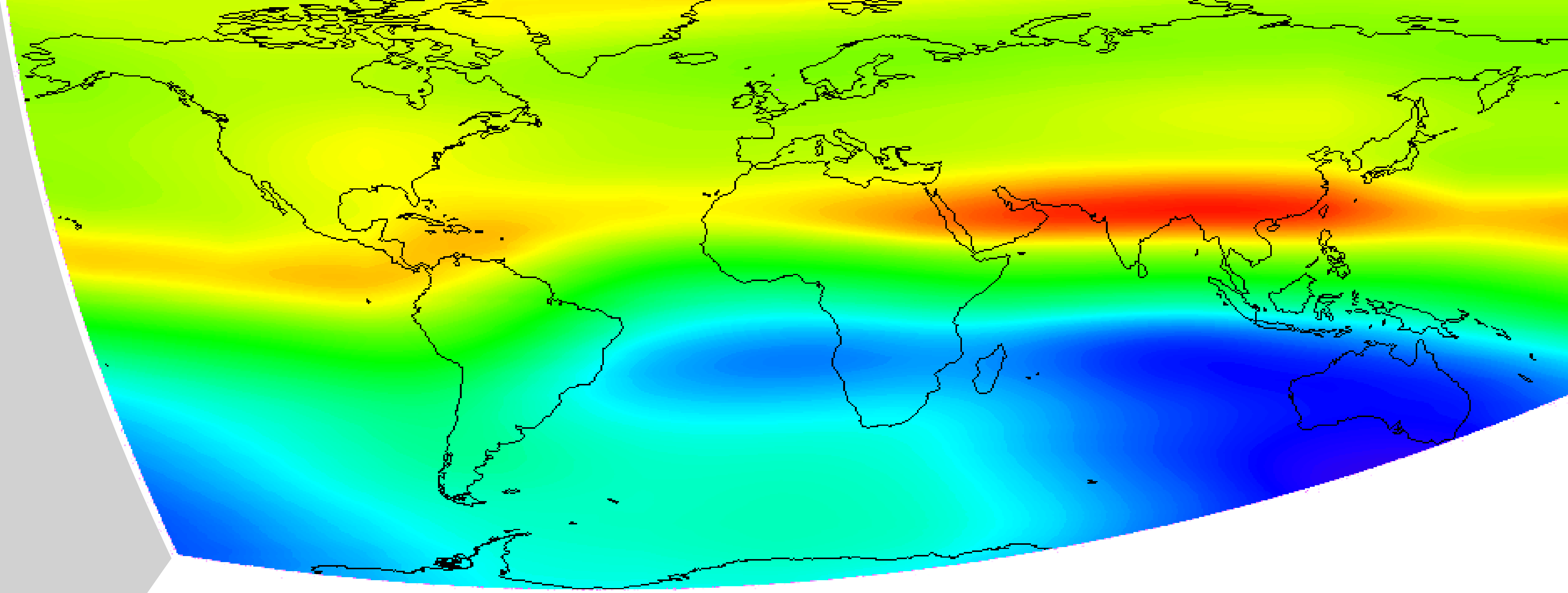

Polarimetric Calibration of Spaceborne SAR Data in the Presence of the Ionosphere by Means of Azimuth Sub-bands

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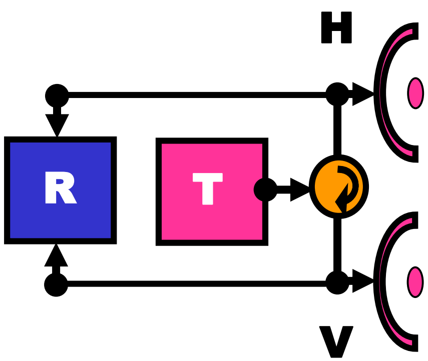
DLR

Polarimetric System Distortion Model



Tx / Rx Distortion:

$$\begin{bmatrix} O_{HH} & O_{HV} \\ O_{VH} & O_{VV} \end{bmatrix} = \underbrace{\begin{bmatrix} R_{HH} & R_{HV} \\ R_{VH} & R_{VV} \end{bmatrix}}_{\text{Receive}} \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix} \underbrace{\begin{bmatrix} T_{HH} & T_{HV} \\ T_{VH} & T_{VV} \end{bmatrix}}_{\text{Transmit}} + \underbrace{\begin{bmatrix} N_{HH} & N_{HV} \\ N_{VH} & N_{VV} \end{bmatrix}}_{\text{Noise}} + \underbrace{\begin{bmatrix} A_{HH} & A_{HV} \\ A_{VH} & A_{VV} \end{bmatrix}}_{\text{Ambiguities}}$$

$$\begin{bmatrix} O_{HH} & O_{HV} \\ O_{VH} & O_{VV} \end{bmatrix} = Y \underbrace{\begin{bmatrix} 1 & \delta_{RH} \\ \delta_{RV} & f_R \end{bmatrix}}_{\text{Pol Dist. on Receive}} \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix} \underbrace{\begin{bmatrix} 1 & \delta_{TH} \\ \delta_{TV} & f_T \end{bmatrix}}_{\text{Pol Dist. on Transmit}} + \begin{bmatrix} N_{HH} & N_{HV} \\ N_{VH} & N_{VV} \end{bmatrix} + \begin{bmatrix} A_{HH} & A_{HV} \\ A_{VH} & A_{VV} \end{bmatrix}$$

X-Talk Ratios: On Receive: $\delta_{RH} := \frac{R_{HV}}{R_{HH}}$ $\quad \delta_{RV} := \frac{R_{VH}}{R_{HH}}$

On Transmit: $\delta_{TH} := \frac{T_{HV}}{T_{HH}}$ $\quad \delta_{TV} := \frac{T_{VH}}{T_{HH}}$

H–V Channel Imbalance: On Receive: $f_R := \frac{R_{VV}}{R_{HH}}$

On Transmit: $f_T := \frac{T_{VV}}{T_{HH}}$

Abs. Gain on Tx & Rx: $Y := R_{HH} T_{HH}$

Polarimetric System Distortion Model

System Tx / Rx Distortion + Propagation (i.e. Faraday Rotation) Distortion :

$$\begin{bmatrix} O_{HH} & O_{HV} \\ O_{VH} & O_{VV} \end{bmatrix} = \underbrace{\begin{bmatrix} R_{HH} & R_{HV} \\ R_{VH} & R_{VV} \end{bmatrix}}_{\text{Receive}} \underbrace{\begin{bmatrix} \cos(\Omega) & \sin(\Omega) \\ -\sin(\Omega) & \cos(\Omega) \end{bmatrix}}_{\text{FR on Receive}} \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix} \underbrace{\begin{bmatrix} \cos(\Omega) & \sin(\Omega) \\ -\sin(\Omega) & \cos(\Omega) \end{bmatrix}}_{\text{FR on Transmit}} \underbrace{\begin{bmatrix} T_{HH} & T_{HV} \\ T_{VH} & T_{VV} \end{bmatrix}}_{\text{Transmit}} + \begin{bmatrix} N_{HH} & N_{HV} \\ N_{VH} & N_{VV} \end{bmatrix} + \begin{bmatrix} A_{HH} & A_{HV} \\ A_{VH} & A_{VV} \end{bmatrix}$$

$$\begin{bmatrix} O_{HH} & O_{HV} \\ O_{VH} & O_{VV} \end{bmatrix} = Y \underbrace{\begin{bmatrix} 1 & \delta_{RH} \\ \delta_{RV} & f_R \end{bmatrix} \begin{bmatrix} \cos(\Omega) & \sin(\Omega) \\ -\sin(\Omega) & \cos(\Omega) \end{bmatrix}}_{\text{Total distortion Matrix } [R^{\Omega}]} \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix} \begin{bmatrix} \cos(\Omega) & \sin(\Omega) \\ -\sin(\Omega) & \cos(\Omega) \end{bmatrix} \begin{bmatrix} 1 & \delta_{TH} \\ \delta_{TV} & f_T \end{bmatrix} + \begin{bmatrix} N_{HH} & N_{HV} \\ N_{VH} & N_{VV} \end{bmatrix} + \begin{bmatrix} A_{HH} & A_{HV} \\ A_{VH} & A_{VV} \end{bmatrix}$$

X-Talk – Faraday Rotation Ambiguity:

$$Y \begin{bmatrix} 1 & \delta_{XH} \\ \delta_{XV} & f_X \end{bmatrix} \begin{bmatrix} \cos(\Omega) & \sin(\Omega) \\ -\sin(\Omega) & \cos(\Omega) \end{bmatrix} = \begin{bmatrix} R^{\Omega}_{HH} & R^{\Omega}_{HV} \\ R^{\Omega}_{VH} & R^{\Omega}_{VV} \end{bmatrix}$$

Polar Decomposition of the X-talk matrix:

$$\begin{bmatrix} 1 & \delta_{XH} \\ \delta_{XV} & f_X \end{bmatrix} = \begin{bmatrix} 1 & \beta_{XH} \\ \beta_{XV} & f_X \end{bmatrix} \begin{bmatrix} \cos(\Omega_X) & \sin(\Omega_X) \\ -\sin(\Omega_X) & \cos(\Omega_X) \end{bmatrix}$$

$$\begin{bmatrix} R^{\Omega}_{HH} & R^{\Omega}_{HV} \\ R^{\Omega}_{VH} & R^{\Omega}_{VV} \end{bmatrix} = Y \begin{bmatrix} 1 & \beta_{XH} \\ \beta_{XV} & f_X \end{bmatrix} \begin{bmatrix} \cos(\Omega_X) & \sin(\Omega_X) \\ -\sin(\Omega_X) & \cos(\Omega_X) \end{bmatrix} \begin{bmatrix} \cos(\Omega) & \sin(\Omega) \\ -\sin(\Omega) & \cos(\Omega) \end{bmatrix} = Y \begin{bmatrix} 1 & \beta_{XH} \\ \beta_{XV} & f_X \end{bmatrix} \begin{bmatrix} \cos(\Omega + \Omega_X) & \sin(\Omega + \Omega_X) \\ -\sin(\Omega + \Omega_X) & \cos(\Omega + \Omega_X) \end{bmatrix}$$

FR and X-Talk Rotation Ambiguity

Total distortion Matrix:

$$\begin{bmatrix} R_{HH}^{\Omega} & R_{HV}^{\Omega} \\ R_{VH}^{\Omega} & R_{VV}^{\Omega} \end{bmatrix} = \begin{bmatrix} R_{HH} & R_{HV} \\ R_{VH} & R_{VV} \end{bmatrix} \begin{bmatrix} \cos(\Omega) & \sin(\Omega) \\ -\sin(\Omega) & \cos(\Omega) \end{bmatrix} = \begin{bmatrix} 1 & \beta_{XH} \\ \beta_{XV} & f_X \end{bmatrix} \begin{bmatrix} \cos(\Omega+\Omega_X) & \sin(\Omega+\Omega_X) \\ -\sin(\Omega+\Omega_X) & \cos(\Omega+\Omega_X) \end{bmatrix}$$

… there is an inherent ambiguity between Ω (i.e. FR) and Ω_X (i.e. rotation component of system dist.)

Calibration error due to residual FR:

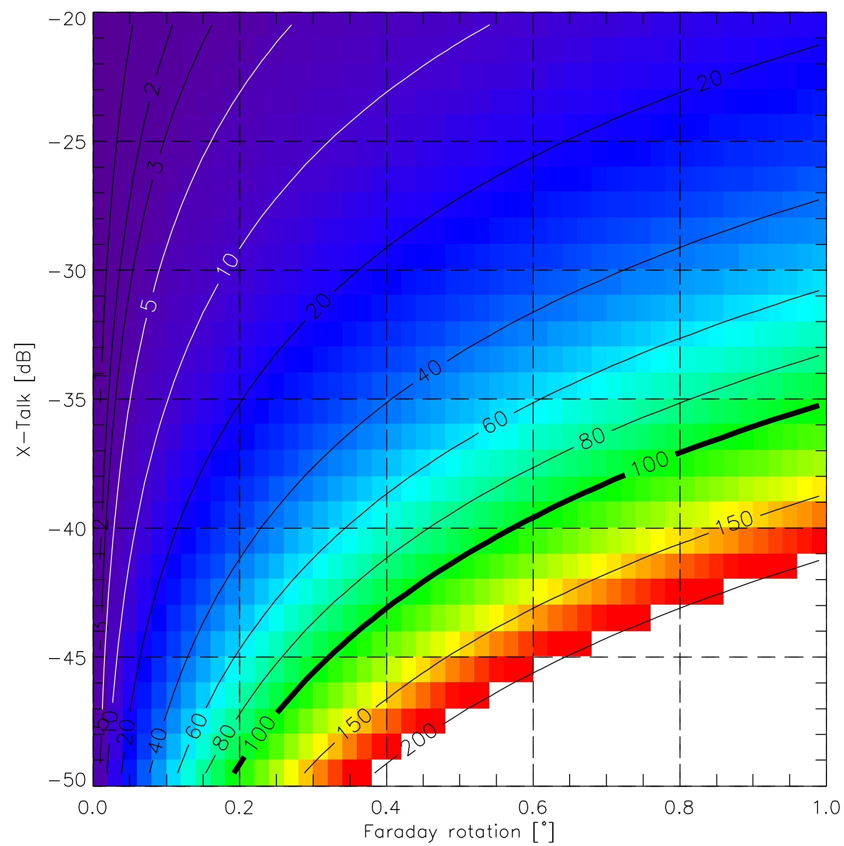
$$\begin{bmatrix} 1 & \delta_{EH} \\ \delta_{EV} & f_X \end{bmatrix} = k \begin{bmatrix} 1 & \delta_H \\ \delta_V & f_X \end{bmatrix} \begin{bmatrix} \cos(\Omega) & -\sin(\Omega) \\ \sin(\Omega) & \cos(\Omega) \end{bmatrix}$$

$$= k \begin{bmatrix} \cos(\Omega)+\delta_H \sin(\Omega) & -\sin(\Omega)+\delta_H \cos(\Omega) \\ \delta_V \cos(\Omega)+f_X \sin(\Omega) & -\delta_V \sin(\Omega)+f_X \cos(\Omega) \end{bmatrix}$$

For small FR angles: $\cos(\Omega) \approx 1$ and $\sin(\Omega) \approx \Omega$

$$\delta_{EH} := -\sin(\Omega)+\delta_H \cos(\Omega) \approx -\Omega+\delta_H$$

$$\delta_{EV} := -f \sin(\Omega)+\delta_V \cos(\Omega) \approx f\Omega+\delta_V$$



Solving the Polarimetric System Calibration Problem cont.

Exploring the $\vec{B}\cdot\vec{\kappa}(\theta_a)$ dependency

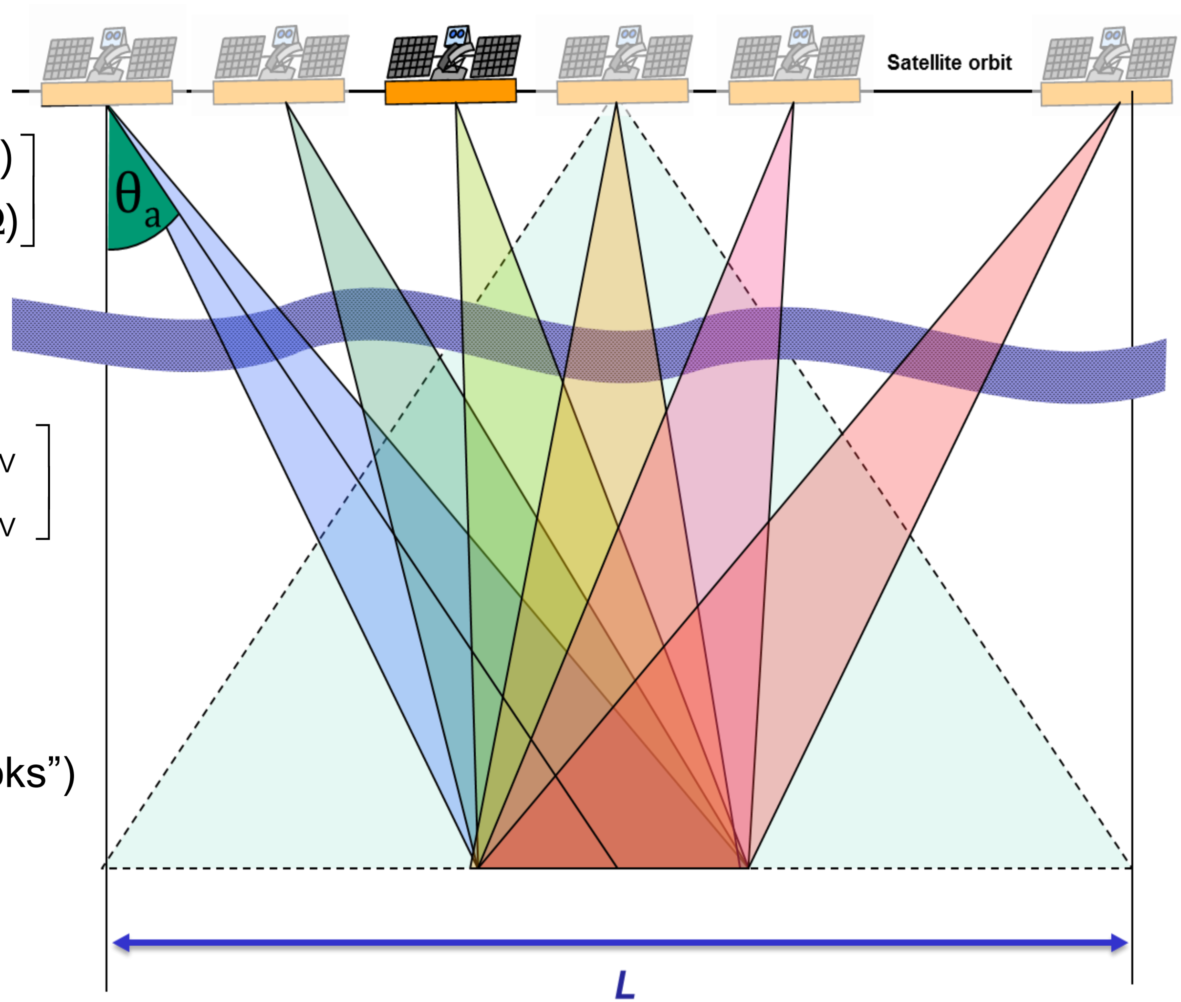
Distortion on receive:

$$\begin{bmatrix} R^{\Omega}_{HH} & R^{\Omega}_{HV} \\ R^{\Omega}_{VH} & R^{\Omega}_{VV} \end{bmatrix} = \begin{bmatrix} R_{HH} & R_{HV} \\ R_{VH} & R_{VV} \end{bmatrix} \begin{bmatrix} \cos(\Omega) & \sin(\Omega) \\ -\sin(\Omega) & \cos(\Omega) \end{bmatrix}$$

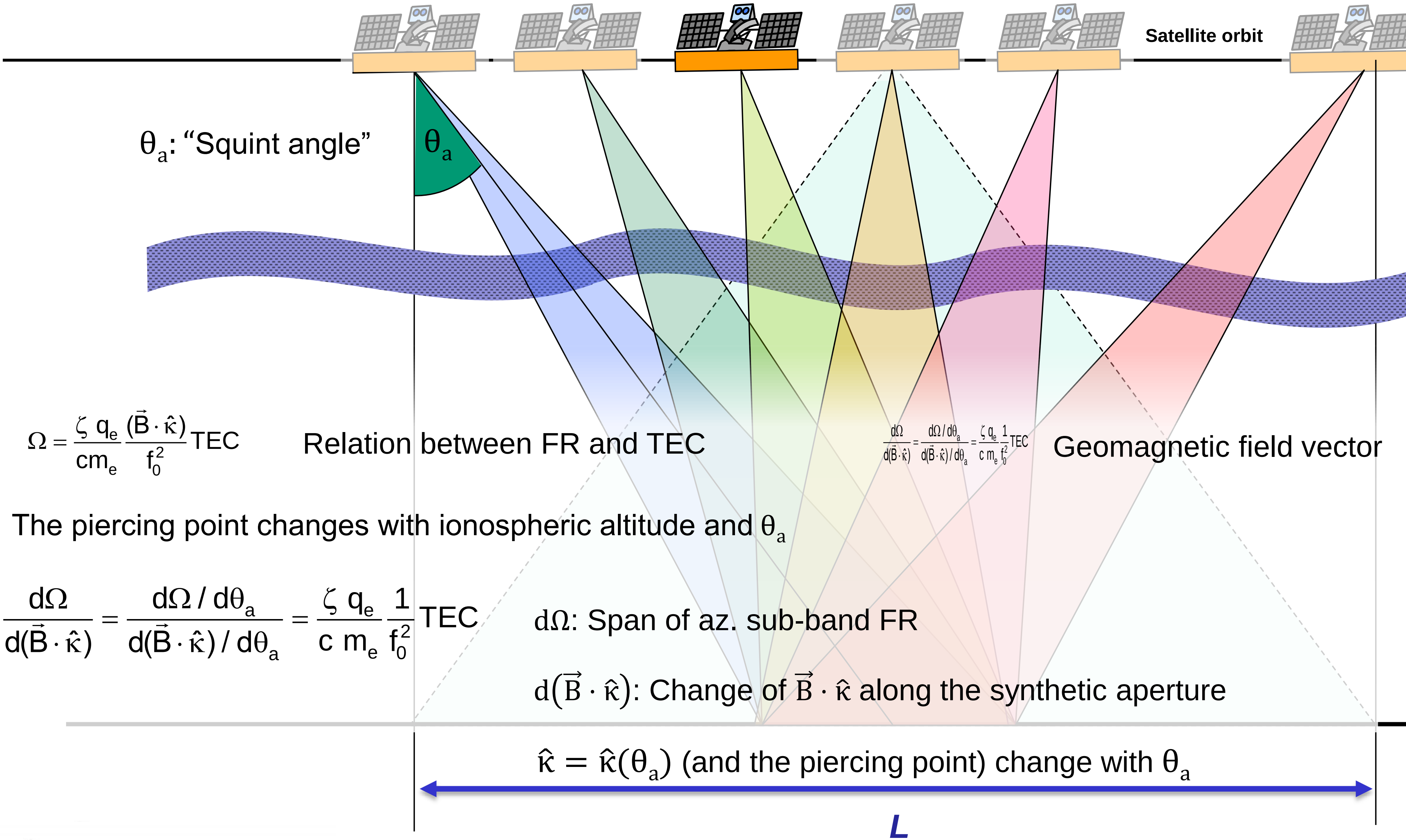
Distortion on transmit:

$$\begin{bmatrix} T^{\Omega}_{HH} & T^{\Omega}_{HV} \\ T^{\Omega}_{VH} & T^{\Omega}_{VV} \end{bmatrix} = \begin{bmatrix} \cos(\Omega) & \sin(\Omega) \\ -\sin(\Omega) & \cos(\Omega) \end{bmatrix} \begin{bmatrix} T_{HH} & T_{HV} \\ T_{VH} & T_{VV} \end{bmatrix}$$

… by exploring the variation across the synthetic aperture (i.e. across Azimuth “Looks”)



Azimuth Dependency of FR



θ_a: "Squint angle"

$$\Omega = \frac{\zeta\, q_e}{c m_e} \frac{(\vec{B} \cdot \hat{\kappa})}{f_0^2} \mathrm{TEC}$$

Relation between FR and TEC

The piercing point changes with ionospheric altitude and θ_a

$$\frac{d\Omega}{d(\vec{B} \cdot \hat{\kappa})} = \frac{d\Omega / d\theta_a}{d(\vec{B} \cdot \hat{\kappa}) / d\theta_a} = \frac{\zeta\, q_e}{c\, m_e} \frac{1}{f_0^2} \mathrm{TEC}$$

$d\Omega$: Span of az. sub-band FR

$d(\vec{B} \cdot \hat{\kappa})$: Change of $\vec{B} \cdot \hat{\kappa}$ along the synthetic aperture

$\hat{\kappa} = \hat{\kappa}(\theta_a)$ (and the piercing point) change with θ_a

Two equations for two unknowns (TEC and h_{iono})!!!

Separation of FR from X-Talk Rotation Component

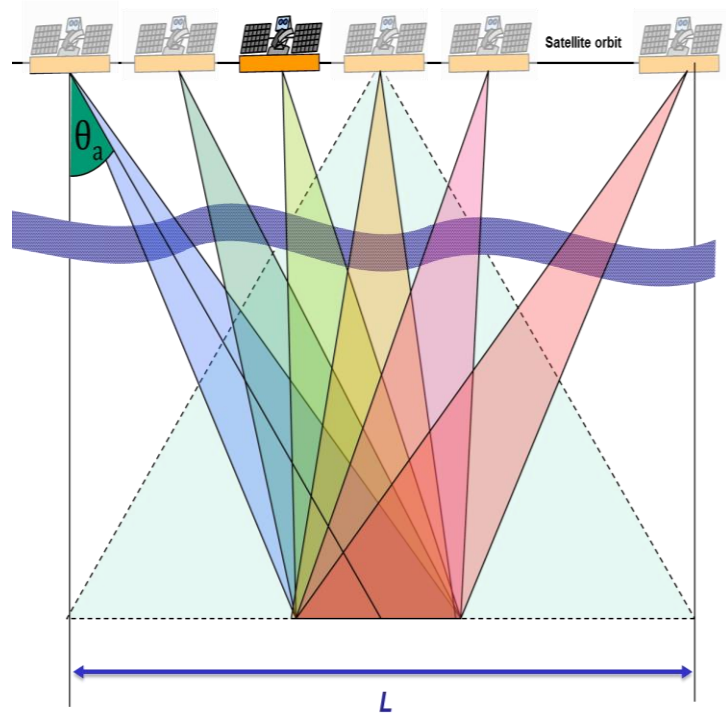
2) Exploring the difference in the azimuth dependency of the two components

Distortion on receive:

$$\begin{bmatrix} R^{\Omega}_{HH}(\theta_a) & R^{\Omega}_{HV}(\theta_a) \\ R^{\Omega}_{VH}(\theta_a) & R^{\Omega}_{VV}(\theta_a) \end{bmatrix} = \begin{bmatrix} R_{HH}(\theta_a) & R_{HV}(\theta_a) \\ R_{VH}(\theta_a) & R_{VV}(\theta_a) \end{bmatrix} \begin{bmatrix} \cos(\Omega\ (\theta_a)) & \sin(\Omega\ (\theta_a)) \\ -\sin(\Omega\ (\theta_a)) & \cos(\Omega\ (\theta_a)) \end{bmatrix}$$

Distortion on transmit:

$$\begin{bmatrix} T^{\Omega}_{HH}(\theta_a) & T^{\Omega}_{HV}(\theta_a) \\ T^{\Omega}_{VH}(\theta_a) & T^{\Omega}_{VV}(\theta_a) \end{bmatrix} = \begin{bmatrix} \cos(\Omega\ (\theta_a)) & \sin(\Omega\ (\theta_a)) \\ -\sin(\Omega\ (\theta_a)) & \cos(\Omega\ (\theta_a)) \end{bmatrix} \begin{bmatrix} T_{HH}(\theta_a) & T_{HV}(\theta_a) \\ T_{VH}(\theta_a) & T_{VV}(\theta_a) \end{bmatrix}$$



FR variation across the synthetic aperture (L):

$$\frac{d\Omega}{d(\vec{B}\cdot\hat{\kappa})} = \frac{d\Omega / d\theta_a}{d(\vec{B}\cdot\hat{\kappa}) / d\theta_a} = \frac{\zeta\ q_e}{c\ m_e}\frac{1}{f_0^2}\mathrm{TEC}$$

$d\Omega$: Span of az. sub-band FR

$d(\vec{B}\cdot\hat{\kappa})$: Change of $\vec{B}\cdot\hat{\kappa}$ along the synthetic aperture

$\hat{\kappa} = \hat{\kappa}(\theta_a)$ (and the piercing point) change with θ_a

Solving the Polarimetric System Calibration Problem cont.

Separation of FR from X-Talk Rotation by exploring the variation across the aperture (Az):

$$\begin{bmatrix} R^{\Omega}_{HH}(\theta_a) & R^{\Omega}_{HV}(\theta_a) \\ R^{\Omega}_{VH}(\theta_a) & R^{\Omega}_{VV}(\theta_a) \end{bmatrix} = \underbrace{\begin{bmatrix} R_{HH}(\theta_a) & R_{HV}(\theta_a) \\ R_{VH}(\theta_a) & R_{VV}(\theta_a) \end{bmatrix}}_{\text{Rx System Distortion}} \underbrace{\begin{bmatrix} \cos(\Omega\,(\theta_a)) & \sin(\Omega\,(\theta_a)) \\ -\sin(\Omega\,(\theta_a)) & \cos(\Omega\,(\theta_a)) \end{bmatrix}}_{\text{FR on Receive}}$$

$$\begin{bmatrix} R_{HH}(\theta_a) & R_{HV}(\theta_a) \\ R_{VH}(\theta_a) & R_{VV}(\theta_a) \end{bmatrix} = \underbrace{\begin{bmatrix} R^{I}_{HH} & R^{I}_{HV} \\ R^{I}_{VH} & R^{I}_{VV} \end{bmatrix}}_{\text{"Instrument" invariant in Az.}} \underbrace{\begin{bmatrix} R^{A}_{HH}(\theta_a) & R^{A}_{HV}(\theta_a) \\ R^{A}_{VH}(\theta_a) & R^{A}_{VV}(\theta_a) \end{bmatrix}}_{\text{"Antenna" variable in Az}}$$

Distortion on receive:

$$\begin{bmatrix} R^{\Omega}_{HH}(\theta_a) & R^{\Omega}_{HV}(\theta_a) \\ R^{\Omega}_{VH}(\theta_a) & R^{\Omega}_{VV}(\theta_a) \end{bmatrix} = \underbrace{\begin{bmatrix} R^{I}_{HH} & R^{I}_{HV} \\ R^{I}_{VH} & R^{I}_{VV} \end{bmatrix}}_{\text{"Instrument"}} \underbrace{\begin{bmatrix} R^{A}_{HH}(\theta_a) & R^{A}_{HV}(\theta_a) \\ R^{A}_{VH}(\theta_a) & R^{A}_{VV}(\theta_a) \end{bmatrix} \begin{bmatrix} \cos(\Omega\,(\theta_a)) & \sin(\Omega\,(\theta_a)) \\ -\sin(\Omega\,(\theta_a)) & \cos(\Omega\,(\theta_a)) \end{bmatrix}}_{\text{Azimuth Variant}}$$

Distortion on transmit:

$$\begin{bmatrix} T^{\Omega}_{HH}(\theta_a) & T^{\Omega}_{HV}(\theta_a) \\ T^{\Omega}_{VH}(\theta_a) & T^{\Omega}_{VV}(\theta_a) \end{bmatrix} = \underbrace{\begin{bmatrix} \cos(\Omega\,(\theta_a)) & \sin(\Omega\,(\theta_a)) \\ -\sin(\Omega\,(\theta_a)) & \cos(\Omega\,(\theta_a)) \end{bmatrix} \begin{bmatrix} T^{A}_{HH}(\theta_a) & T^{A}_{HV}(\theta_a) \\ T^{A}_{VH}(\theta_a) & T^{A}_{VV}(\theta_a) \end{bmatrix}}_{\text{Azimuth Variant}} \underbrace{\begin{bmatrix} T^{I}_{HH} & T^{I}_{HV} \\ T^{I}_{VH} & T^{I}_{VV} \end{bmatrix}}_{\text{"Instrument"}}$$

Separation of FR from X-Talk Rotation component cont.

Assumption: Antenna patterns characterise the Az. variable system term:

$$\begin{bmatrix} R_{HH}(\theta_a) & R_{HV}(\theta_a) \\ R_{VH}(\theta_a) & R_{VV}(\theta_a) \end{bmatrix} = \underbrace{\begin{bmatrix} R^I_{HH} & R^I_{HV} \\ R^I_{VH} & R^I_{VV} \end{bmatrix}}_{\text{"Instrument" invariant in Az.}} \underbrace{\begin{bmatrix} R^A_{HH}(\theta_a) & R^A_{HV}(\theta_a) \\ R^A_{VH}(\theta_a) & R^A_{VV}(\theta_a) \end{bmatrix}}_{\text{"Antenna" variable in Az}}$$

FR variation across the synthetic aperture (L):

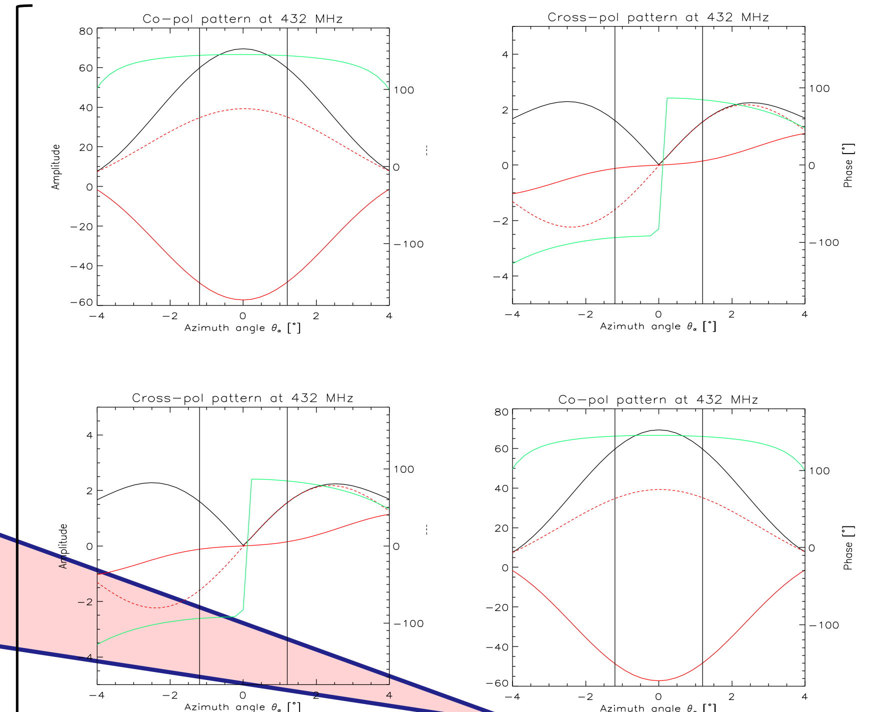
$$\frac{d\Omega}{d(\vec{B}\cdot\hat{\kappa})} = \frac{d\Omega / d\theta_a}{d(\vec{B}\cdot\hat{\kappa}) / d\theta_a} = \frac{\zeta\, q_e}{c\, m_e} \frac{1}{f_0^2} TEC$$

$d\Omega$: Span of az. sub-band FR

$d(\vec{B}\cdot\hat{\kappa})$: Change of $\vec{B}\cdot\hat{\kappa}$ along the synthetic aperture

$\hat{\kappa} = \hat{\kappa}(\theta_a)$ (and the piercing point) change with θ_a

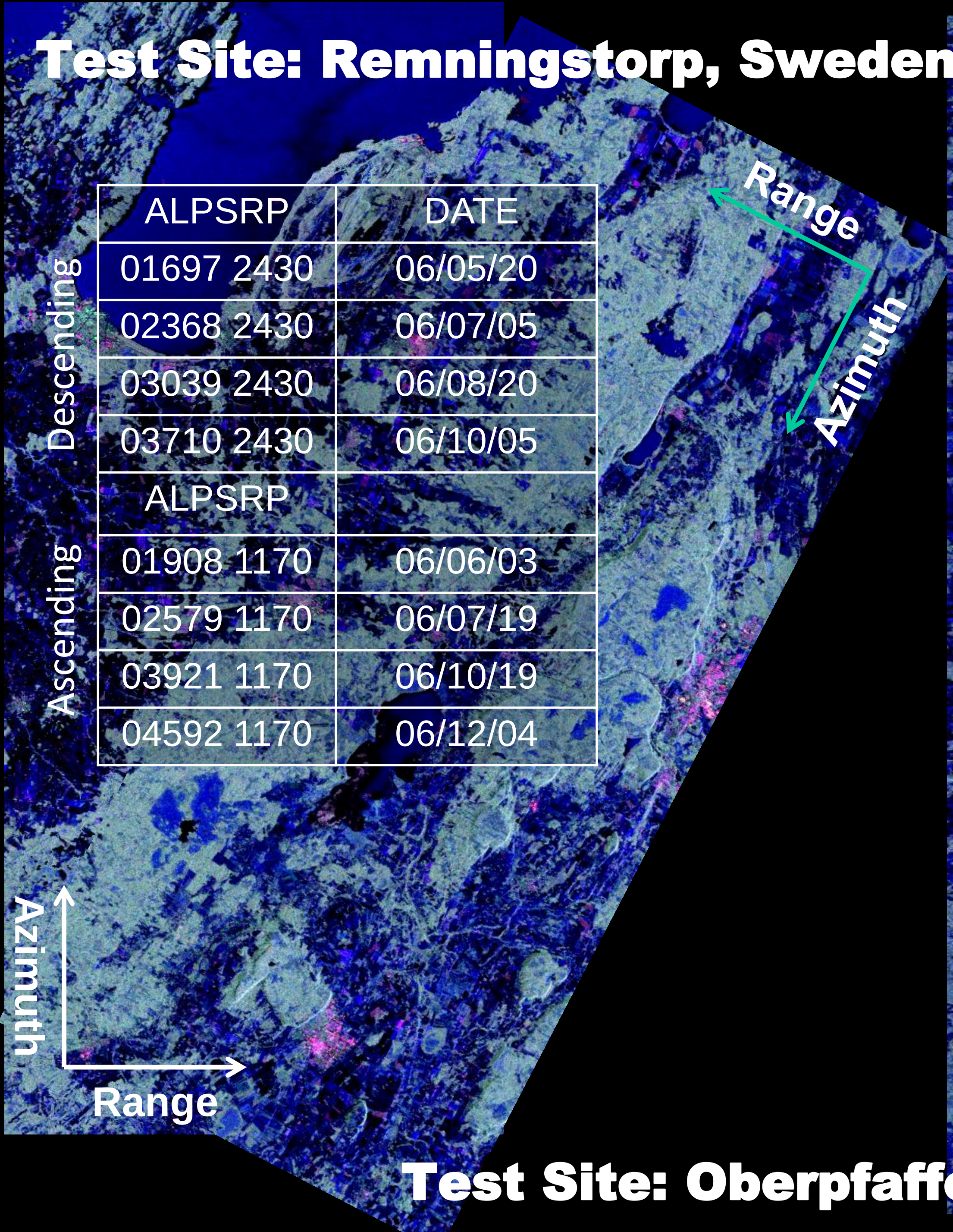
$$\begin{bmatrix} R^A_{HH}(\theta_a) & R^A_{HV}(\theta_a) \\ R^A_{VH}(\theta_a) & R^A_{VV}(\theta_a) \end{bmatrix} =$$



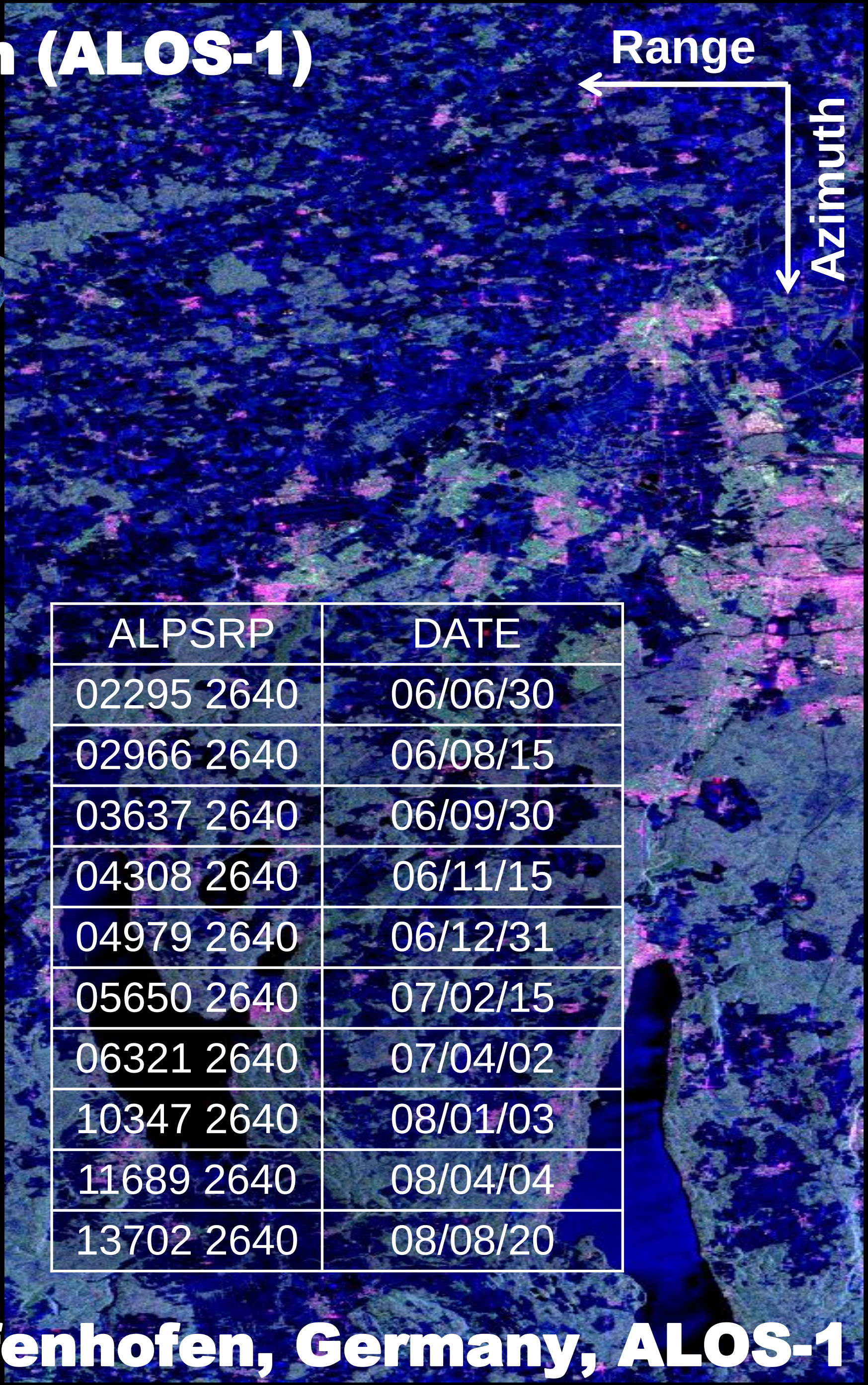
Distortion on receive:

$$\begin{bmatrix} R^\Omega_{HH}(\theta_a) & R^\Omega_{HV}(\theta_a) \\ R^\Omega_{VH}(\theta_a) & R^\Omega_{VV}(\theta_a) \end{bmatrix} = \begin{bmatrix} R^I_{HH} & R^I_{HV} \\ R^I_{VH} & R^I_{VV} \end{bmatrix} \underbrace{\begin{bmatrix} R^A_{HH}(\theta_a) & R^A_{HV}(\theta_a) \\ R^A_{VH}(\theta_a) & R^A_{VV}(\theta_a) \end{bmatrix} \begin{bmatrix} \cos(\Omega\,(\theta_a)) & \sin(\Omega\,(\theta_a)) \\ -\sin(\Omega\,(\theta_a)) & \cos(\Omega\,(\theta_a)) \end{bmatrix}}_{\text{Azimuth Variant}}$$

Test Site: Remningstorp, Sweden (ALOS-1)

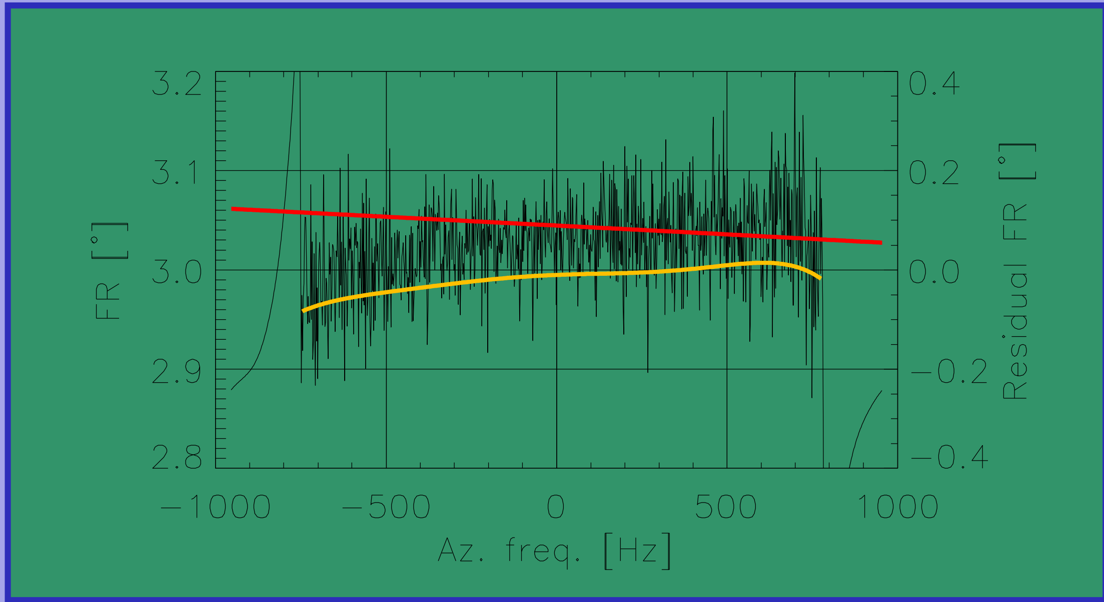


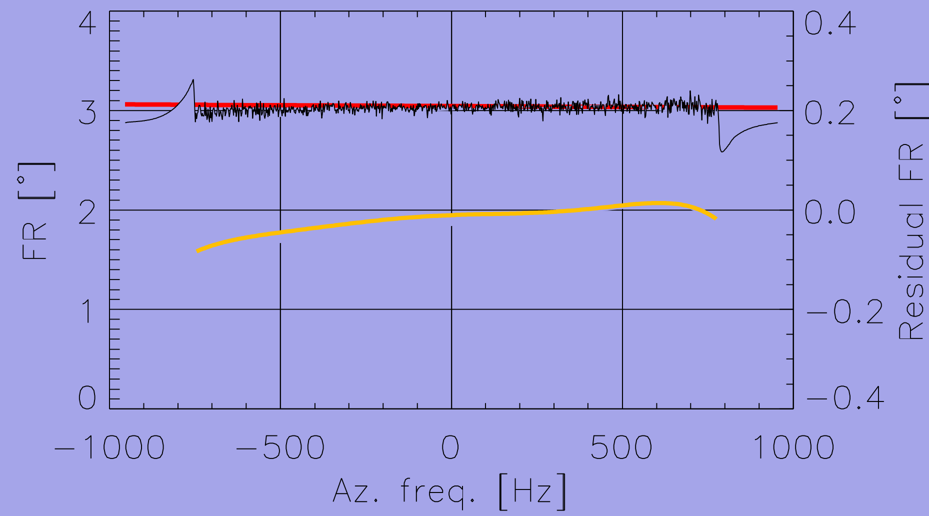
	ALPSRP	DATE
Descending	01697 2430	06/05/20
	02368 2430	06/07/05
	03039 2430	06/08/20
	03710 2430	06/10/05
	ALPSRP	
Ascending	01908 1170	06/06/03
	02579 1170	06/07/19
	03921 1170	06/10/19
	04592 1170	06/12/04

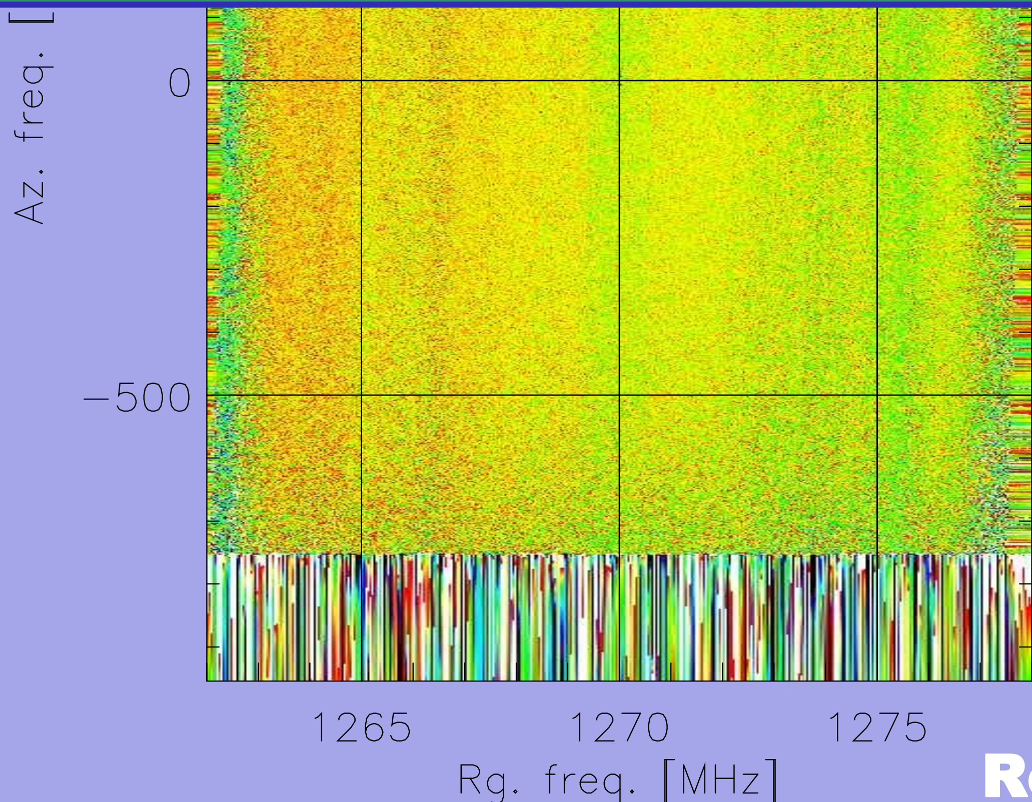


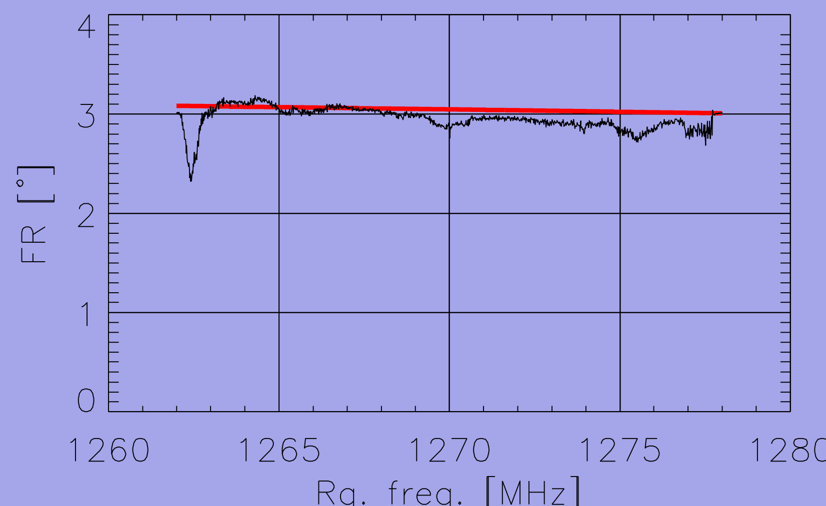
ALPSRP	DATE
02295 2640	06/06/30
02966 2640	06/08/15
03637 2640	06/09/30
04308 2640	06/11/15
04979 2640	06/12/31
05650 2640	07/02/15
06321 2640	07/04/02
10347 2640	08/01/03
11689 2640	08/04/04
13702 2640	08/08/20

Test Site: Oberpfaffenhofen, Germany, ALOS-1



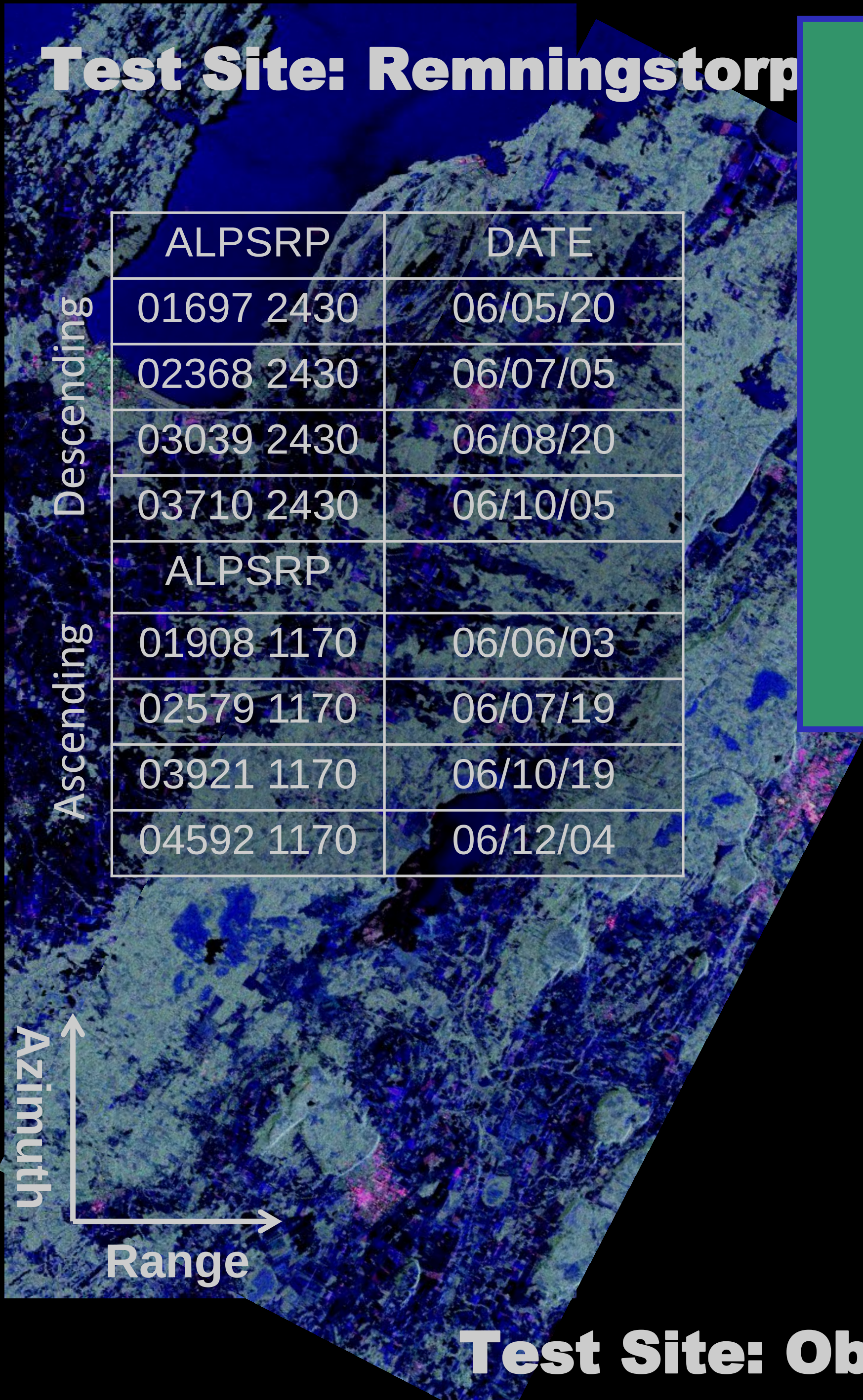




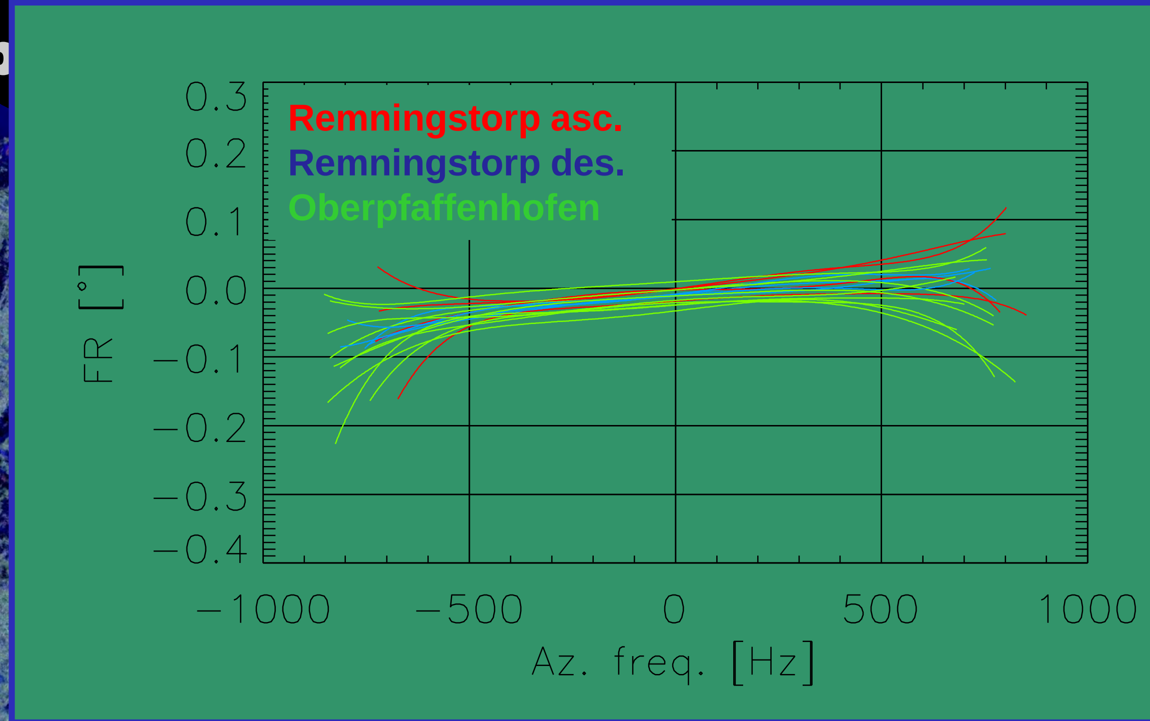


Remningstorp, Sweden (ALOS-1)

Test Site: Remningstorp



	ALPSRP	DATE
Descending	01697 2430	06/05/20
	02368 2430	06/07/05
	03039 2430	06/08/20
	03710 2430	06/10/05
	ALPSRP	
Ascending	01908 1170	06/06/03
	02579 1170	06/07/19
	03921 1170	06/10/19
	04592 1170	06/12/04

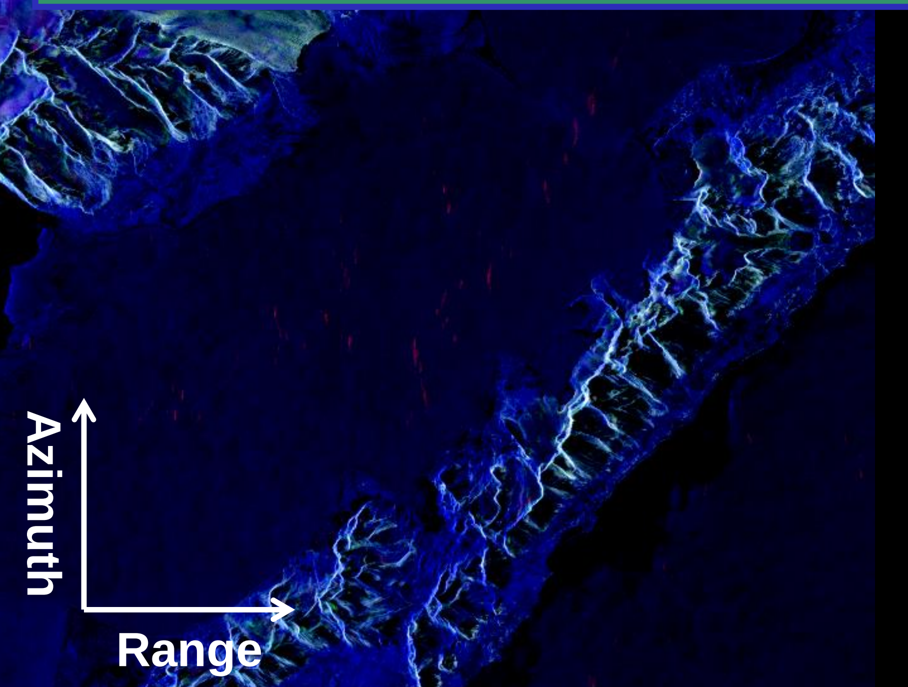


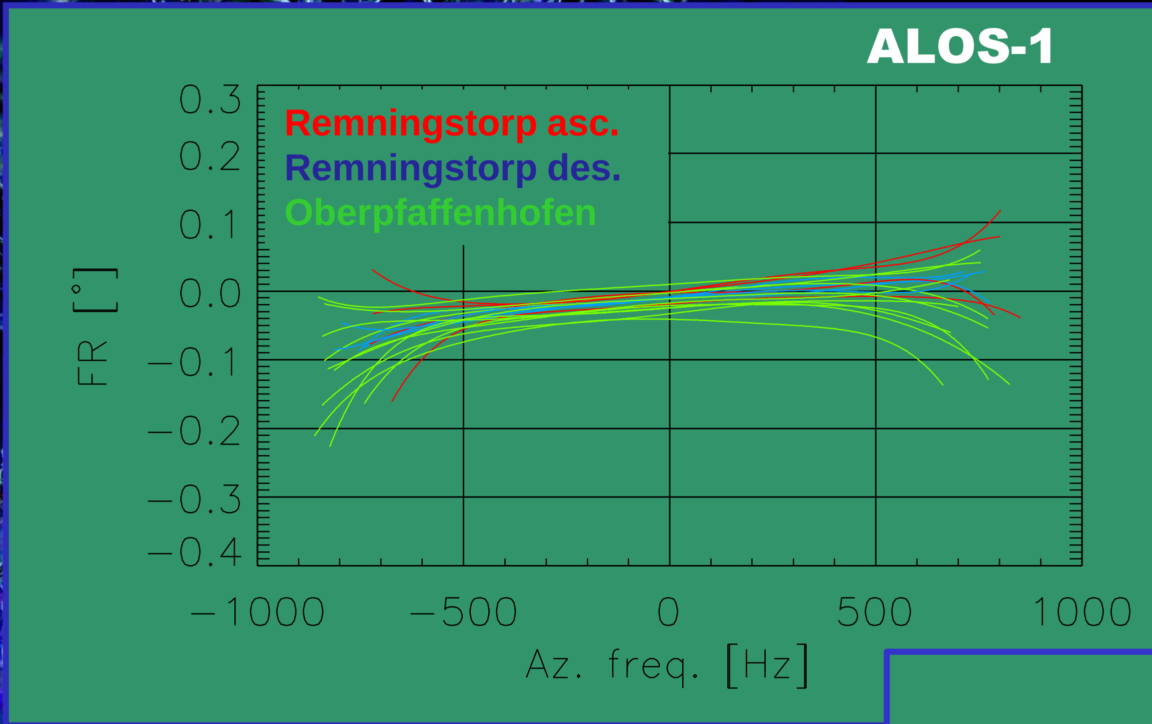
02966 2640	06/08/15
03637 2640	06/09/30
04308 2640	06/11/15
04979 2640	06/12/31
05650 2640	07/02/15
06321 2640	07/04/02
10347 2640	08/01/03
11689 2640	08/04/04
13702 2640	08/08/20

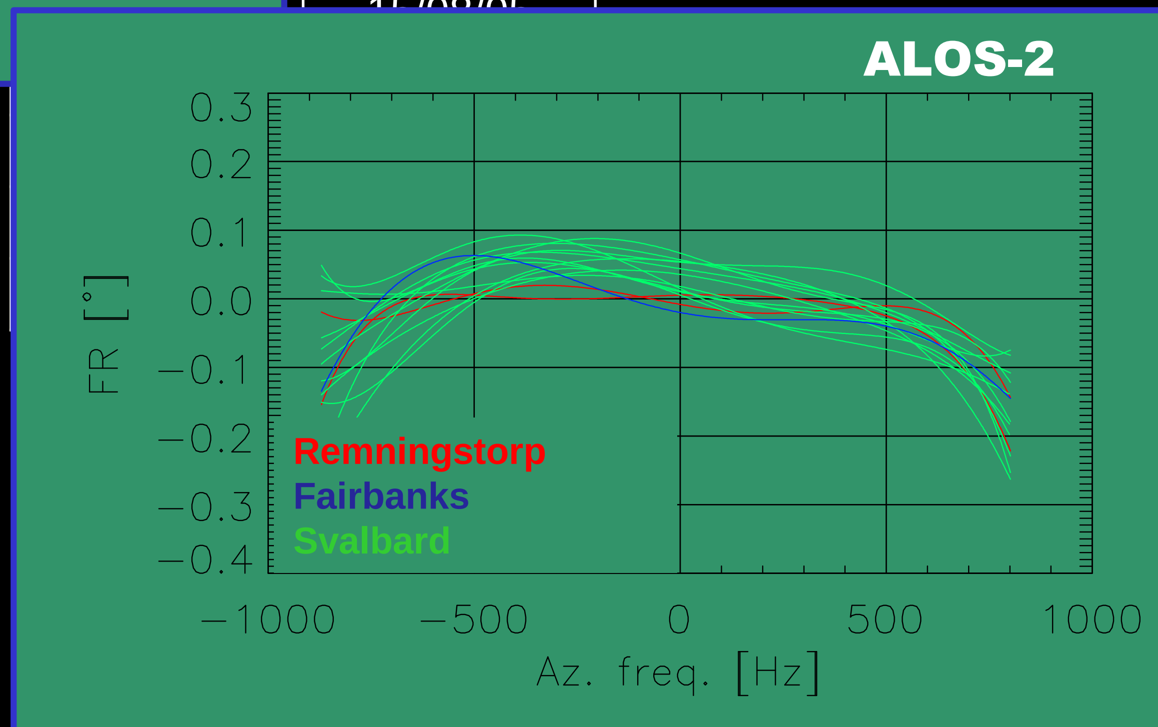
Test Site: Oberpfaffenhofen, Germany, ALOS-1

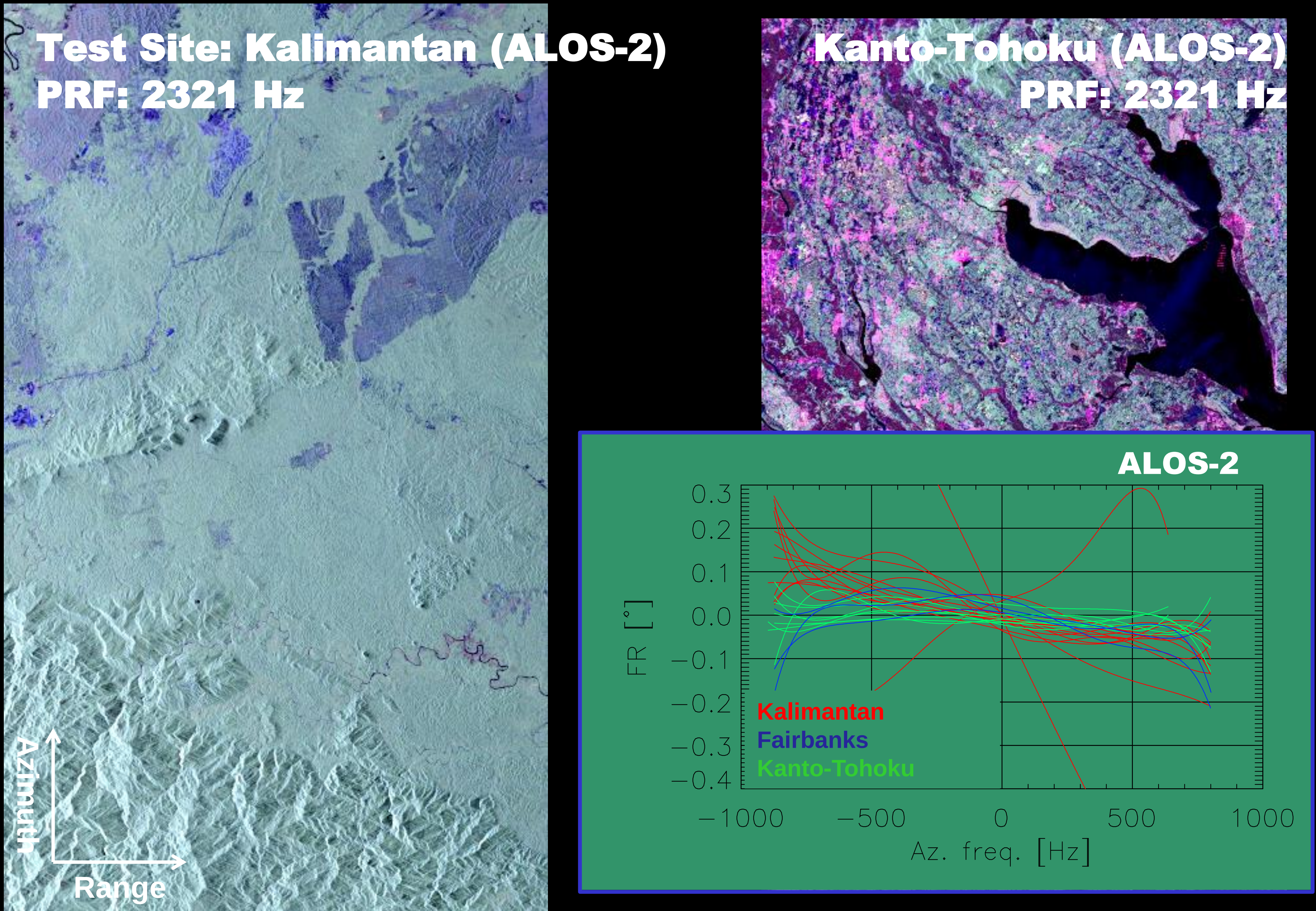
Svalbard, Norway (ALOS-2)
PRF: 2261 Hz

DATE
14/12/24
15/03/04
15/04/15
15/05/13
15/06/10
15/07/08



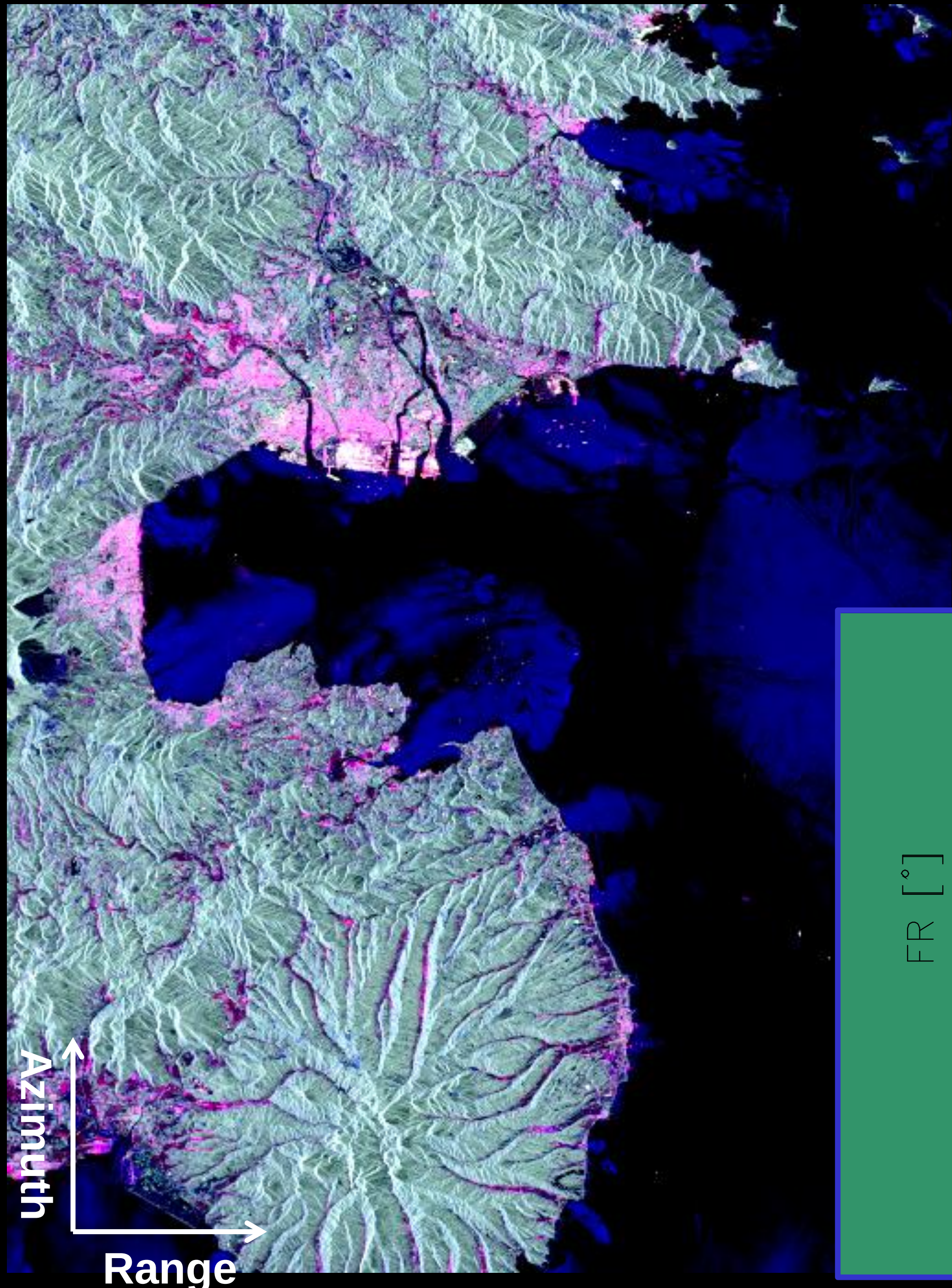


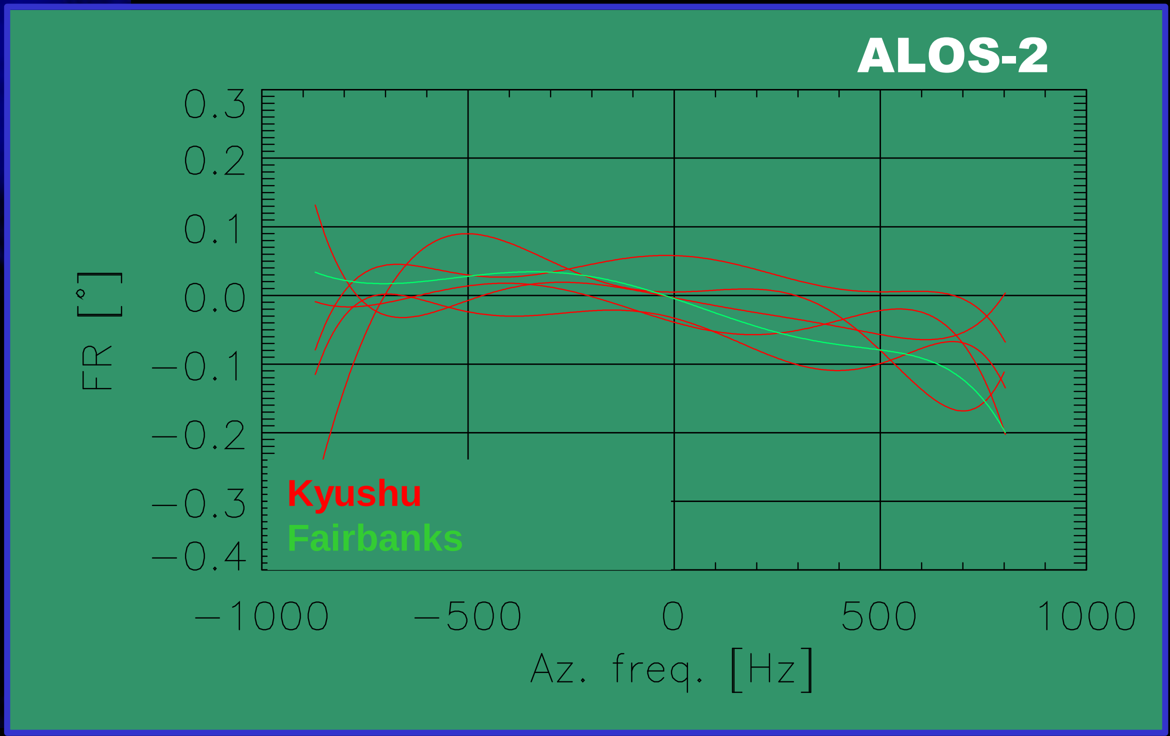




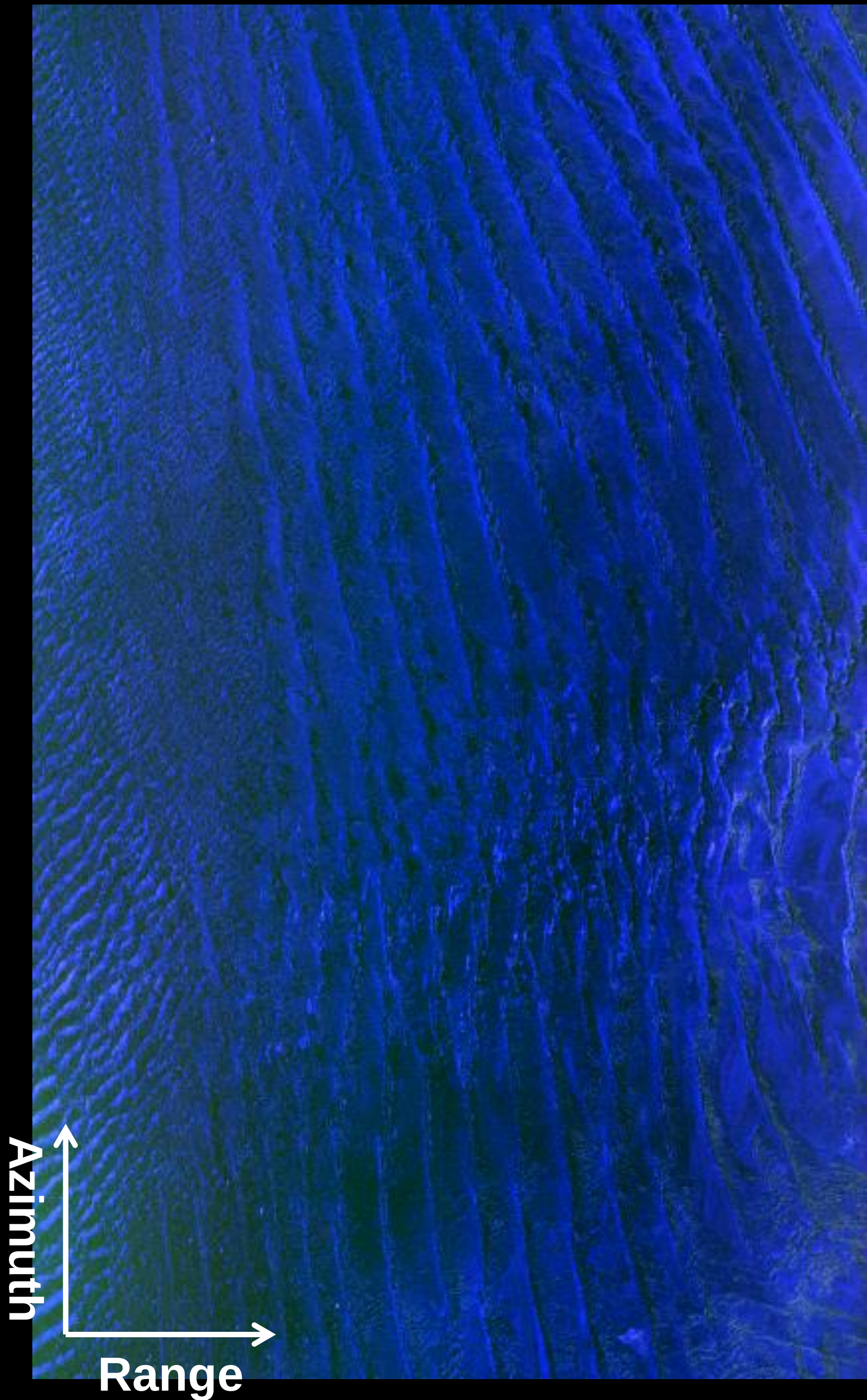
Test Site: Kalimantan (ALOS-2)
PRF: 2321 Hz
Kanto-Tohoku (ALOS-2)
PRF: 2321 Hz
Azimuth
Range
ALOS-2
FR [°]
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
−1000
−500
0
500
1000
Az. freq. [Hz]
Kalimantan
Fairbanks
Kanto-Tohoku

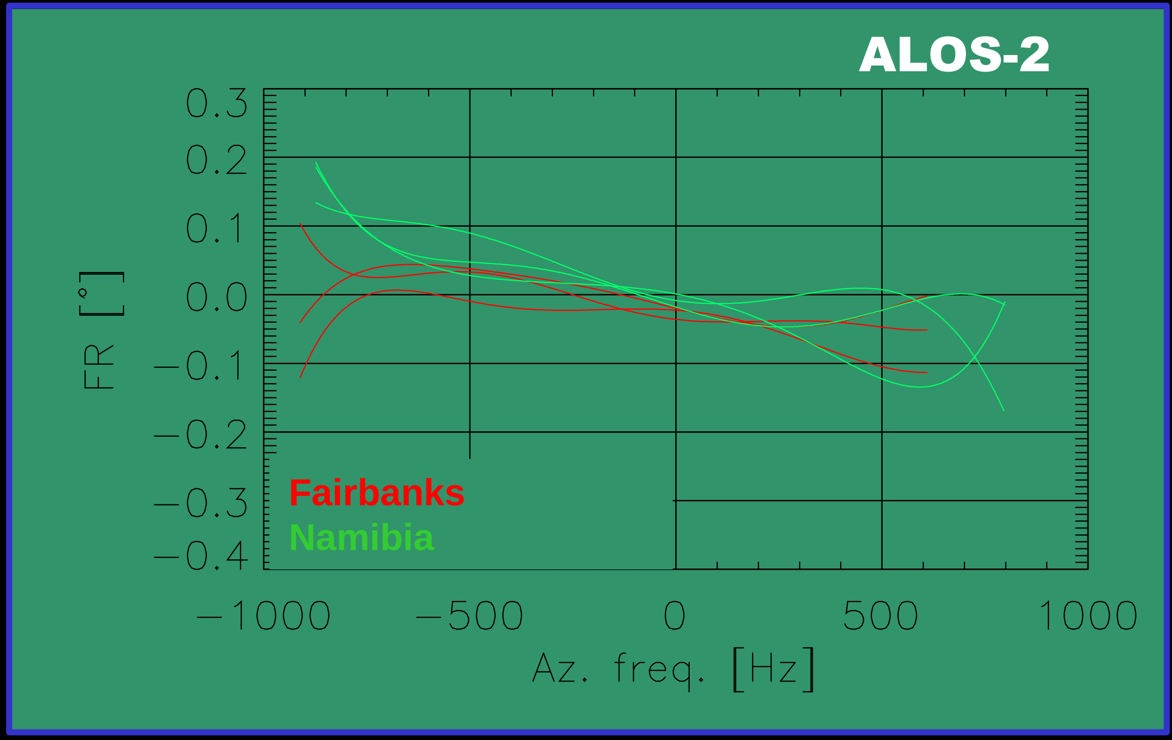
Test Site: Kyushu (ALOS-2)
PRF: 2610 Hz





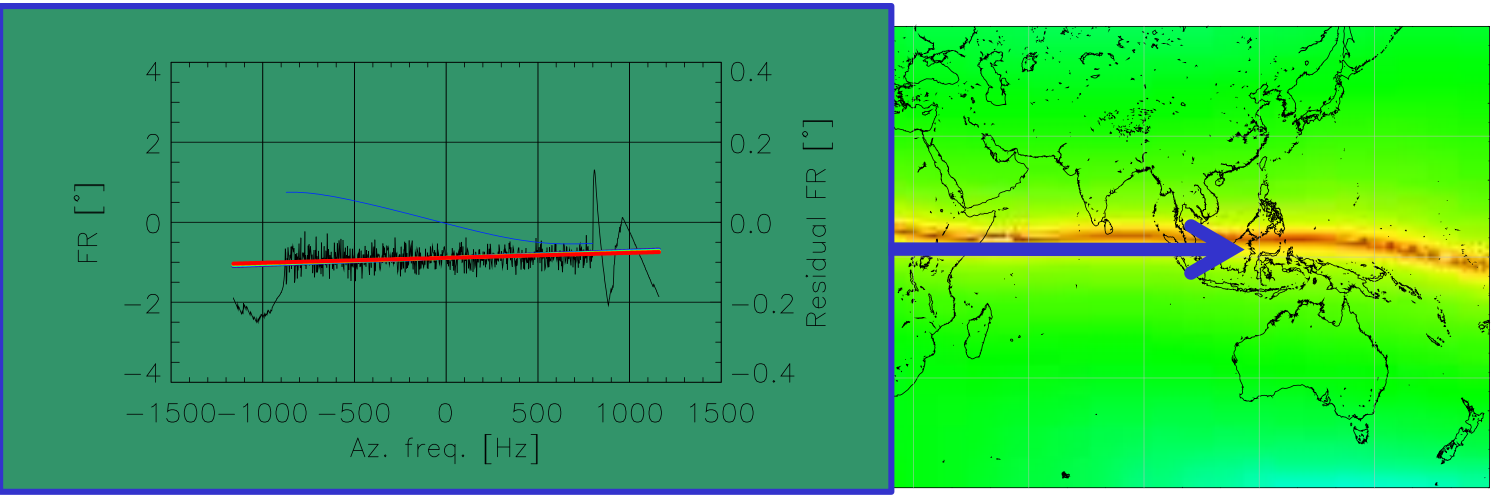
Test Site: Namibia (ALOS-2)
PRF: 2596 Hz





Dependencies on Model Height

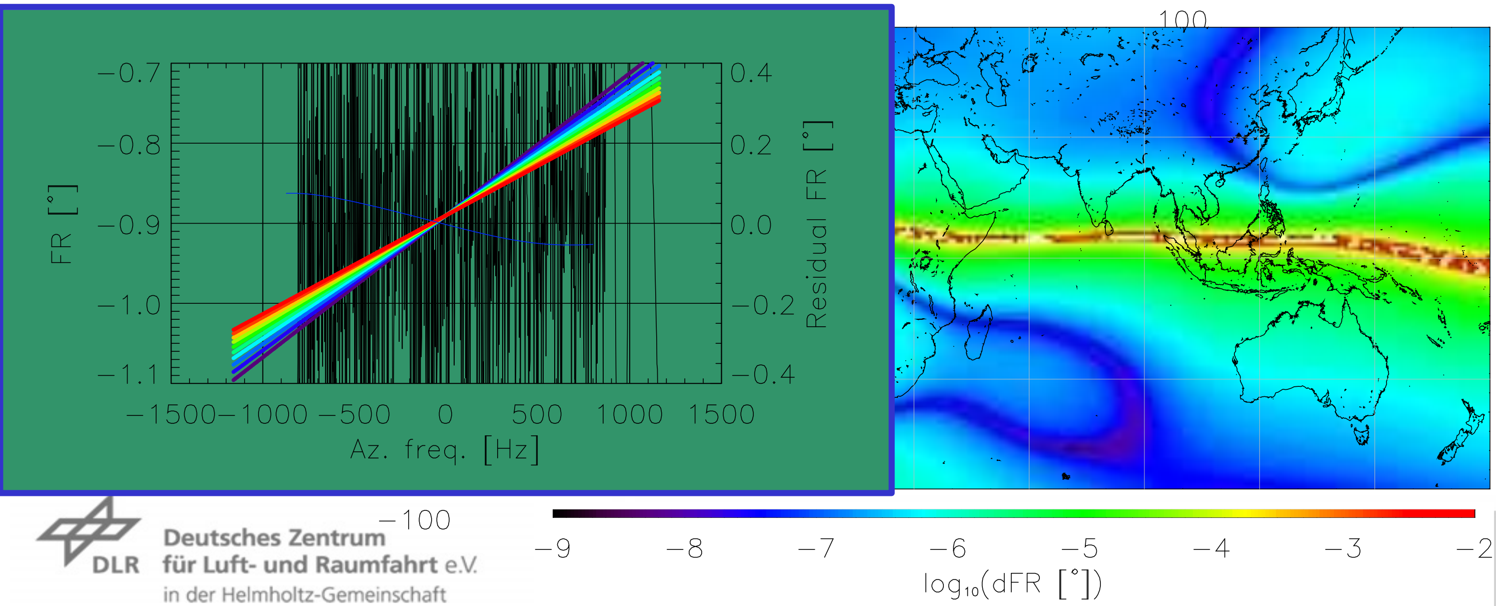
- The squint dependency of FR is a function of (geomagnetic) latitude, and altitude



Azimuth dependent FR at extrema of bandwidth (@ 300 km alt.)

$$\frac{d\Omega}{d\beta}\cdot\frac{\beta_0}{2}$$

(β_0: beam width)

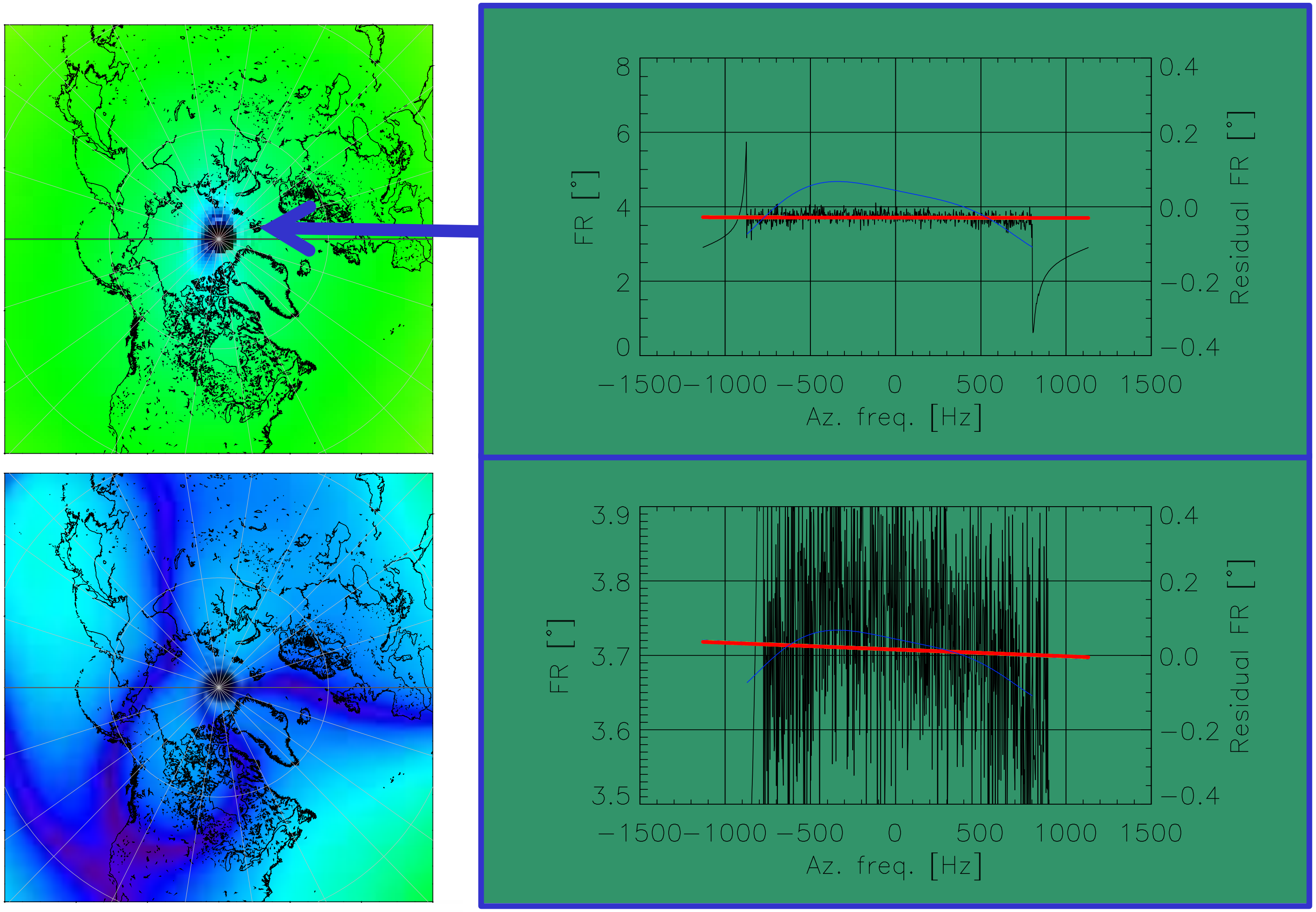


Span of residual FR at extrema of bandwidth for altitude change

$$\max\left(\frac{d\Omega}{d\beta}\cdot\frac{\beta_0}{2}\right)-\min\left(\frac{d\Omega}{d\beta}\cdot\frac{\beta_0}{2}\right)$$

Dependencies on Height

- The squint dependency of FR is a function of (geomagnetic) latitude, and altitude



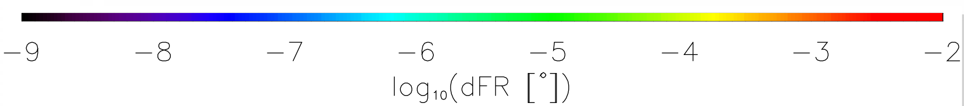
Azimuth dependent FR at extrema of bandwidth

$$\frac{d\Omega}{d\beta} \cdot \frac{\beta_0}{2}$$

(β_0: beam width)

Span of residual FR at extrema of bandwidth for altitude change

$$\max\left(\frac{d\Omega}{d\beta} \cdot \frac{\beta_0}{2}\right) - \min\left(\frac{d\Omega}{d\beta} \cdot \frac{\beta_0}{2}\right)$$

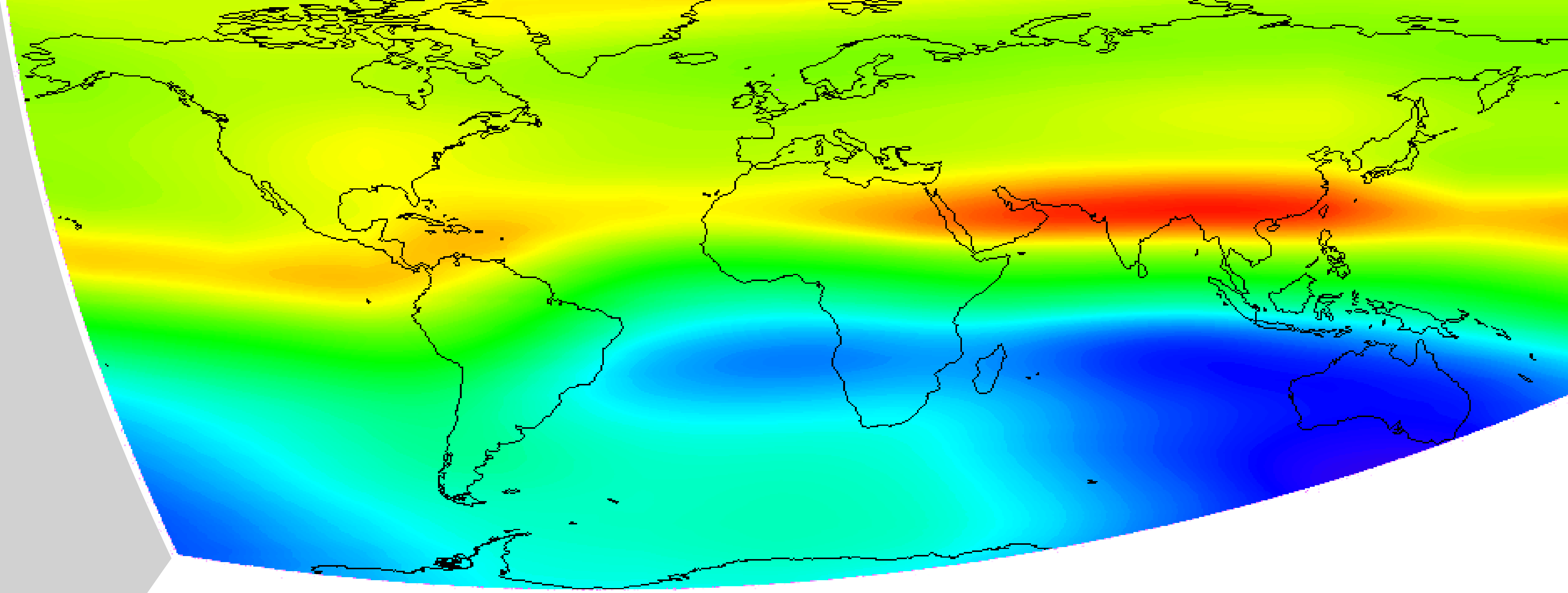


Conclusions

- There is an **inherent ambiguity** between FR distortion and the rotation component of the system distortion (x-talk);
- The azimuth variation of the FR provides a way to separate the FR distortion from system induced distortion for the calibration of spaceborne polarimetric data
- Determination of the azimuth dependency of FR relies on mean FR estimates and $\vec{B} \cdot \hat{\kappa}$.
- At low latitudes $\vec{B} \cdot \hat{\kappa}$ becomes too sensitive with respect to the ionospheric height assumption.
- The proposed algorithm relaxes significantly the constrains imposed by conventional polarimetric calibration approaches in the sense that:

  1) there are no calibration devices (i.e. reflectors, transponders, etc.) required at the geomagnetic equator but they can still be located in areas where **B·k=0;**

  2) it allows the estimation of X-Talk levels from each single scene and not only where **B·k=0** is fulfilled.
- Performance analysis (e.g. investigating scene-dependent deviation, etc.) to be done.



Polarimetric Calibration of Spaceborne SAR Data in the Presence of the Ionosphere by Means of Azimuth Sub-bands

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