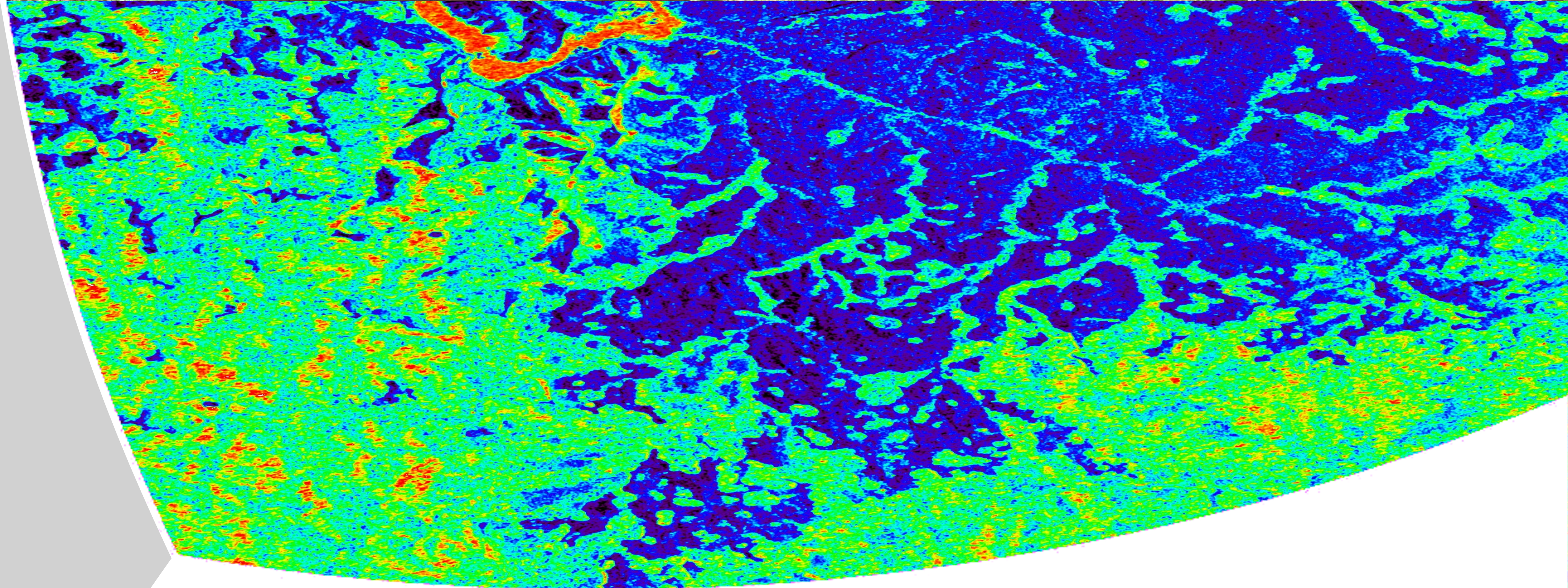

Polarimetric SAR for the Reconstruction of the Ionospheric Electron Density Profile: Observation Requirements

S. De Palma, M. Pardini, J-S. Kim, F. Lobardini and K. Papathanassiou

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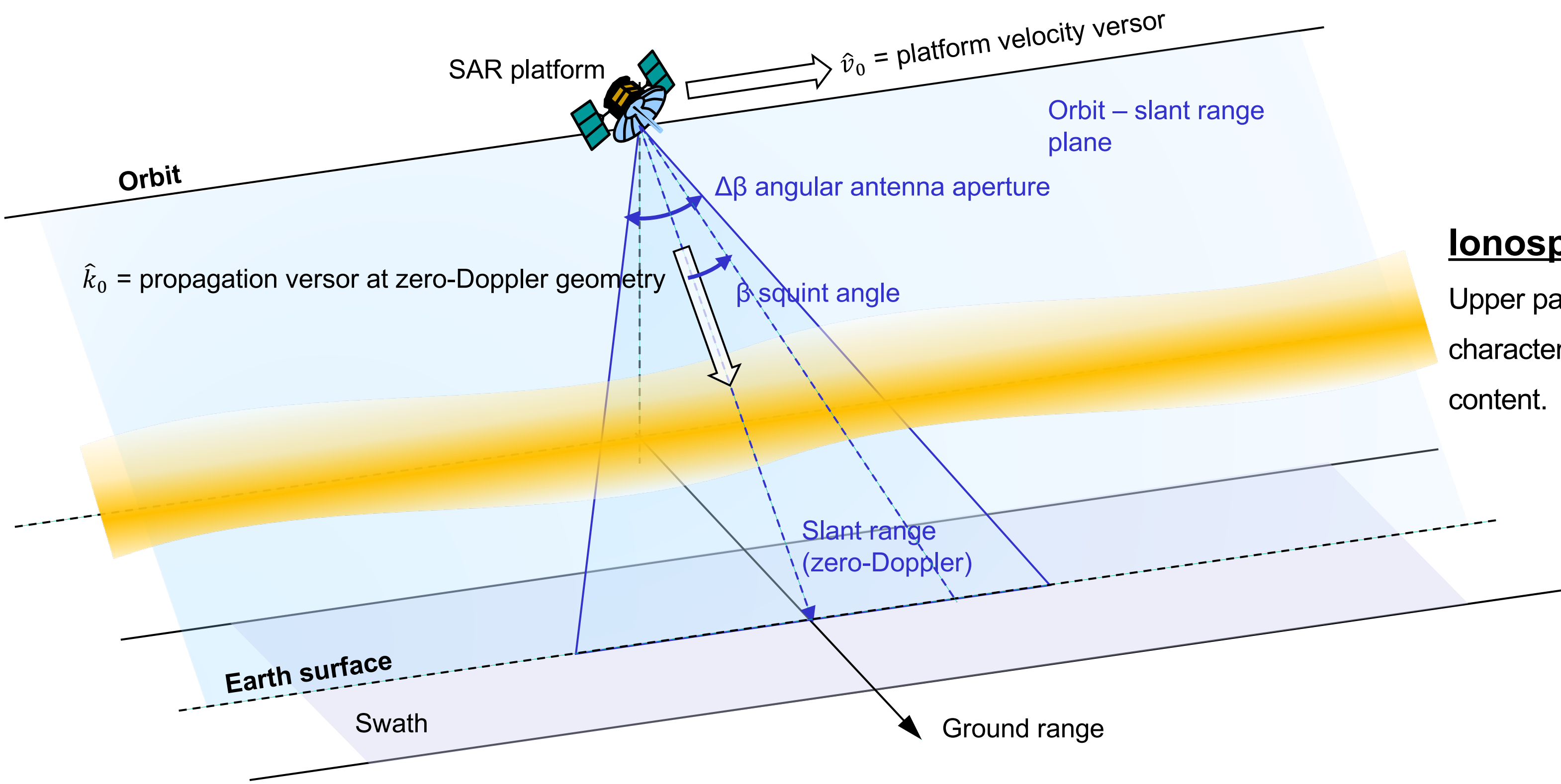
University of Pisa

Introduction



Ionosphere

Upper part of Earth's atmosphere characterized by ion and free-electron content.

Effects on SAR images:

- Attenuation
- Range defocussing
- Azimuth shift
- Faraday Rotation

All the effects of ionosphere on SAR images can be corrected using:

$$TEC = \int_{C(\ell)} N_e(C(\ell);\ell)\, d\ell$$

Electron density profile

Total Electron Content

from measurements of:

$$\Omega = C_0 \int_{C(\ell)} N_e(C(\ell);\ell)\, \vec{B}\cdot\hat{k}\, d\ell$$

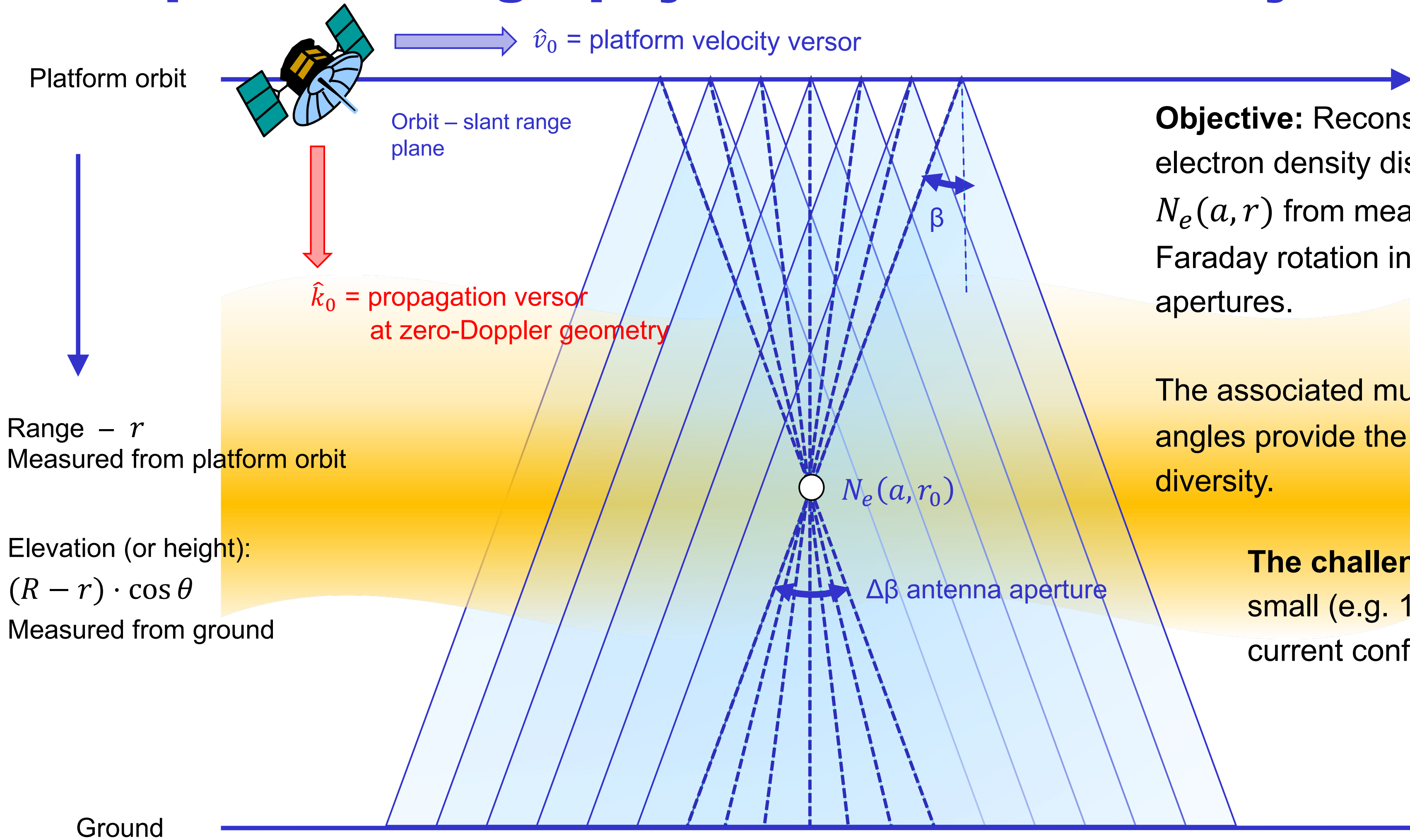
Magnetic field

Propagation vektor

Faraday rotation

- The knowledge of the underlying electron density profile allow the correction of the ionospheric distorsions in SAR images.
- A thin-layer assumption can lead to 10-20% errors in the estimated TECU assuming a known ionosphere height.
- Faraday rotation can be estimated with centi-degree accuracy from polarimetric SAR data, and is the key to access electron density profiles !!!

Ionosphere tomography from SAR: Geometry



Objective: Reconstruction of the electron density distribution $N_e(a, r)$ from measurements of Faraday rotation in multiple sub-apertures.

The associated multiple squint angles provide the required viewing diversity.

The challenge: Δβ is very small (e.g. 1.5° for ALOS) for current configurations

Faraday rotation at an azimuth a and for an angle β: $\Omega(a;\beta) = C_0 \int N_e(a + r\sin\beta, r)\, \vec{B}(a + r\sin\beta, r) \cdot \hat{k}(\beta)\; dr$

In the orbit-range plane: $\hat{k}(\beta) = \cos(\beta)\,\hat{k}_0 + \sin(\beta)\,\hat{v}_0$

from which: $\vec{B}(a + r\sin\beta, r) \cdot \hat{k}(\beta) = B_K(a + r\sin\beta, r)\cos\beta + B_V(a + r\sin\beta, r)\sin\beta$

Role of the Earth magnetic field

The orientation of the magnetic field affects directly the sensitivity of the Faraday rotation as a function of β (sub-apertures) to profile changes

$$\Omega(a;\beta) = C_0 \int N_e(a + r\sin\beta\,, r)[B_K(a + r\sin\beta\,, r\,)\cos\beta + B_V(a + r\sin\beta\,, r\,)\sin\beta]\;dr$$

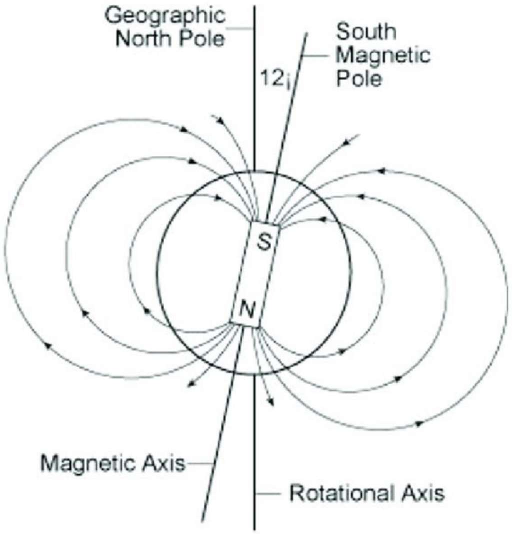
For small β:

Parallel to zero-Doppler range | **Parallel to platform movement**

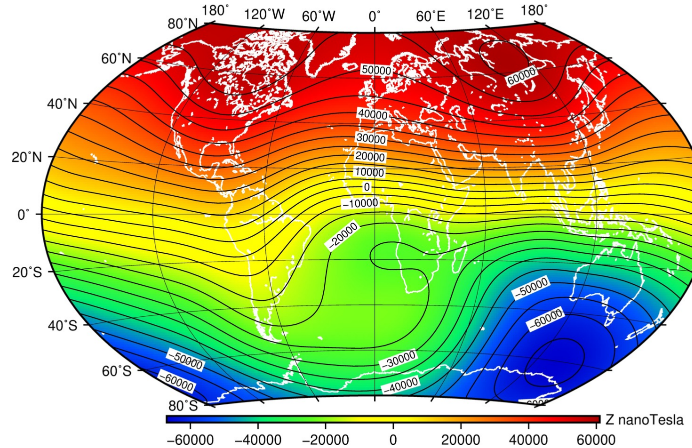
$$\Omega(a;\beta) \approx C_0 \int N_e(a + r\sin\beta\,, r)\;B_K(a + r\sin\beta\,, r\,)\;dr + \beta\;C_0 \int N_e(a + r\sin\beta\,, r)\;B_V(a + r\sin\beta\,, r\,)\;dr$$

Minimizing B_K / maximizing B_V is critical to allow ionospheric reconstructions !!! For a polar-orbiting SAR:

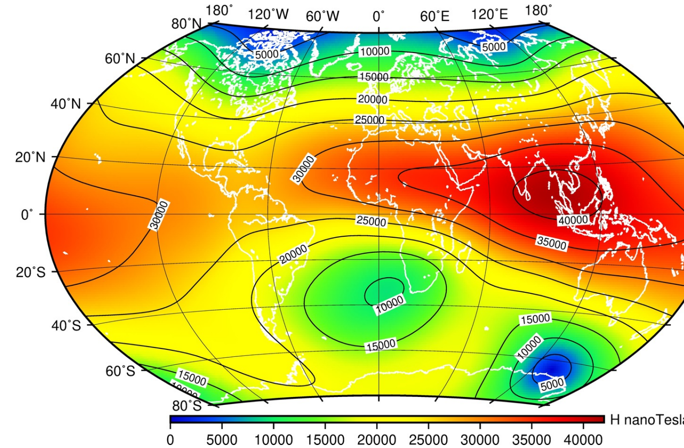
- ▶ Moving towards high latitudes (e.g. boreal zones): the geomagnetic field becomes more and more radial ▶ B_K becomes significant
- ▶ Moving towards the equator: the horizontal component of the geomagnetic field dominates ▶ B_K is very small (tending to 0)



Dipolar representation of the geomagnetic field
Image credit: DOI: 10.1007/s12045-020-0951-9

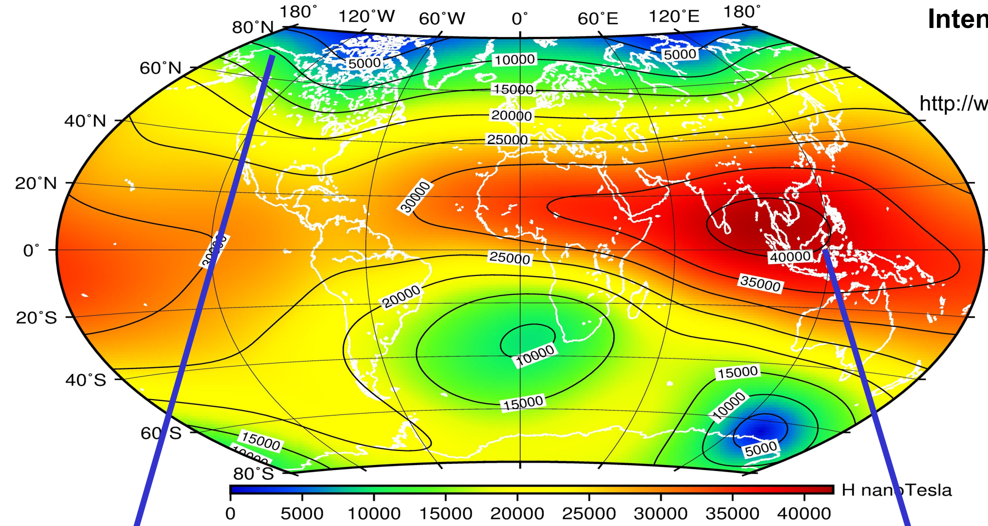


Intensity of the radial component of the geomagnetic field
Image credit:
http://www.geomag.bgs.ac.uk/education/earthmag.html



Intensity of the horizontal component of the geomagnetic field
Image credit:
http://www.geomag.bgs.ac.uk/education/earthmag.html

Considered locations



Intensity of the horizontal component of the geomagnetic field

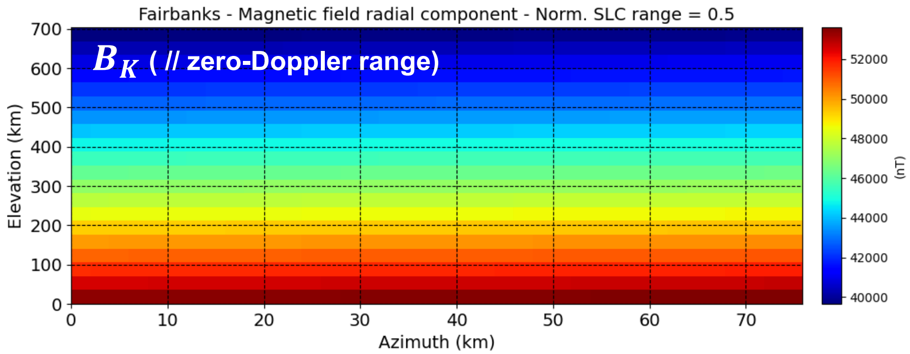
Image credit:
http://www.geomag.bgs.ac.uk/education/earthmag.html

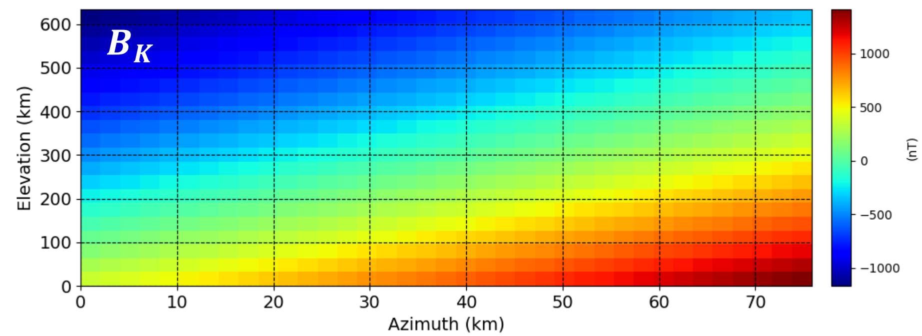
Boreal latitudes

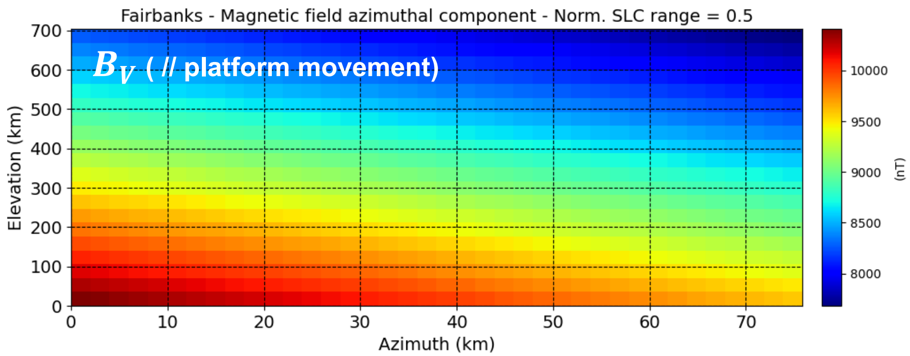
ALOS 'Fairbanks' geometry

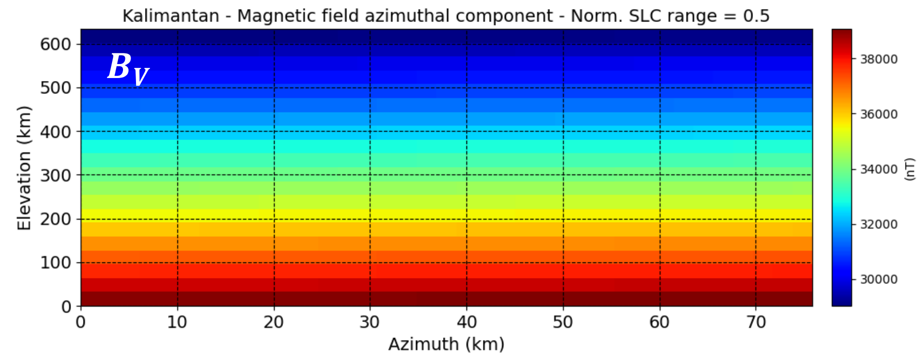
Equatorial latitudes

ALOS-2 'Malaysia' geometry





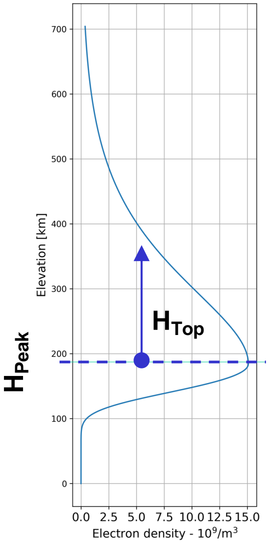




Sensitivity of Faraday rotation to profile parameters

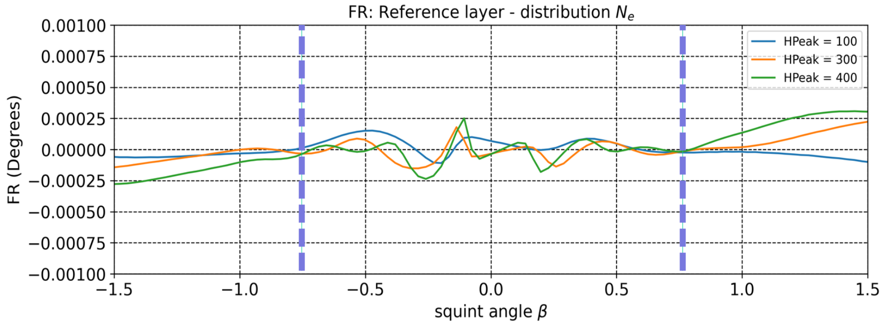
Plots:
Difference between Ω(β) for the different profiles and Ω(β) in the reference case after compensating mean values

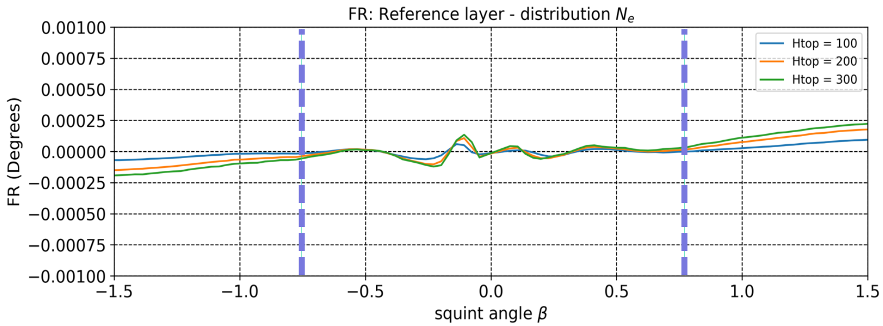
Chapman layer

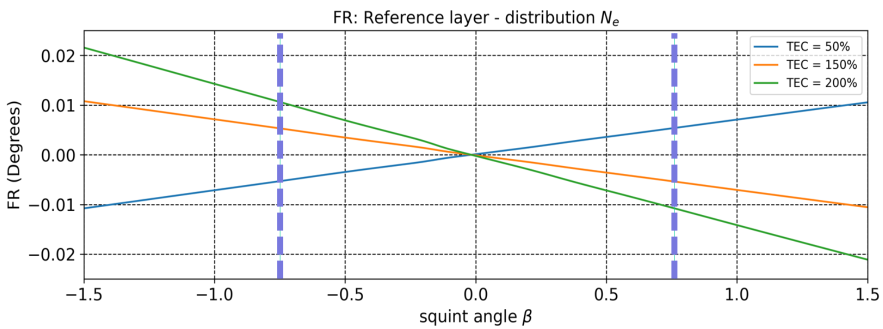


Reference case:
H_{Peak} = 200 km
H_{Top} = 50 km
TEC = TEC_0

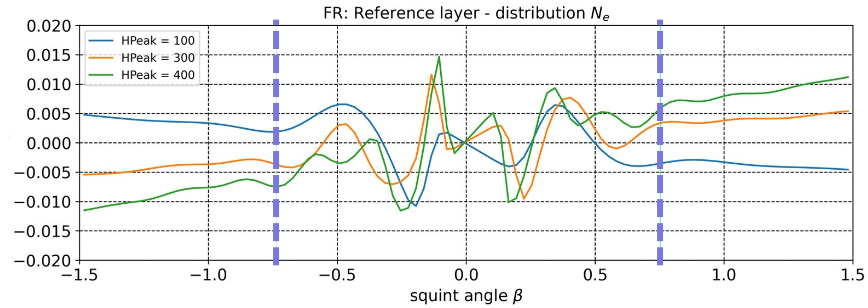
Boreal latitudes – ALOS 'Fairbanks' geometry

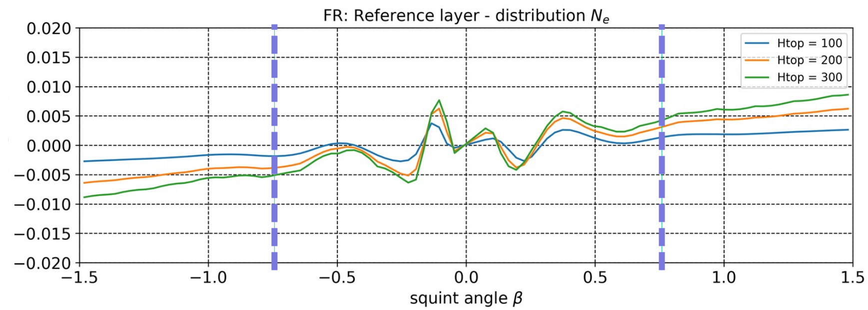


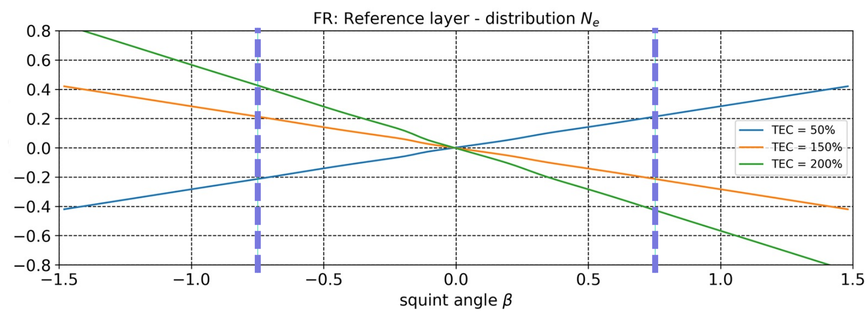




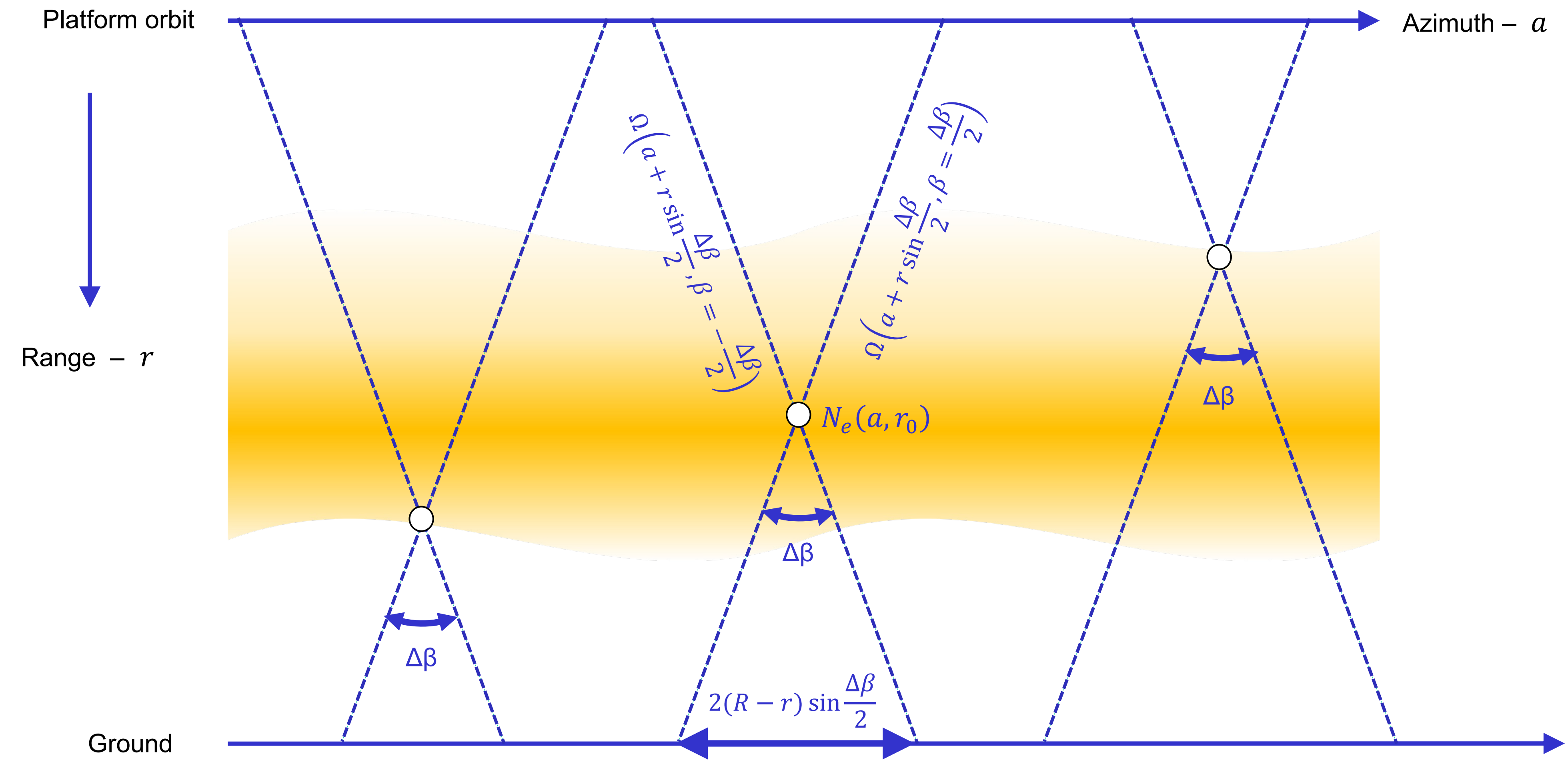
Equatorial latitudes – ALOS-2 'Malaysia' geometry







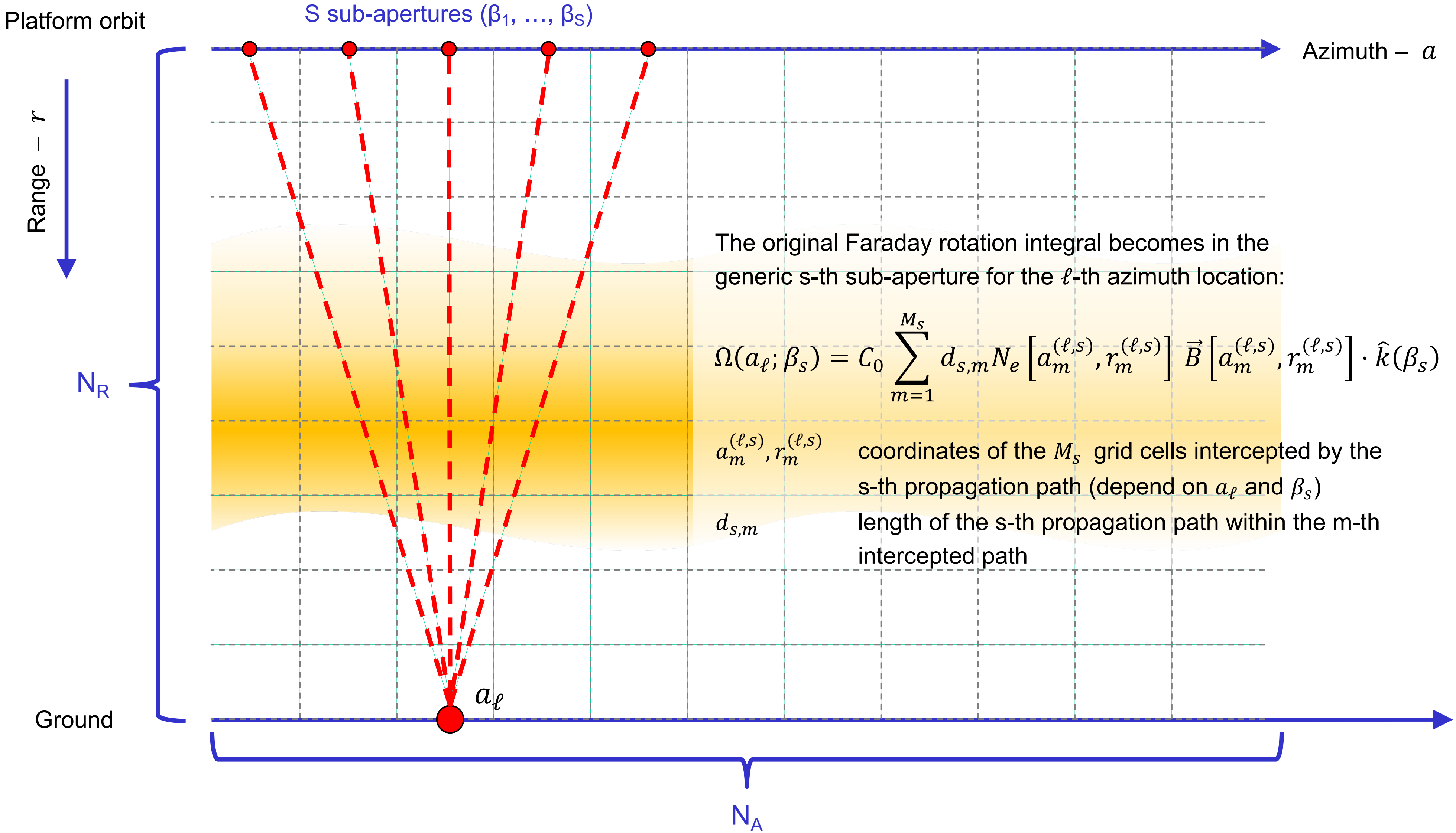
Ionosphere tomography: Inversion geometry



$$\Omega(a - r\sin\beta, \beta) = C_0 \int N_e(a, r) \left[B_K(a, r)\cos\beta + B_V(a, r)\sin\beta\right] dr$$

- Higher elevations (low ranges) rely on larger azimuth intervals;
- At lower elevations (high ranges), the usable azimuth intervals become narrower and the inversion relies more on the variability of the magnetic field across the sub-aperture: equatorial latitudes are favored, while for boreal ones the availability of a larger aperture becomes critical.

Ionosphere tomography: Implementation



The original Faraday rotation integral becomes in the generic s-th sub-aperture for the ℓ-th azimuth location:

$$\Omega(a_\ell; \beta_s) = C_0 \sum_{m=1}^{M_s} d_{s,m} N_e \left[a_m^{(\ell,s)}, r_m^{(\ell,s)}\right] \vec{B}\left[a_m^{(\ell,s)}, r_m^{(\ell,s)}\right] \cdot \hat{k}(\beta_s)$$

$a_m^{(\ell,s)}, r_m^{(\ell,s)}$ coordinates of the M_s grid cells intercepted by the s-th propagation path (depend on a_ℓ and β_s)

$d_{s,m}$ length of the s-th propagation path within the m-th intercepted path

- The orbit-range plane is discretized into $N_R \times N_A$ cells.
- The original Faraday rotation integral becomes a sum and is calculated for S sub-apertures.
- The process is repeated for L azimuth locations. Working assumption: $L = N_A$

Ionosphere tomography: Implementation

Sub-apertures at the azimuth location 1

$$\Omega(a_1;\beta_1) = C_0 \sum_{m=1}^{M_1} d_{1,m} N_e\left[a_m^{(1,1)}, r_m^{(1,1)}\right] \vec{B}\left[a_m^{(1,1)}, r_m^{(1,1)}\right] \cdot \hat{k}(\beta_1)$$

$$\vdots$$

$$\Omega(a_1;\beta_S) = C_0 \sum_{m=1}^{M_S} d_{S,m} N_e\left[a_m^{(1,S)}, r_m^{(1,S)}\right] \vec{B}\left[a_m^{(1,S)}, r_m^{(1,S)}\right] \cdot \hat{k}(\beta_S)$$

⋮

Measurements

Unknowns

Sub-apertures at the azimuth location L

$$\Omega(a_L;\beta_1) = C_0 \sum_{m=1}^{M_1} d_{1,m} N_e\left[a_m^{(L,1)}, r_m^{(L,1)}\right] \vec{B}\left[a_m^{(L,1)}, r_m^{(L,1)}\right] \cdot \hat{k}(\beta_1)$$

$$\vdots$$

$$\Omega(a_L;\beta_S) = C_0 \sum_{m=1}^{M_S} d_{S,m} N_e\left[a_m^{(L,S)}, r_m^{(L,S)}\right] \vec{B}\left[a_m^{(L,S)}, r_m^{(L,S)}\right] \cdot \hat{k}(\beta_S)$$

$N_S \times L$

$N_R \times N_A$

Linear system of equations:

$$\mathbf{\Omega} = \mathbf{A}\,\mathbf{n}$$

Least-squares solution: $\mathbf{n} = (\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T\mathbf{\Omega}$

With regularization: $\mathbf{n} = (\mathbf{A}^T\mathbf{A} + \delta\,\mathbf{I})^{-1}\mathbf{A}^T\mathbf{\Omega}$

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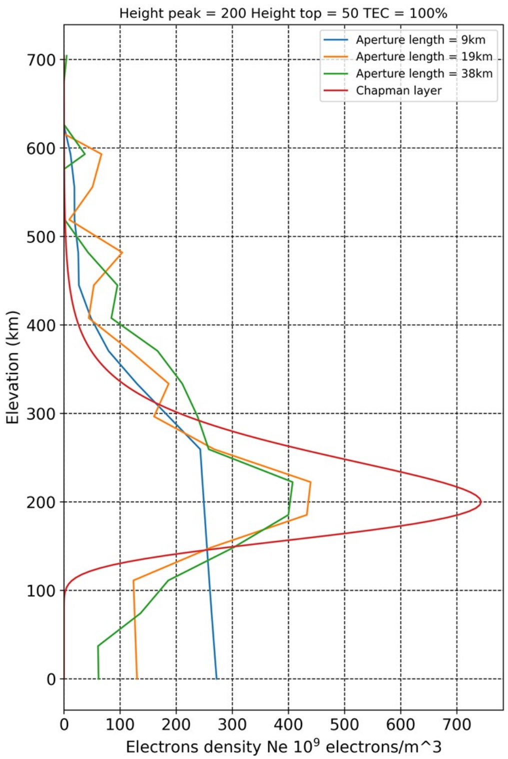
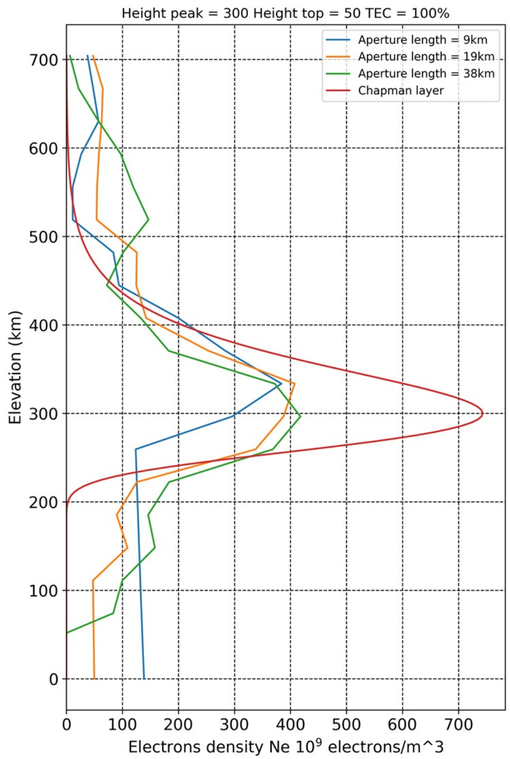
Examples of inverted profiles

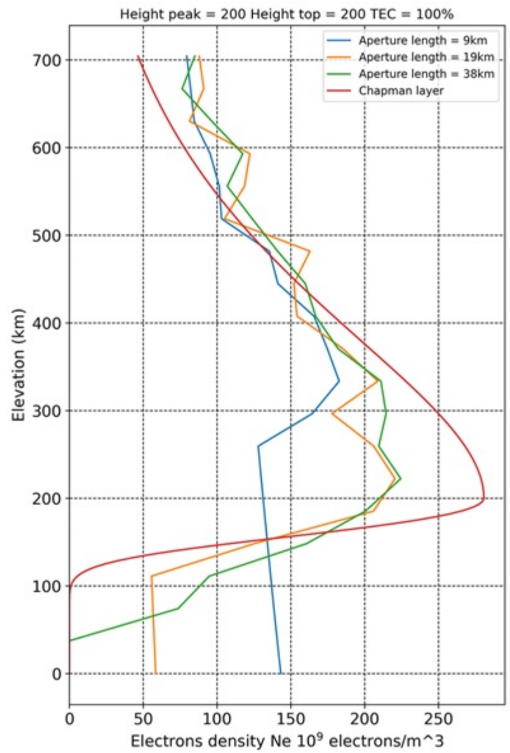
Boreal latitudes – ALOS ‘Fairbanks’ geometry



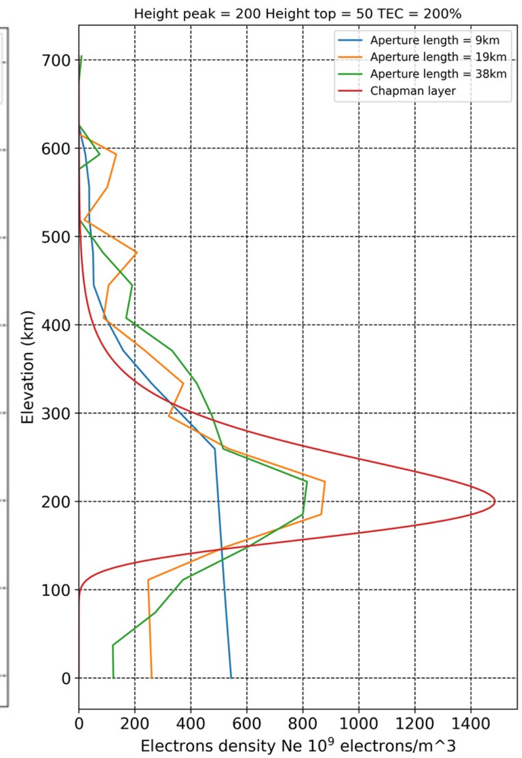
H_{Peak} = 200 km
H_{Top} = 50 km
TEC = TEC_0



H_{Peak} = <u>300 km</u>
H_{Top} = 50 km
TEC = TEC_0



H_{Peak} = 300 km
H_{Top} = <u>150 km</u>
TEC = TEC_0

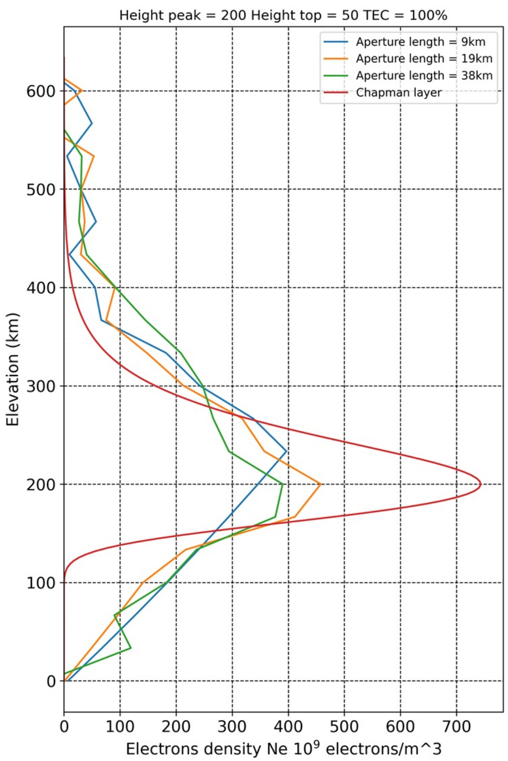


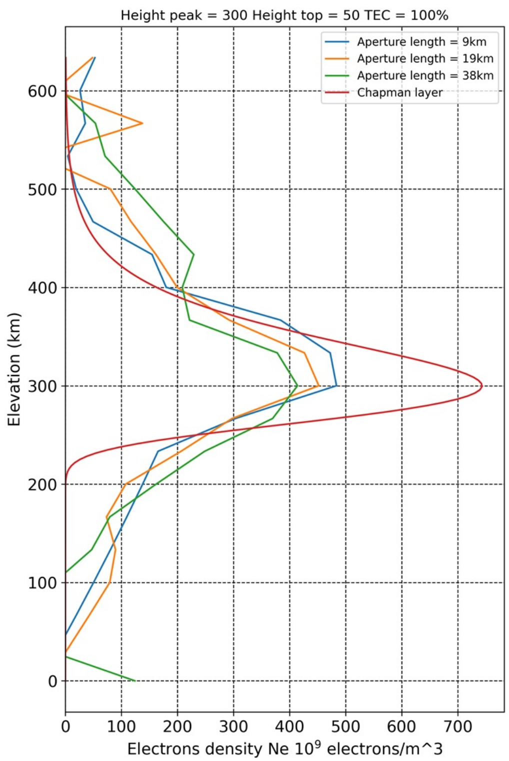
H_{Peak} = 300 km
H_{Top} = 50 km
TEC = <u>$2TEC_0$</u>

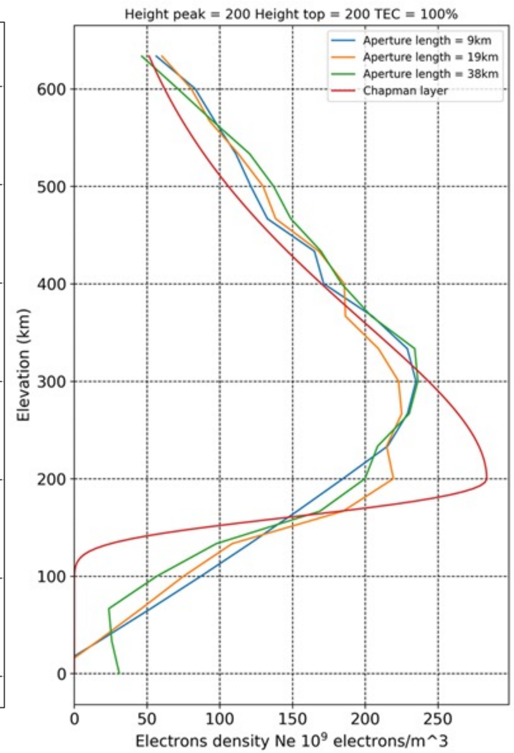
The smallest tested aperture (9 km = 0.75° L-band, 4.5 m az. res.) does not allow an inversion below a 300 km.

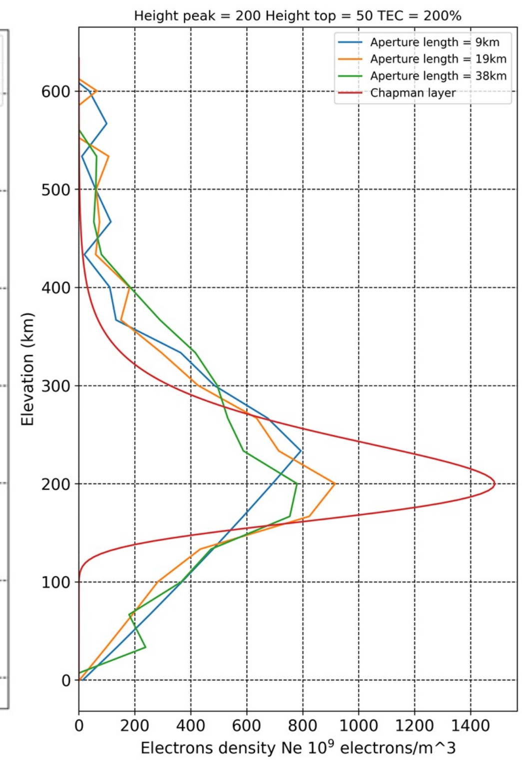
Examples of inverted profiles

Equatorial latitudes – ALOS-2 ‘Malaysia’ geometry









H_{Peak} = 200 km	H_{Peak} = <u>300 km</u>	H_{Peak} = 300 km	H_{Peak} = 300 km
H_{Top} = 50 km	H_{Top} = 50 km	H_{Top} = <u>150 km</u>	H_{Top} = 150 km
TEC = TEC_0	TEC = TEC_0	TEC = TEC_0	TEC = <u>$2TEC_0$</u>

The variability of the magnetic field across sub-apertures allows the inversion below 300 km also for the smallest aperture, but a larger one allow better reconstructions.

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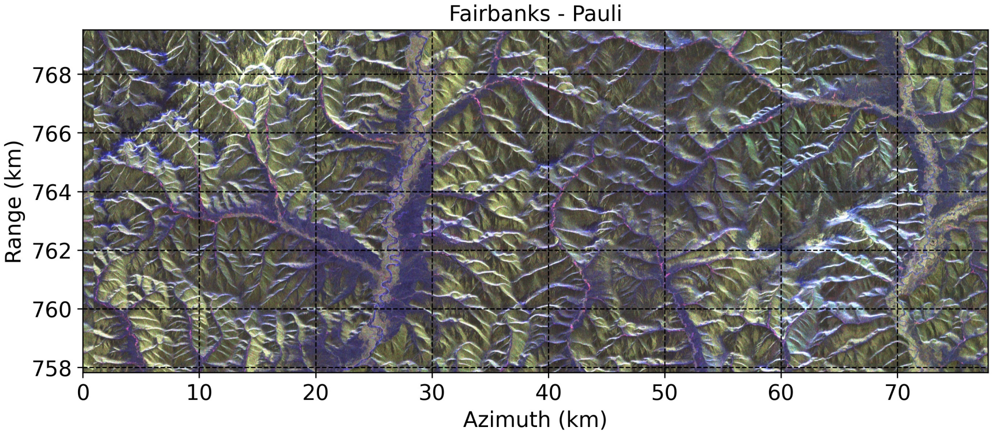
First real data results

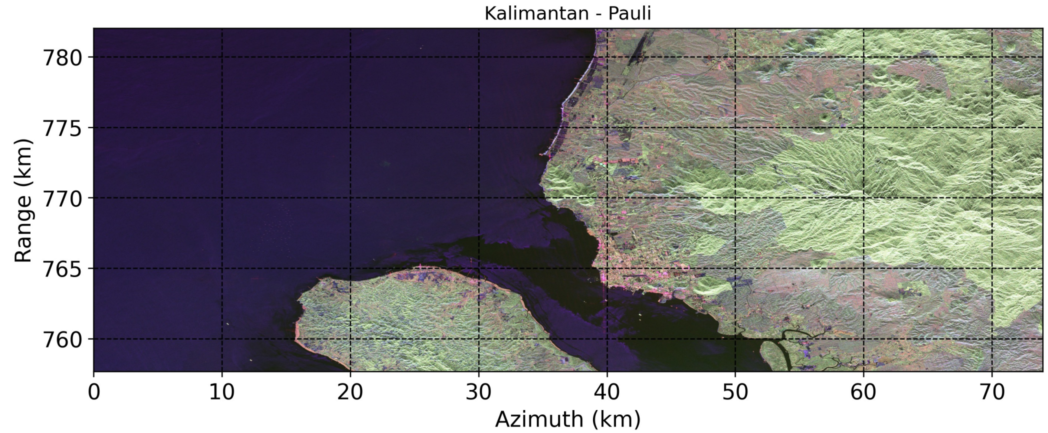
Fairbanks (Alaska) – ALOS

31.03.2007 - Resolution: 12.5 m × 4.48 m (sl. range × azimuth)



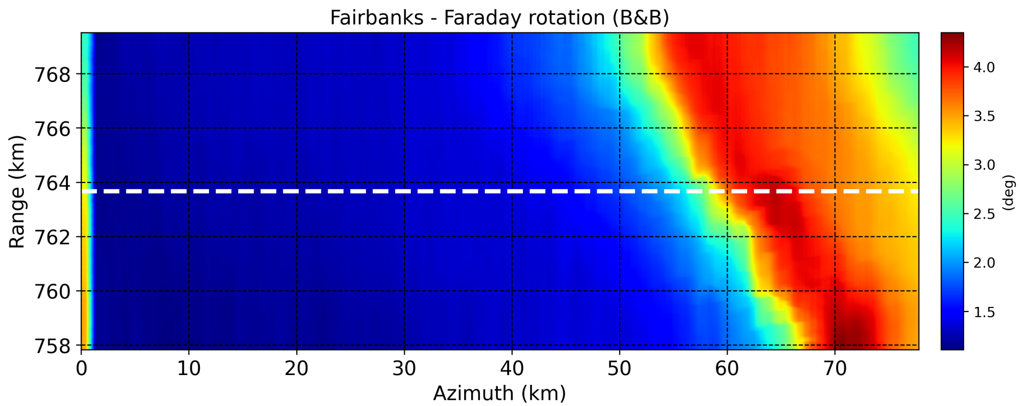
Malaysia – ALOS-2

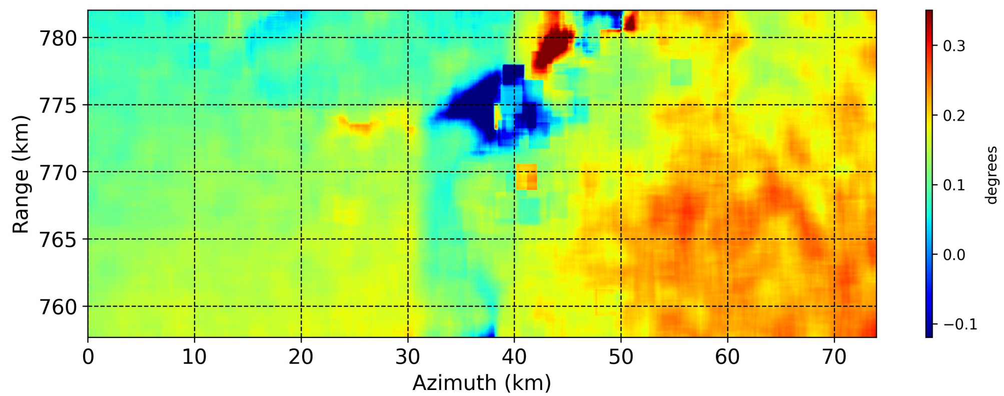
04.08.2015 - Resolution: 12.5 m × 4.48 m (sl. range × azimuth)



Faraday rotations estimated by means of Bickel & Bates

Multilook 2 km × 2 km (sl. range × azimuth)





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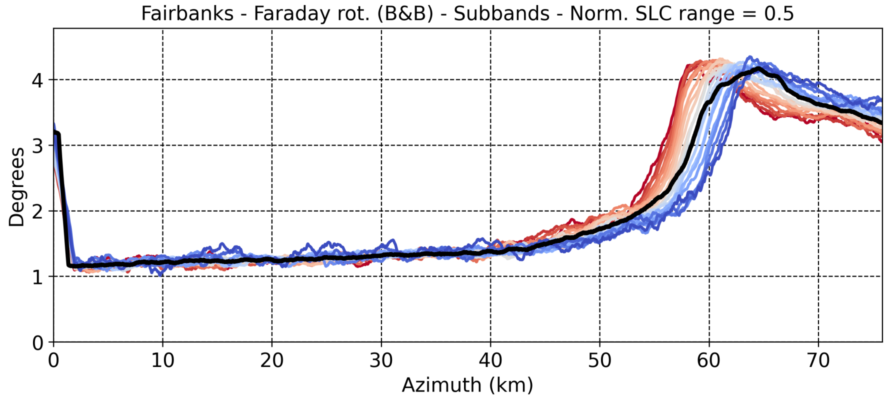
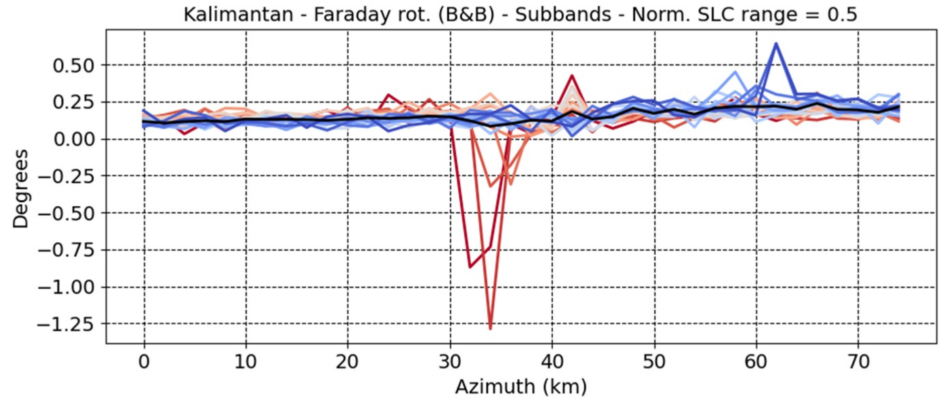
First real data results

Faraday rotations estimated by means of Bickel & Bates in 20 sub-apertures

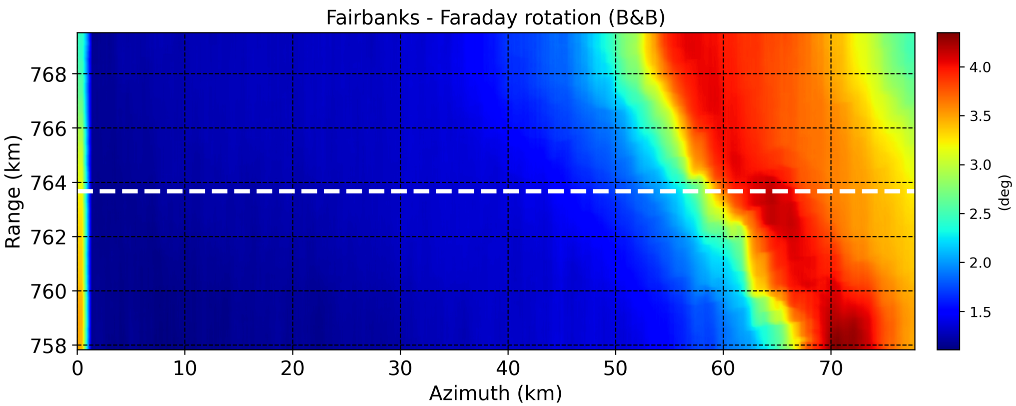
Multilook 2 km × 2 km (sl. range × azimuth)

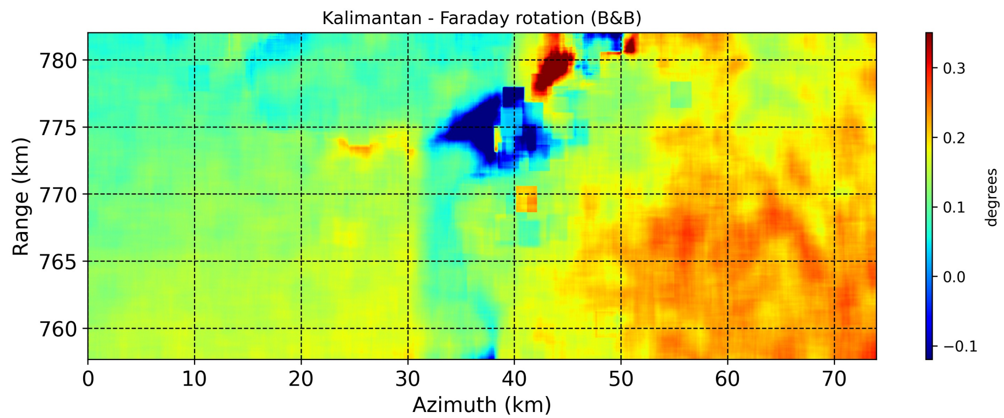




Faraday rotations estimated by means of Bickel & Bates

Multilook 2 km × 2 km (sl. range × azimuth)

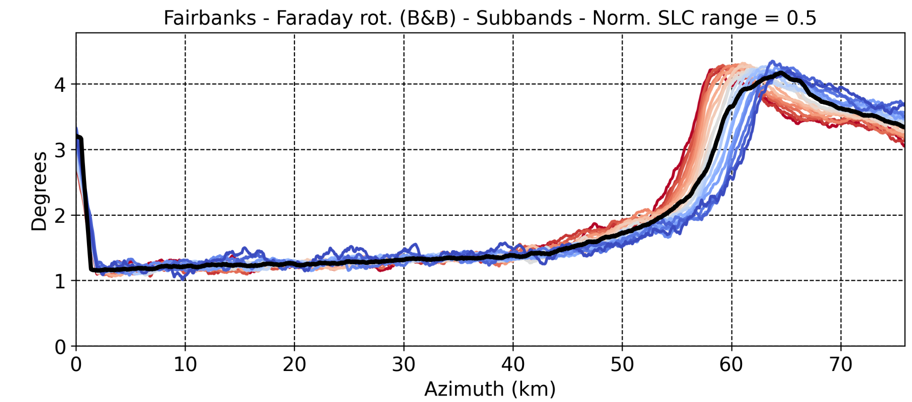


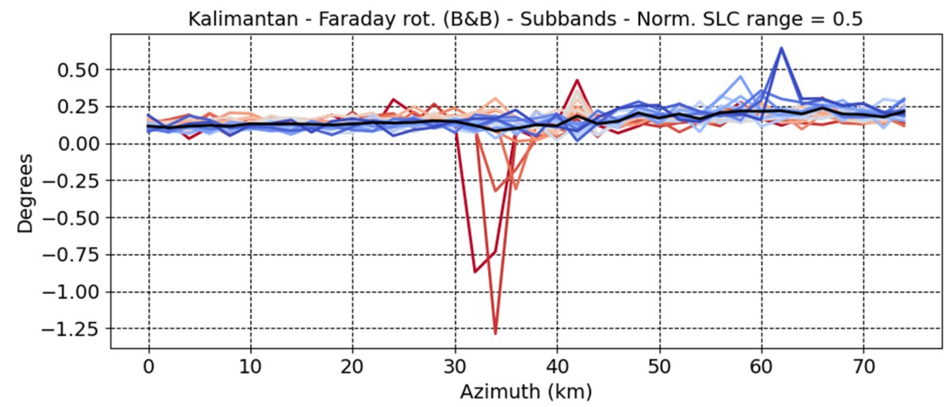


First real data results

Faraday rotations estimated by means of Bickel & Bates in 20 sub-apertures

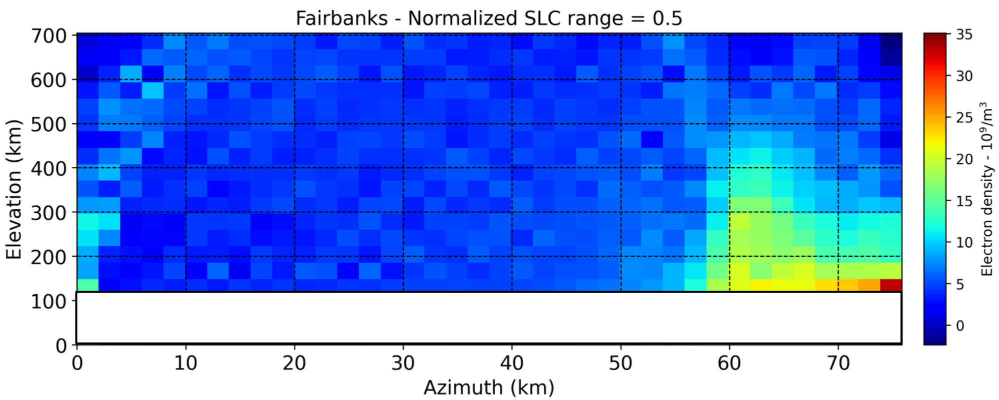
Multilook 2 km × 2 km (sl. range × azimuth)

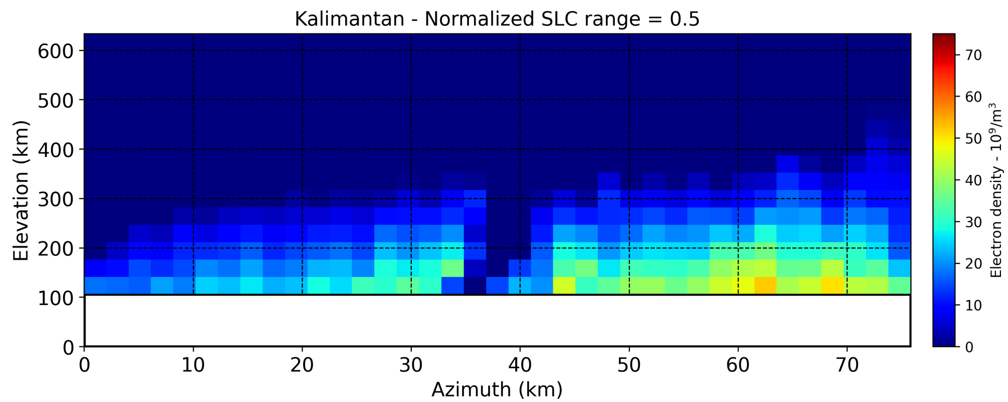




Reconstructed tomographic profiles

(equation system inversion with regularization)





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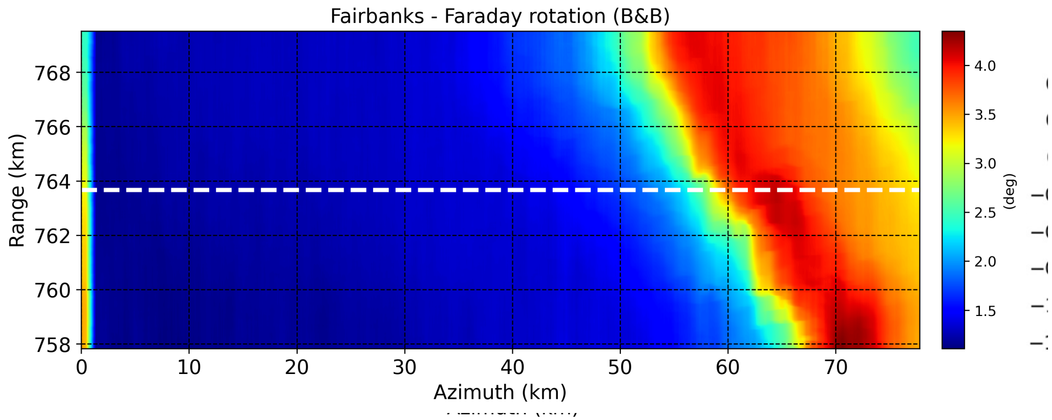
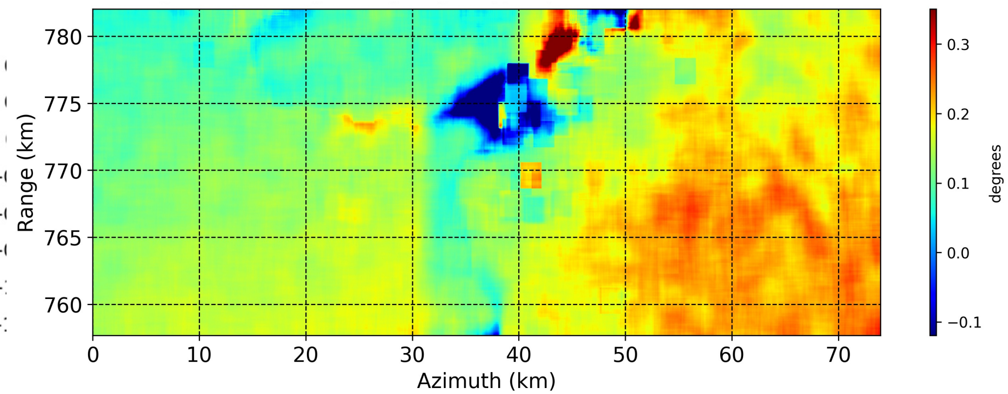
First real data results

Faraday rotations estimated by means of Bickel & Bates in 20 sub-apertures

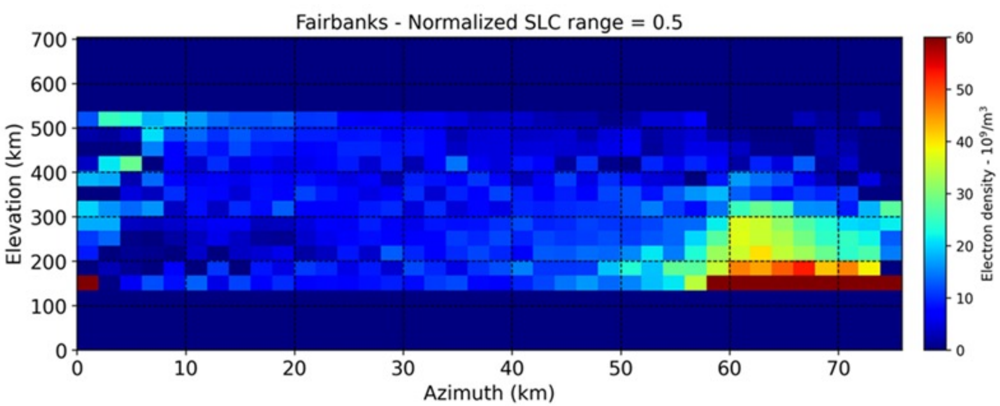
Multilook 2 km × 2 km (sl. range × azimuth)

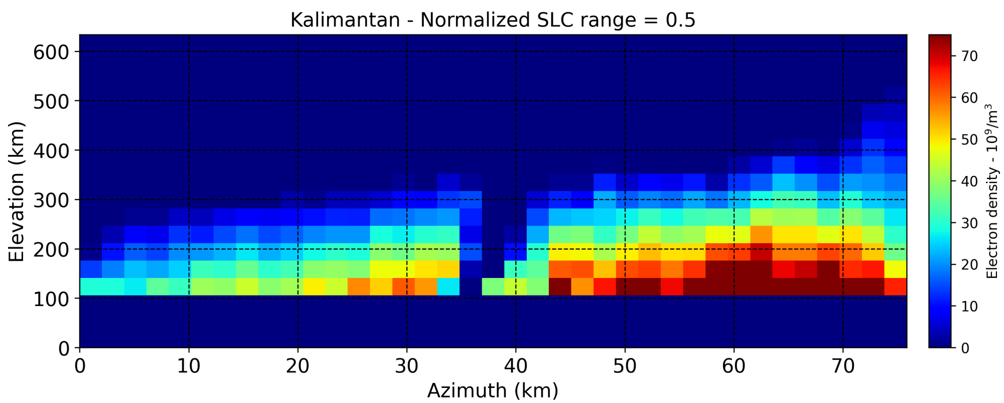




Reconstructed tomographic profiles

(equation system inversion with regularization and elevation constraints)





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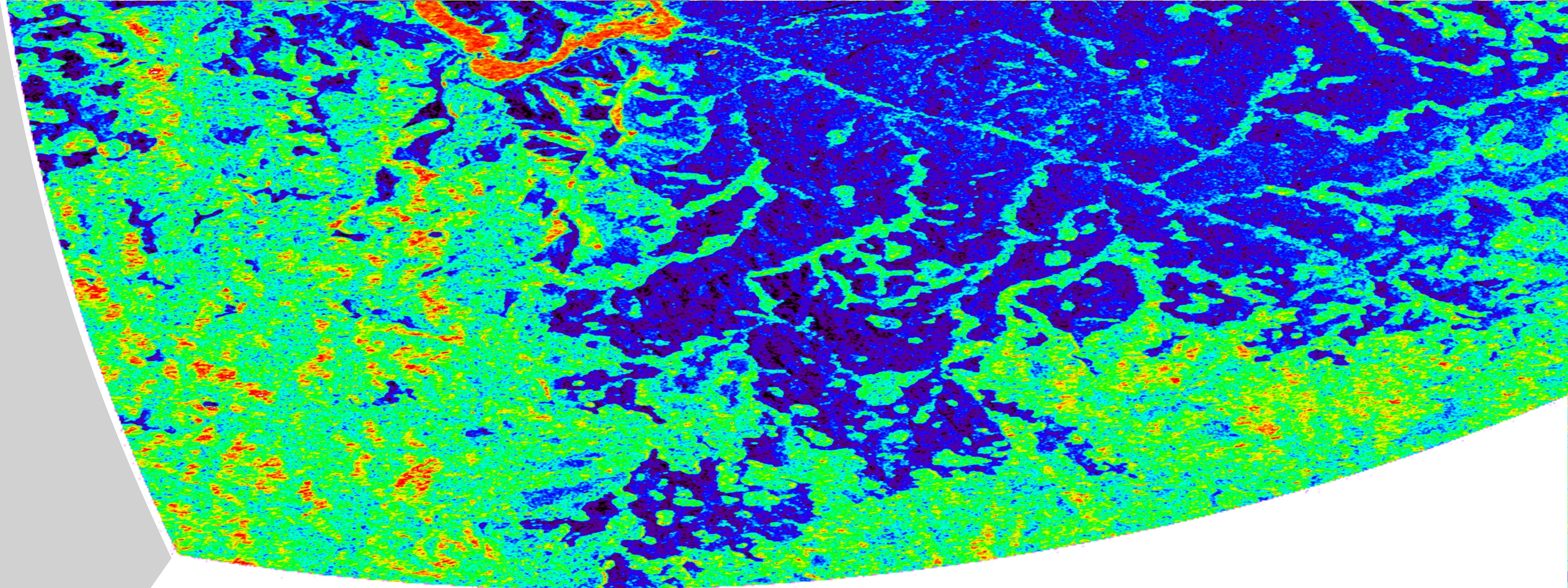
Conclusions

- An approach for the reconstruction of electron density profiles using measurements of Faraday rotation from multiple sub-apertures of polarimetric SAR acquisitions has been considered.

- Two critical performance factors:
  - The relative orientation between the geomagnetic field and the line of sight. Equatorial l atitudes maximise the variation of the magnetic field within the synthetic aperture, hence the sensitivity to the profile features.
  - The (typically small) available aperture. Larger apertures affect not only the resolution of the reconstruction, but also allow a more accurate reconstruction at lower elevations.

- Inversions results show interesting potentials: position and width of ionosphere layers can be reconstructed, but the retrieved electron density is biased. But positional features are still important information supporting ionosphere observation and effect correction.



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