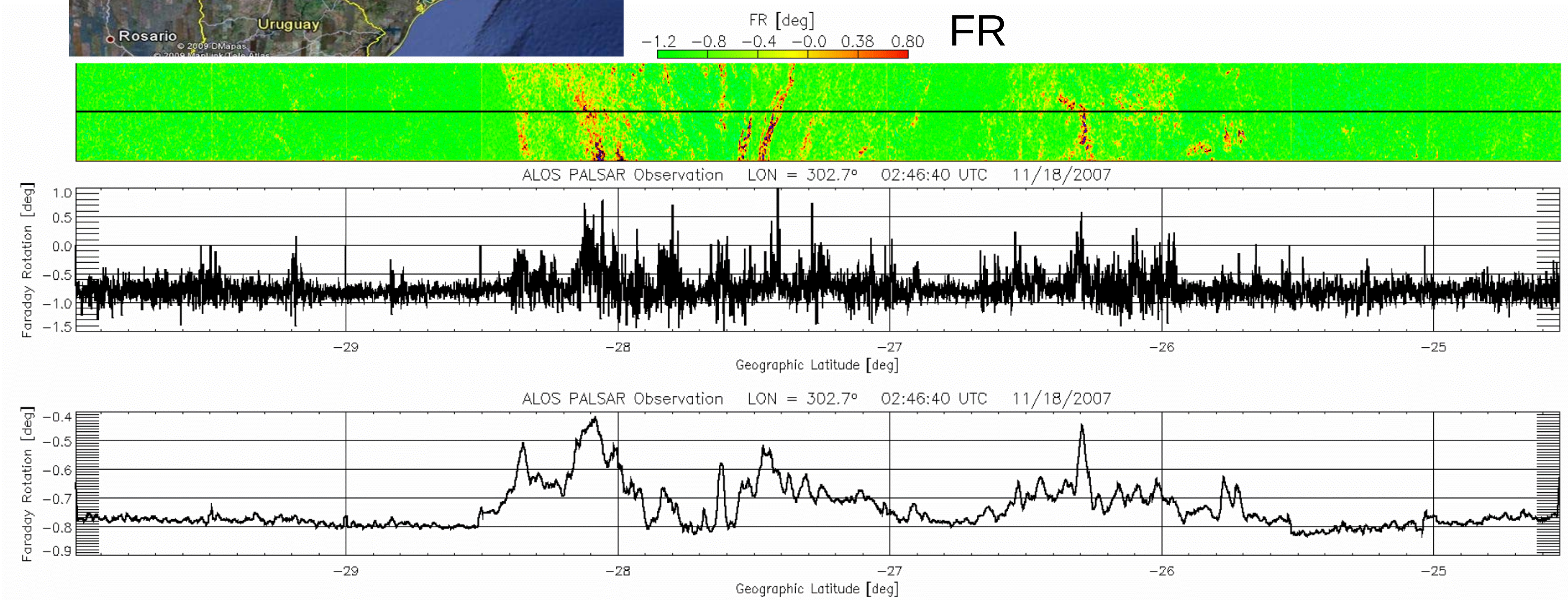


Ionospheric Scintillation and Plasma Bubbles

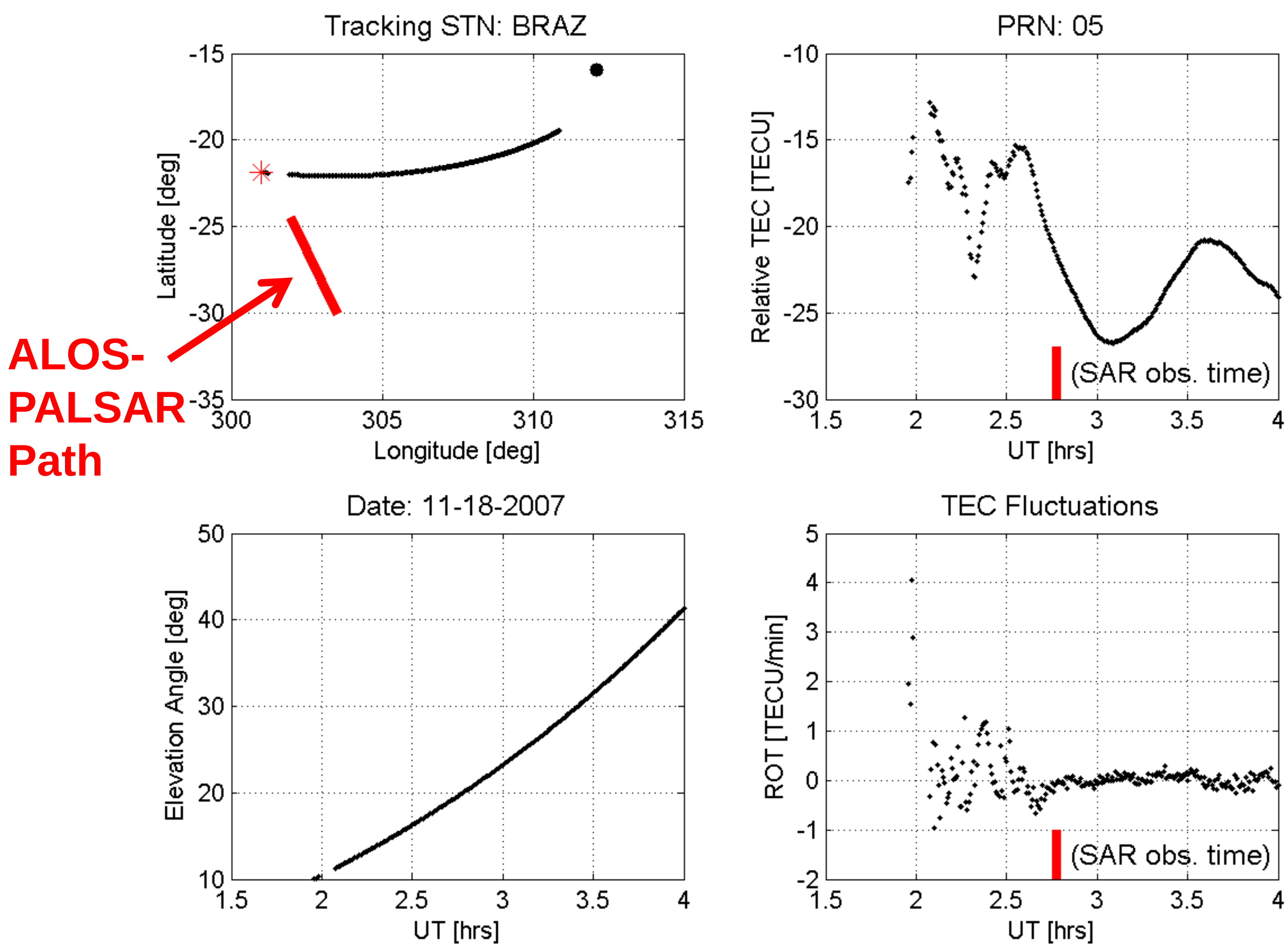
Polarimetric observations made using ALOS PALSAR at low latitudes

- Faraday rotation scintillation
- Ionospheric depletion/bubbles

FR

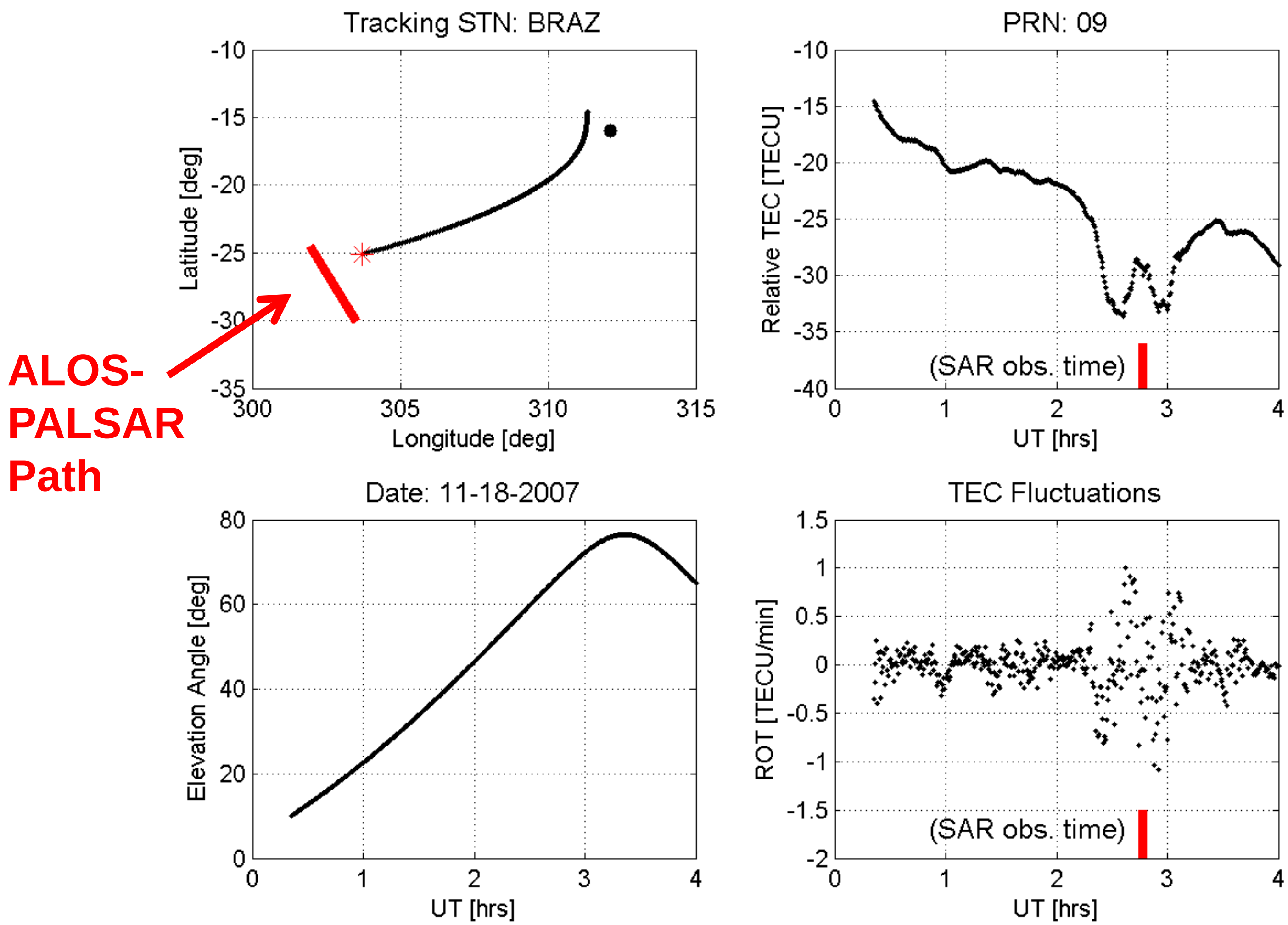


TEC Depletion and Irregularities Measured Using GPS



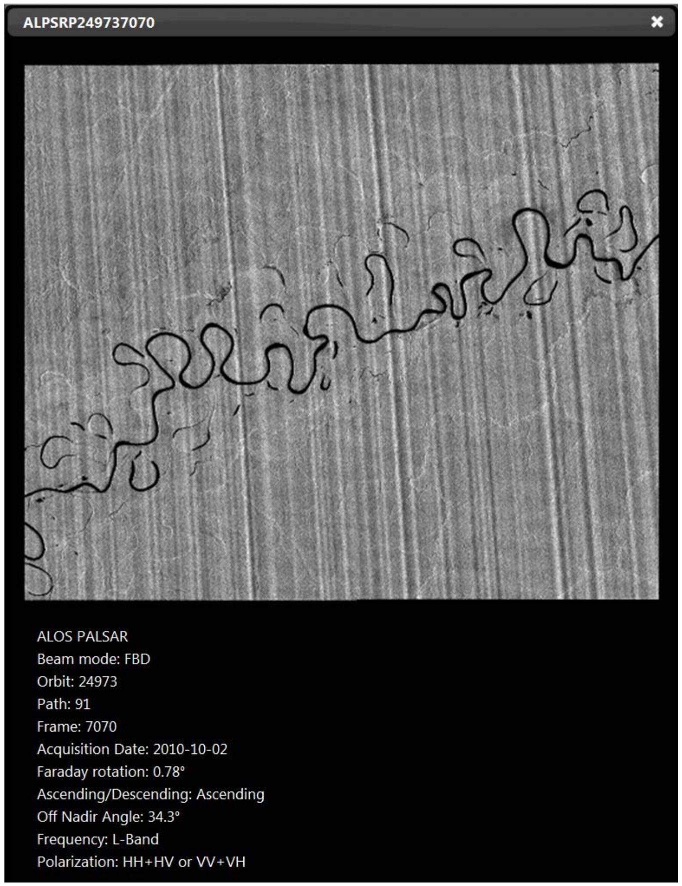
Ionospheric Irregularities /scintillation were observed in the ALOS-PALSAR path before ALOS passed by.

Ionospheric Irregularities Observed Using GPS near a PALSAR Path

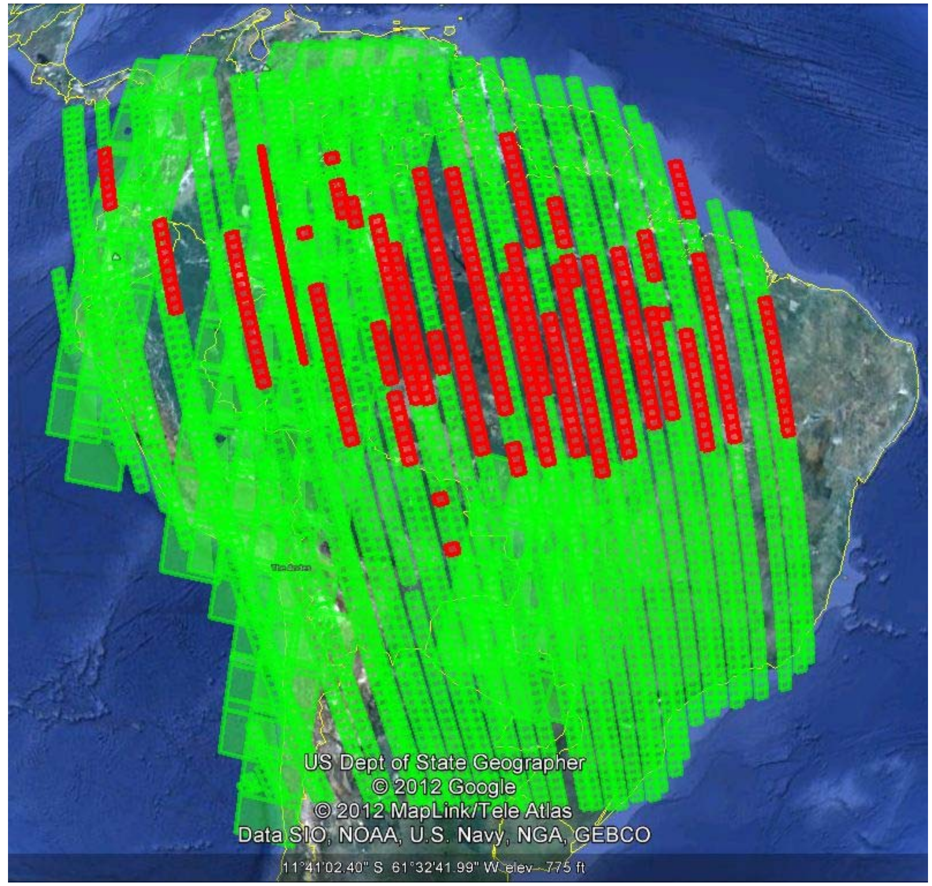


Ionospheric Irregularities /scintillation were observed near the ALOS-PALSAR path when ALOS passed by.

Effects of Ionospheric Scintillation



Example of streaks in PALSAR images (effects on ionospheric scintillation)



A survey of scintillation effects during Oct 2010 (with Meyer and Chotoo):

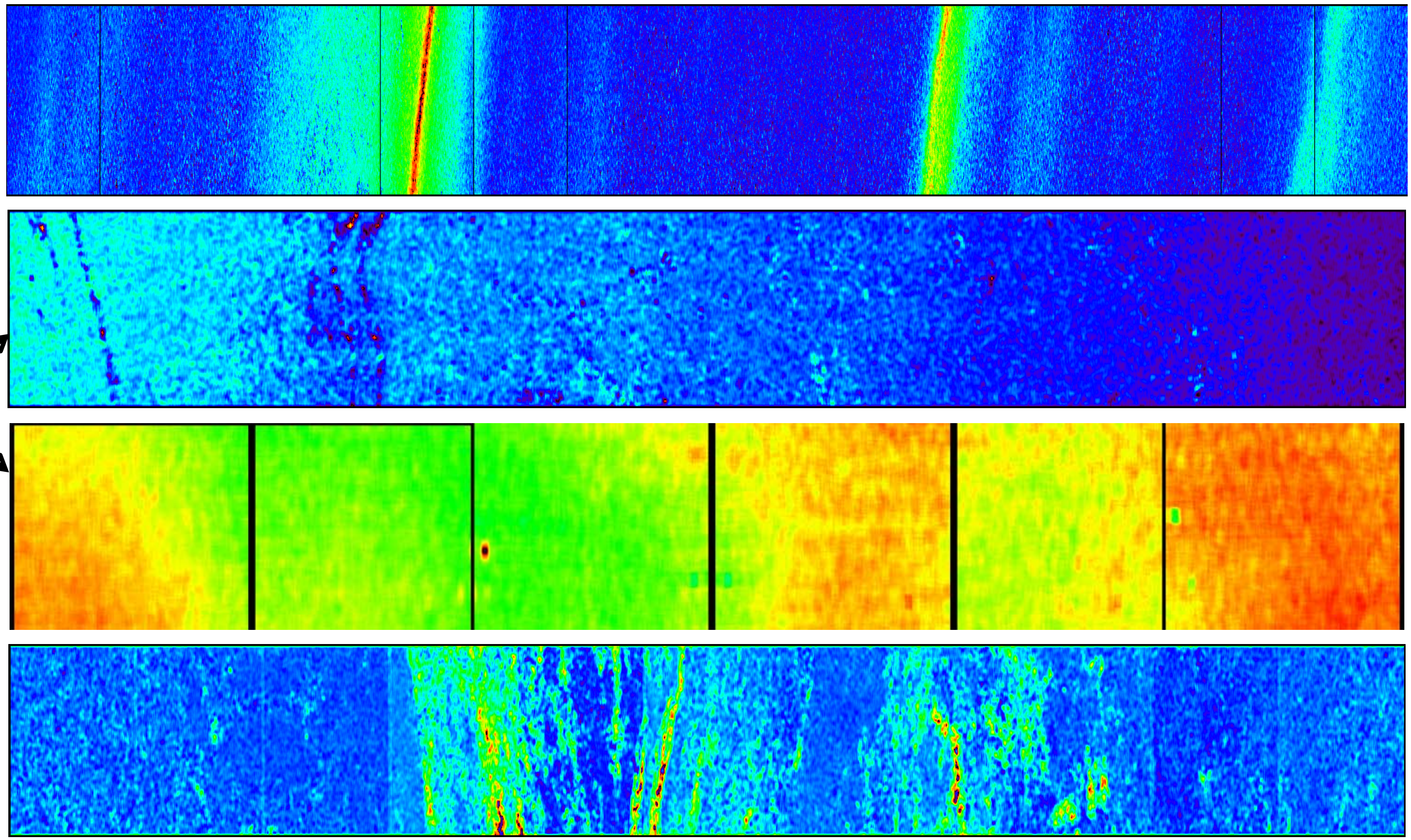
- Total images: 2779
- 14% Images and 74% days affected

Summary
Imaging the Ionosphere Using SAR

High Lat

Mid Lat

Low Lat



[Images are not in a same scale in → direction.]

Summary (Cont.)

Advantages

- High resolution: a few hundred meters → ~2 km
- Much less sensitive to weather
  - No concerns about light sources
  - No day/night restriction
- Global coverage
- A new and powerful technique to explore further ionospheric inhomogeneities and irregularities
- Will support InSAR and PolSAR ionospheric calibration to ensure Earth imagery quality (PolSAR, Split spectrum, etc.)
- Potential to realize lower frequency SAR (P-band)
- A single mission serves both Earth and space sciences

Limitations

- Very significant data amount with the quad-pol approach
  - requires extraordinary data downlink capacity for continuous operation
- Split-spectral technique can only measure TEC difference under certain conditions
- Limited local time coverage
  - Sun-synchronous orbits
- Relatively low temporal resolution (orbital observations)