Calibration of Dual-Pol SAR data: a possible approach for Sentinel-1

Marco Lavalle[1-3], B. Rosich[3] , T. Ainsworth[4], E. Pottier [2], D. Solimini[1]

[1]DISP, Tor Vergata University, Rome, Italy

[2] IETR UMR CNRS 6164, University of Rennes 1, Rennes, France

[3]European Space Agency, ESA-ESRIN, Frascati, Italy

[4]Naval Research Laboratory, Remote Sensing Division, Washington D. C. 20375

PolInSAR Workshop 26-31 Jan 2008

Outline

- Introduction: ESA Sentinel-1 C-band SAR
- Dual-pol radiometric calibration
  - Dual-pol distortion model
  - Response of passive calibration targets
  - Estimation of polarimetric distortion parameters
- Performance using Sentinel-1 system parameters
  - Performance results
  - Design and location of calibration targets
- Conclusions

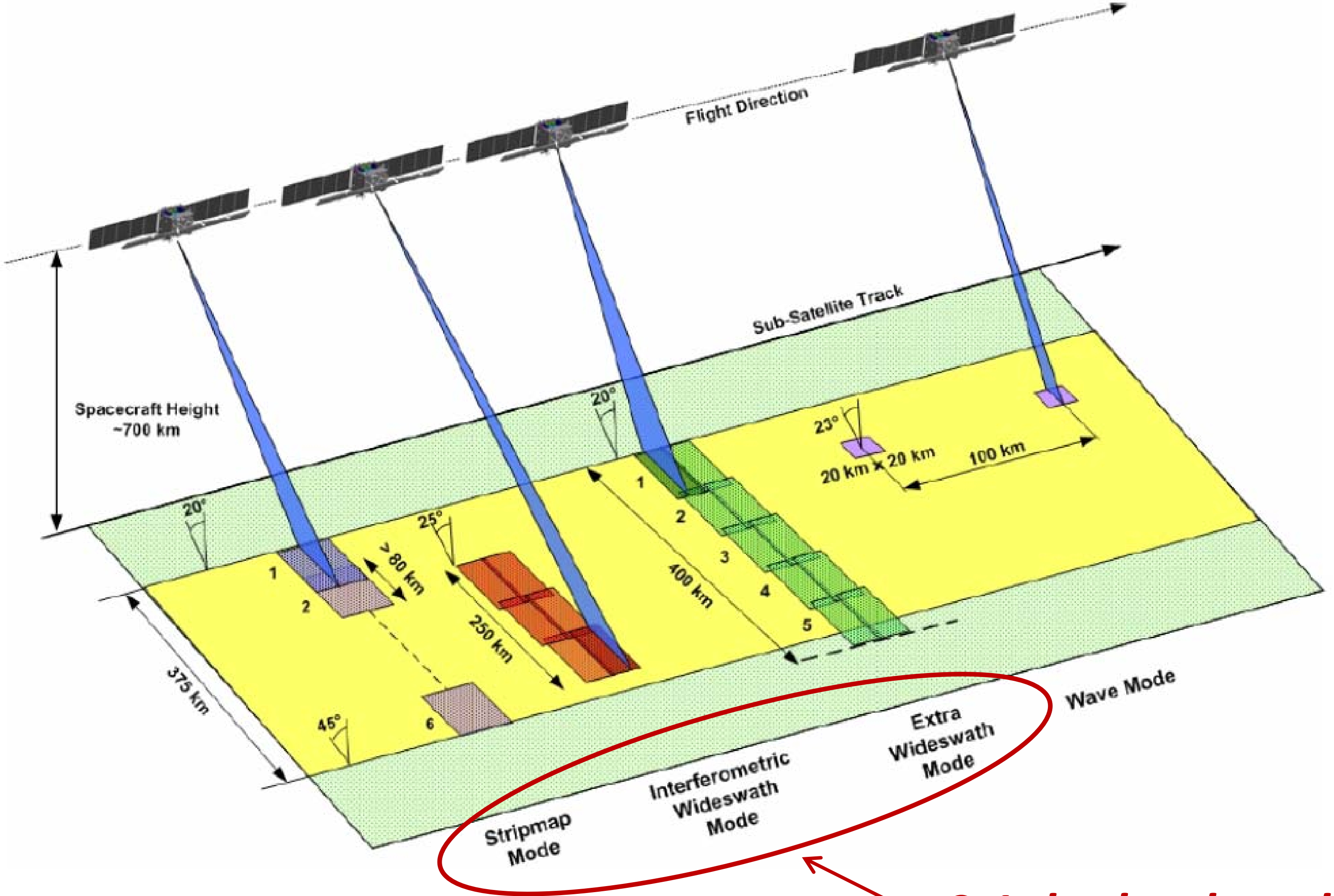
Sentinel-1 C-band SAR

Key parameters

Parameter	Value
Revisit time	12 days
Center frequency	5.405 GHz
Bandwidth	< 100 MHz
Polarization	HH/HV – VV/VH
Antenna azimuth size	12.4 m
Antenna elevation size	0.821 m
Spatial resolution	> 5 m
Pulse width	< 100 us
PRF	1000-3000 Hz

Sentinel-1 C-band SAR

Dual Polarimetric modes

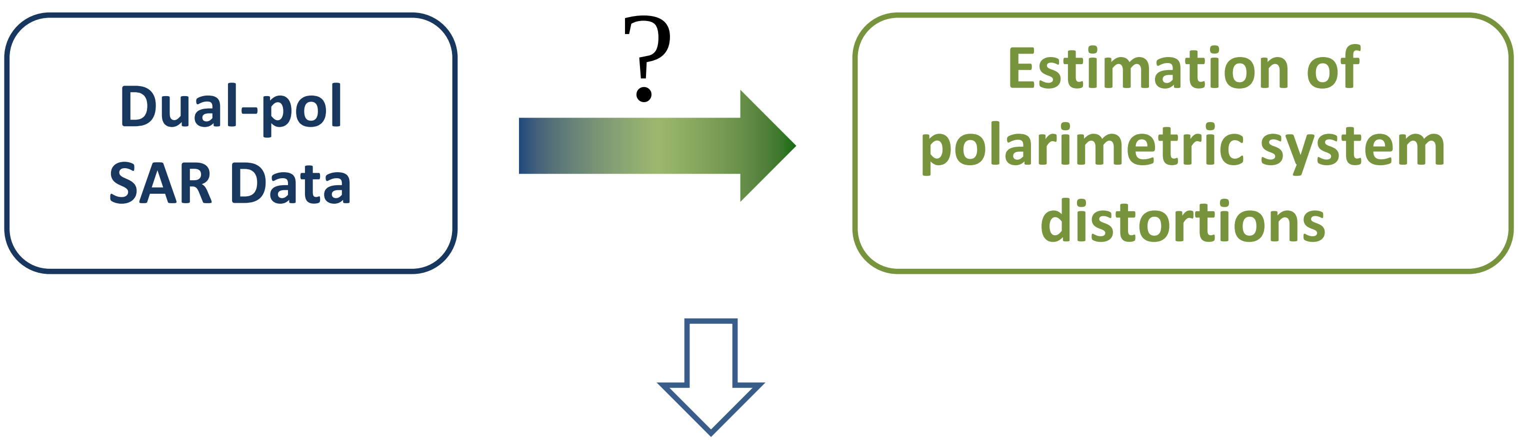


S-1 dual-pol modes

Objective

To provide a polarimetric calibration procedure of dual-pol data

- *when the SAR does not operate the full-pol mode*
- *using passive calibration targets*



1. *Dual-pol distortion model*
2. *Response of some calibration targets*
3. *Performance according S-1 system parameters*

Full-Pol Distortion Model

Transmitted and received field

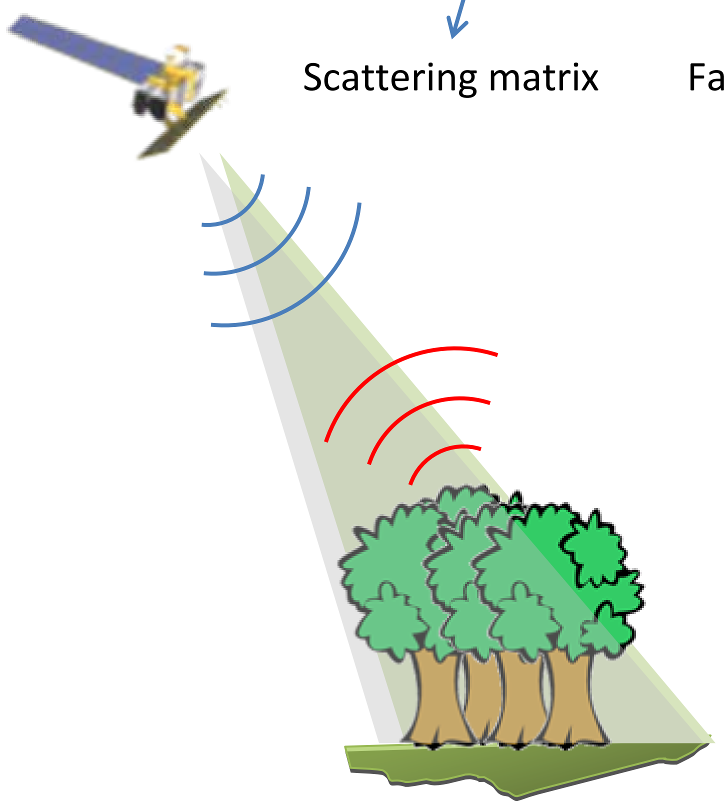
$$\begin{pmatrix} \mathbf{E}_h^r \\ \mathbf{E}_v^r \end{pmatrix} = Ae^{j\phi} \begin{pmatrix} 1 & \delta_2 \\ \delta_1 & f_1 \end{pmatrix} \begin{pmatrix} \cos\Omega & \sin\Omega \\ -\sin\Omega & \cos\Omega \end{pmatrix} \begin{pmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{pmatrix} \begin{pmatrix} \cos\Omega & \sin\Omega \\ -\sin\Omega & \cos\Omega \end{pmatrix} \begin{pmatrix} 1 & \delta_3 \\ \delta_4 & f_2 \end{pmatrix} \begin{pmatrix} \mathbf{E}_h^t \\ \mathbf{E}_v^t \end{pmatrix}$$

Distortion Rx

Scattering matrix

Faraday rotation

Distortion Tx



Full-Pol Distortion Model

Distortion parameters

$$\begin{pmatrix} M_{HH} & M_{HV} \\ M_{VH} & M_{VV} \end{pmatrix} = Ae^{j\phi} \begin{pmatrix} 1 & \delta_2 \\ \delta_1 & f_1 \end{pmatrix} \begin{pmatrix} \cos\Omega & \sin\Omega \\ -\sin\Omega & \cos\Omega \end{pmatrix} \begin{pmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{pmatrix} \begin{pmatrix} \cos\Omega & \sin\Omega \\ -\sin\Omega & \cos\Omega \end{pmatrix} \begin{pmatrix} 1 & \delta_3 \\ \delta_4 & f_2 \end{pmatrix} + \begin{pmatrix} N_{HH} & N_{HV} \\ N_{VH} & N_{VV} \end{pmatrix}$$

→ System distortion parameters

- → X-talk: $\delta_1, \delta_2, \delta_3, \delta_4$
- → Channel imbalance: f_1, f_2

} 6 system distortion parameters

→ Calibration matrices can be estimated using distributed target

- → Target reciprocity: $S_{ij} = S_{ji}$
- → Reflection symmetry: $\langle S_{ii} S_{ij}^* \rangle = 0$
- → Known HH-VV phase difference (eg. surface scattering = 0)

Dual-Pol Distortion Model

→ Dual-pol model = (Full-pol model) x $(1 \quad 0)^T$

→ Case of H-transmission

$$\begin{pmatrix} M_{HH} \\ M_{VH} \end{pmatrix} = Ae^{j\phi} \begin{pmatrix} 1 & \delta_2 \\ \delta_1 & f \end{pmatrix} \begin{pmatrix} \cos\Omega & \sin\Omega \\ -\sin\Omega & \cos\Omega \end{pmatrix} \begin{pmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{pmatrix} \begin{pmatrix} \cos\Omega & \sin\Omega \\ -\sin\Omega & \cos\Omega \end{pmatrix} \begin{pmatrix} 1 \\ \delta_3 \end{pmatrix}$$

Cross-talk: $\delta_1, \delta_2, \delta_3$

Channel imbalance: f

} 4 system distortion parameters

→ The receiving distortion matrix is the same as in full-pol mode (e.g. HH/HV)

Dual-Pol Distortion Model

Azimuthally distributed target

→ Measured scattering elements (assuming reciprocity and zero FR)

$$M_{HH} = S_{HH} + (\delta_2 + \delta_3) S_{VH} + \delta_2 \delta_3 S_{VV}$$
$$M_{VH} = \delta_1 S_{HH} + (\delta_1 \delta_3 + f) S_{VH} + f \delta_3 S_{VV}$$

Dual-Pol Distortion Model

Azimuthally distributed target

→ Measured scattering elements (assuming reciprocity and zero FR)

$$M_{HH} = S_{HH} + (\delta_2 + \delta_3) S_{VH} + \delta_2 \delta_3 S_{VV}$$
$$M_{VH} = \delta_1 S_{HH} + (\delta_1 \delta_3 + f) S_{VH} + f \delta_3 S_{VV}$$

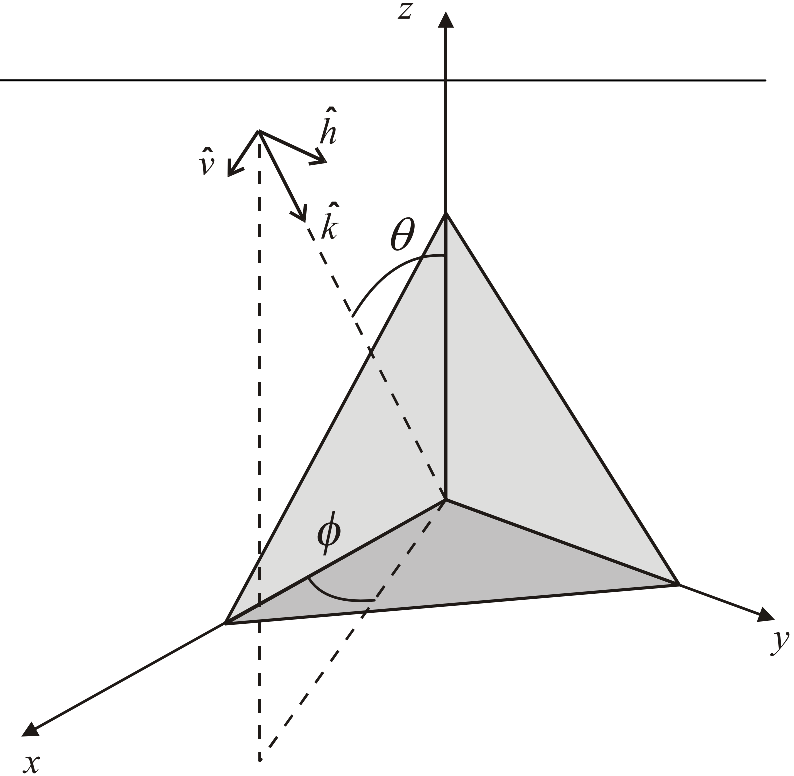
→ Observed covariance elements (assuming azimuthal symmetry)

$$O_{11} \cong |S_{HH}|^2$$
$$O_{12} \cong (\delta_1^* + f^* \delta_3^*) |S_{HH}|^2 + (f^* \delta_2 + f^* \delta_3 - 2 f^* \delta_3^*) |S_{VH}|^2$$
$$O_{22} \cong |f^2| |S_{VV}|^2$$

$$|f^2| \delta_3^* O_{11} + f (\delta_1^* O_{11} - O_{12}) + (\delta_2 + \delta_3 - 2\delta_3^*) O_{22} = 0 \quad (1)$$

We need 3 additional equations

Trihedral



→ Ideal response

$$[S_t] = A_t(\theta,\phi)e^{j\phi_t(\theta,\phi)}\begin{pmatrix}1 & 0\\ 0 & 1\end{pmatrix}$$

→ Measured response in the dual-pol mode

$\delta_2, \delta_3 << 1$

$$M_{HH}^t = A_{cf}A_t e^{j\phi_t}(1+\delta_2\delta_3) \cong A_{cf}A_t e^{j\phi_t} \longrightarrow A_{cf} = \frac{M_{VH}^t}{A_t e^{j\phi_t}}$$

Absolute calibration factor

$$M_{VH}^t = A_{cf}A_t e^{j\phi_t}(\delta_1 + f\delta_3) \longrightarrow \tilde{M}_{VH}^t = \delta_1 + f\delta_3$$

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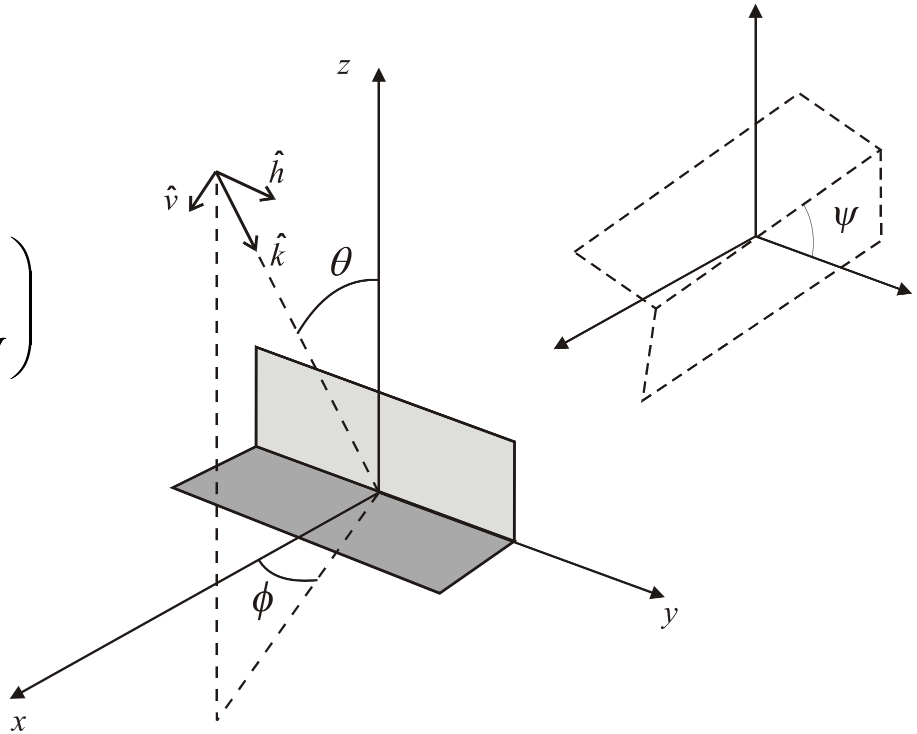
Oriented Dihedral

→ Ideal response

$$[S_d] = A_d(\theta,\phi) e^{j\phi_d(\theta,\phi)} \begin{pmatrix} \cos 2\psi & \sin 2\psi \\ \sin 2\psi & -\cos 2\psi \end{pmatrix}$$



→ Dihedral oriented at 45 deg

$$[S_d]_{\psi=\pi/4} = A_d e^{j\phi_d} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

→ Measured response using the dual-pol model

$$\tilde{M}^d_{HH} = \delta_2 + \delta_3$$ (3)

$$\tilde{M}^d_{VH} = \delta_1\delta_3 + f \cong f$$ (4)

Estimation of distortion parameters

First approach

→ Distributed target + trihedral + 45-dihedral

→ Combining the four equations the solution is unique

{ 1, 2, 3, 4 } ⇒ Estimation of distortion parameters from dual-pol data

→ Dual-pol distortion parameters

$$f = \tilde{M}^{d}_{VH}$$

$$\delta_1 = \tilde{M}^{t}_{VH} - \tilde{M}^{d}_{VH} \frac{\tilde{M}^{d*}_{VH}\tilde{M}^{t*}_{VH}O^{*}_{11} + \tilde{M}^{d*}_{HH}O^{*}_{22} - O^{*}_{12}}{2O^{*}_{22}}$$

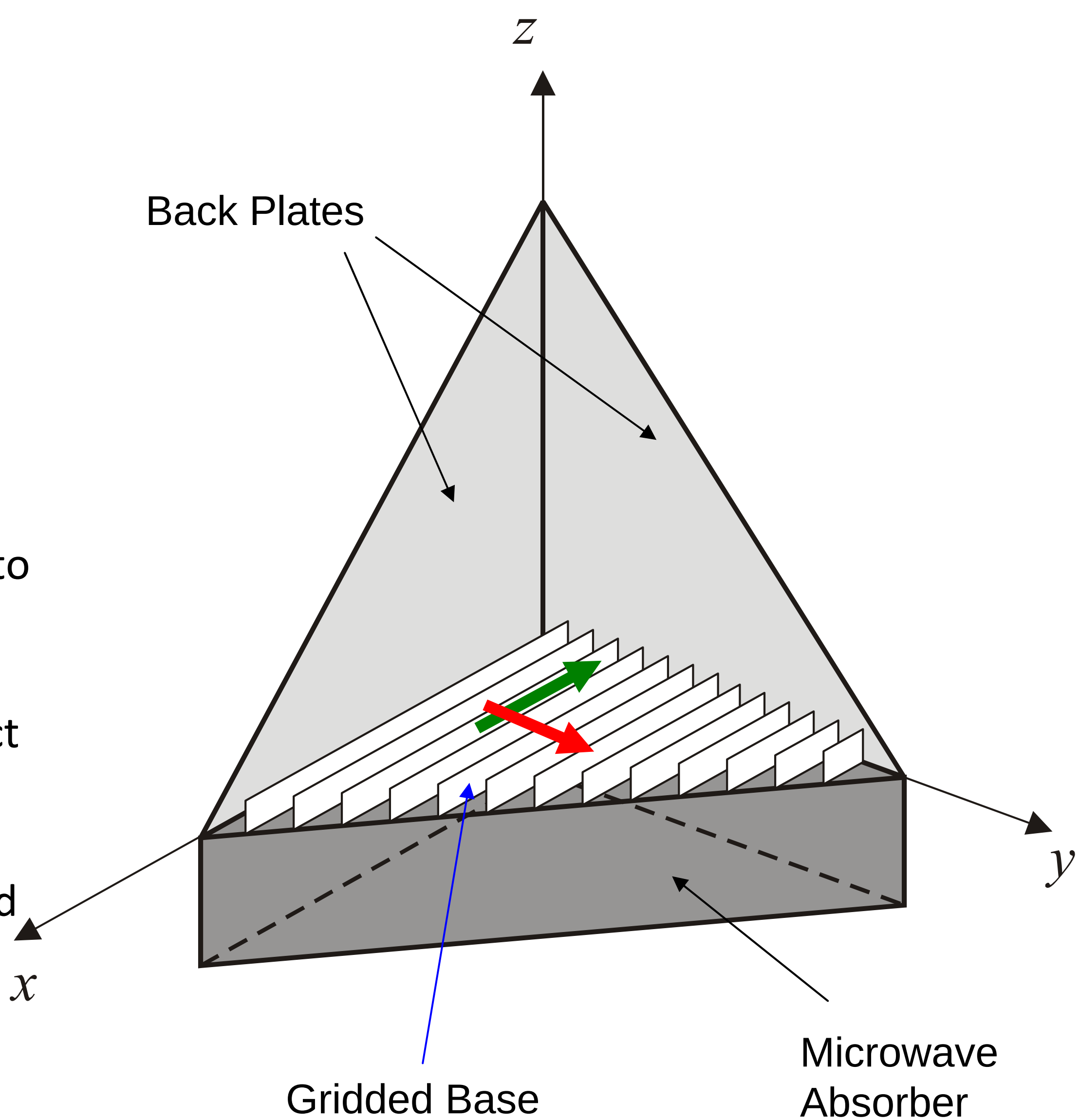
$$\delta_2 = \tilde{M}^{d}_{HH} - \frac{\tilde{M}^{d*}_{VH}\tilde{M}^{t*}_{VH}O^{*}_{11} + \tilde{M}^{d*}_{HH}O^{*}_{22} - O^{*}_{12}}{2O^{*}_{22}}$$

$$\delta_3 = \frac{\tilde{M}^{d*}_{VH}\tilde{M}^{t*}_{VH}O^{*}_{11} + \tilde{M}^{d*}_{HH}O^{*}_{22} - O^{*}_{12}}{2O^{*}_{22}}$$

Gridded Trihedral

Second approach

- → Classical trihedral with gridded base wires or thin plates (Ainsworth, 2006)
- → The polarization parallel to the grid is reflected (green arrow)
- → The polarization perpendicular to the grid is absorbed (red arrow)
- → Back plates have the same effect as in the classical trihedral
- → Grid spacing *d* is small compared to the wavelength



Gridded Trihedral

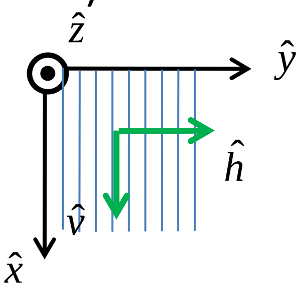
Second approach

→ General scattering matrix (Sheen, 1992)

$$[S_{gt}] = \frac{A_{gt}e^{j\phi_{gt}}}{\sin^2(\phi)+\cos^2(\phi)\sin^2(\theta)} \begin{pmatrix} \sin^2(\phi) & -\sin(\phi)\cos(\phi)\sin(\theta) \\ -\sin(\phi)\cos(\phi)\sin(\theta) & \cos^2(\phi)\sin^2(\theta) \end{pmatrix}$$

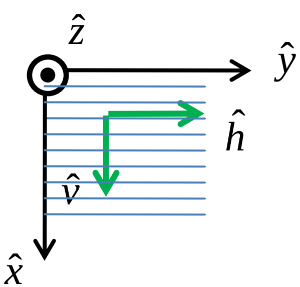
→ Ideal response (vertical grid, $\phi = 0$):

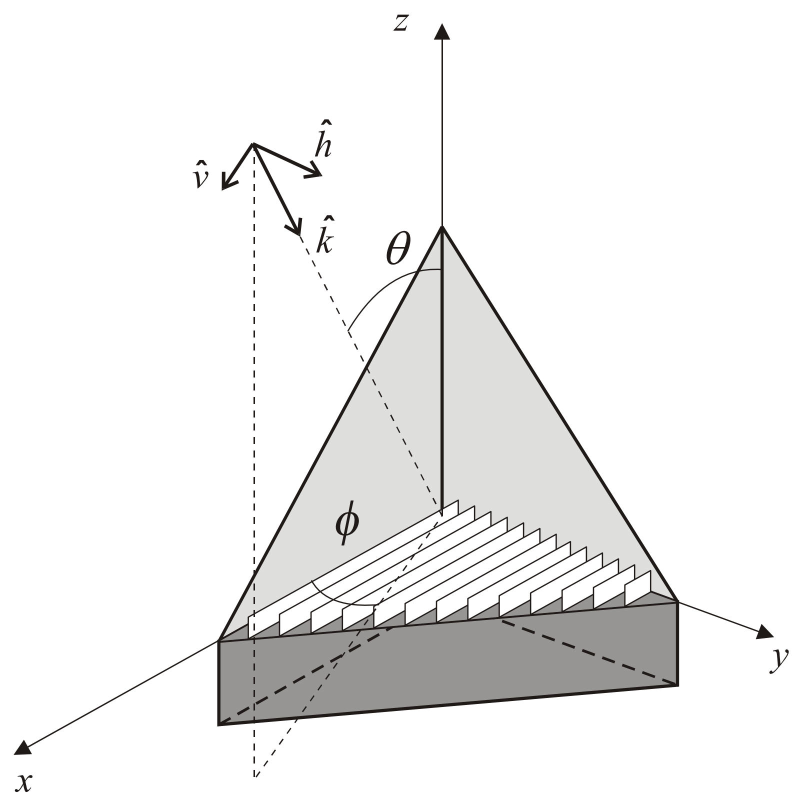
$$[S_{gt}]_1 = A_{gt}e^{j\phi_{gt}} \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$$



→ Ideal response (horizontal grid, $\phi = \pi / 2$):

$$[S_{gt}]_2 = A_{gt}e^{j\phi_{gt}} \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$





Estimation of distortion parameters

Second approach

→ Measured response in the dual-pol mode:

→ H-gridded trihedral:

$$\tilde{M}^{gt}_{HH_1} = \delta_2\delta_3 \quad (2)$$

$$\tilde{M}^{gt}_{VH_1} = \delta_3 f \quad (3)$$

→ V-gridded trihedral:

$$\tilde{M}^{gt}_{VH_2} = \delta_1 \quad (4)$$

→ Equations from: 1 simple trihedral + 2 gridded trihedrals

1, 2, 3, 4 ⇒

$$f = \sqrt{\frac{\tilde{M}^{gt}_{VH_1}}{\tilde{M}^{gt}_{HH_1}}\left(\tilde{M}^{t}_{VH} - \tilde{M}^{gt}_{VH_2}\right)} \qquad \delta_2 = \sqrt{\frac{\tilde{M}^{gt}_{HH_1}}{\tilde{M}^{gt}_{VH_1}}\left(\tilde{M}^{t}_{VH} - \tilde{M}^{gt}_{VH_2}\right)}$$

$$\delta_1 = \tilde{M}^{gt}_{VH_2} \qquad \delta_3 = \frac{\tilde{M}^{gt}_{VH_1}}{\sqrt{\frac{\tilde{M}^{gt}_{VH_1}}{\tilde{M}^{gt}_{HH_1}}\left(\tilde{M}^{t}_{VH} - \tilde{M}^{gt}_{VH_2}\right)}}$$

Dual-Pol Data Calibration

Dual-pol VS single- and quad-pol calibration

→ **Single Polarization**

→ Trihedral Corner Reflector

→ **Quad Polarization**

→ Trihedral Corner Reflector + Distributed target

→ **Dual Polarization**

→ Trihedral Corner Reflector + (Distributed target) + Additional targets

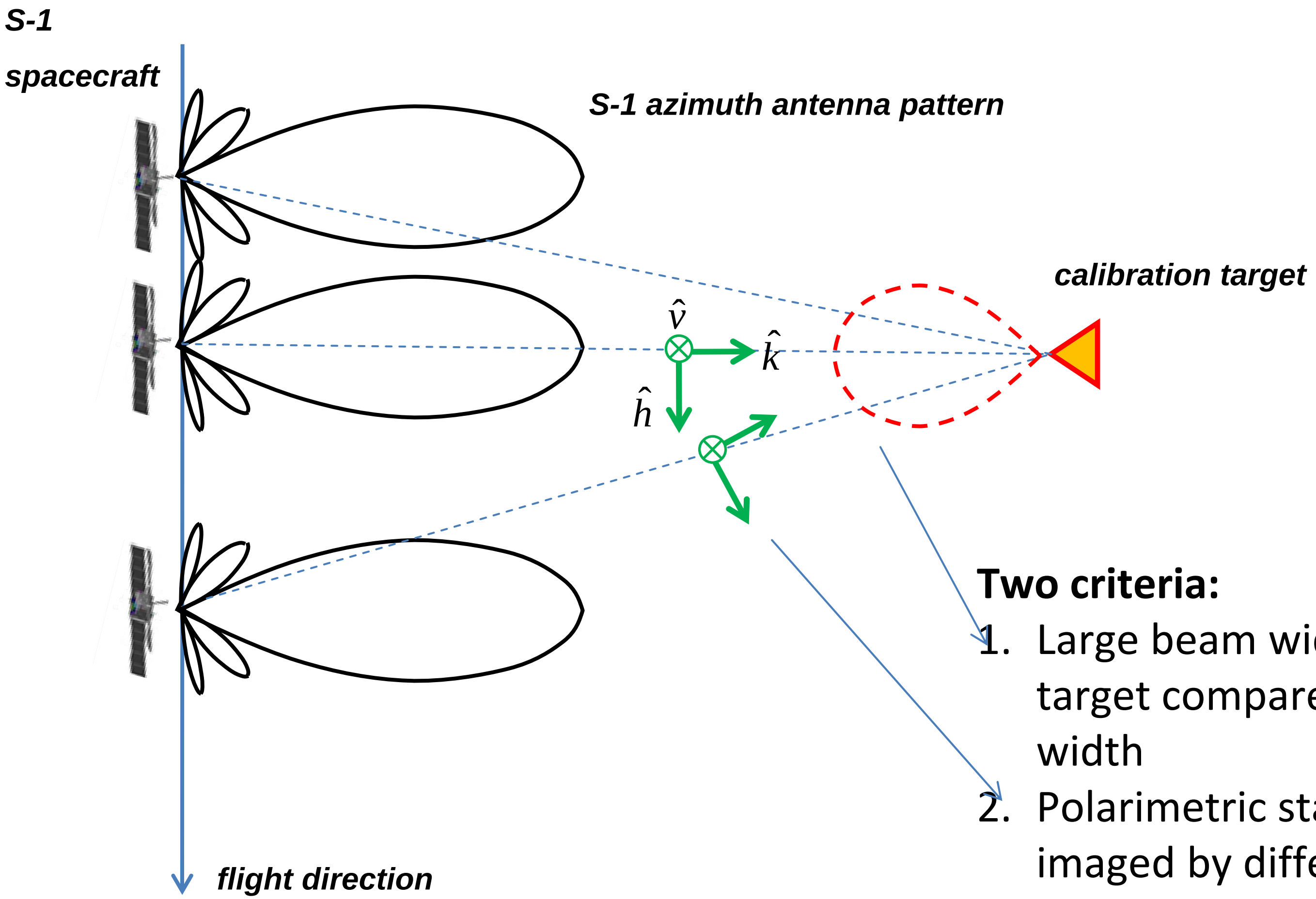
Oriented dihedral **Gridded trihedral**

Performance of the targets as seen by S-1?

Performance Evaluation
Sentinel-1

Performance evaluation

Gridded trihedral and oriented dihedral

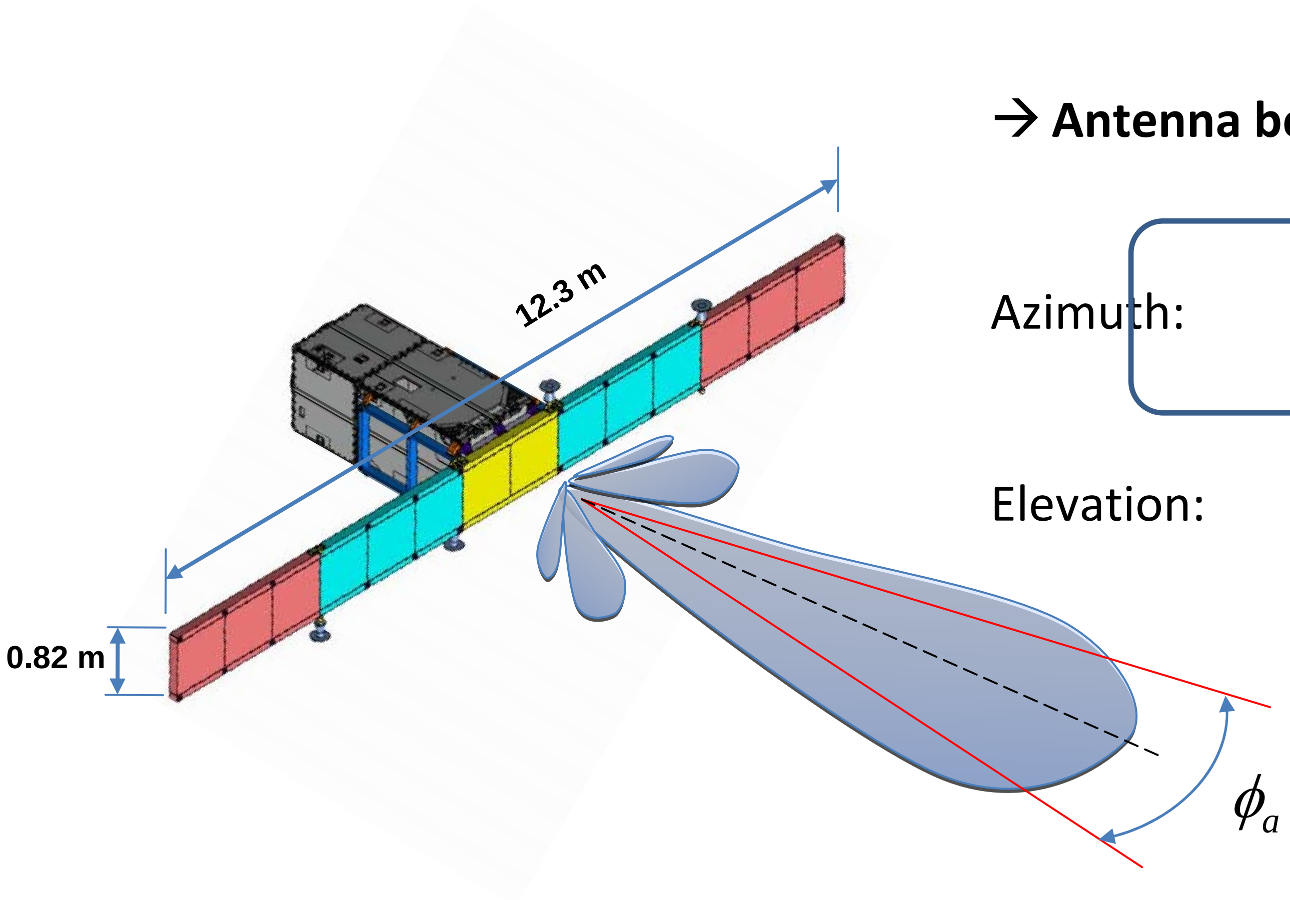


Two criteria:

1. Large beam width of the calibration target compared with S-1 azimuth beam width
2. Polarimetric stationarity of the target as imaged by different azimuth angles (including pointing stability)

Performance evaluation

Sentinel-1: antenna beamwidth



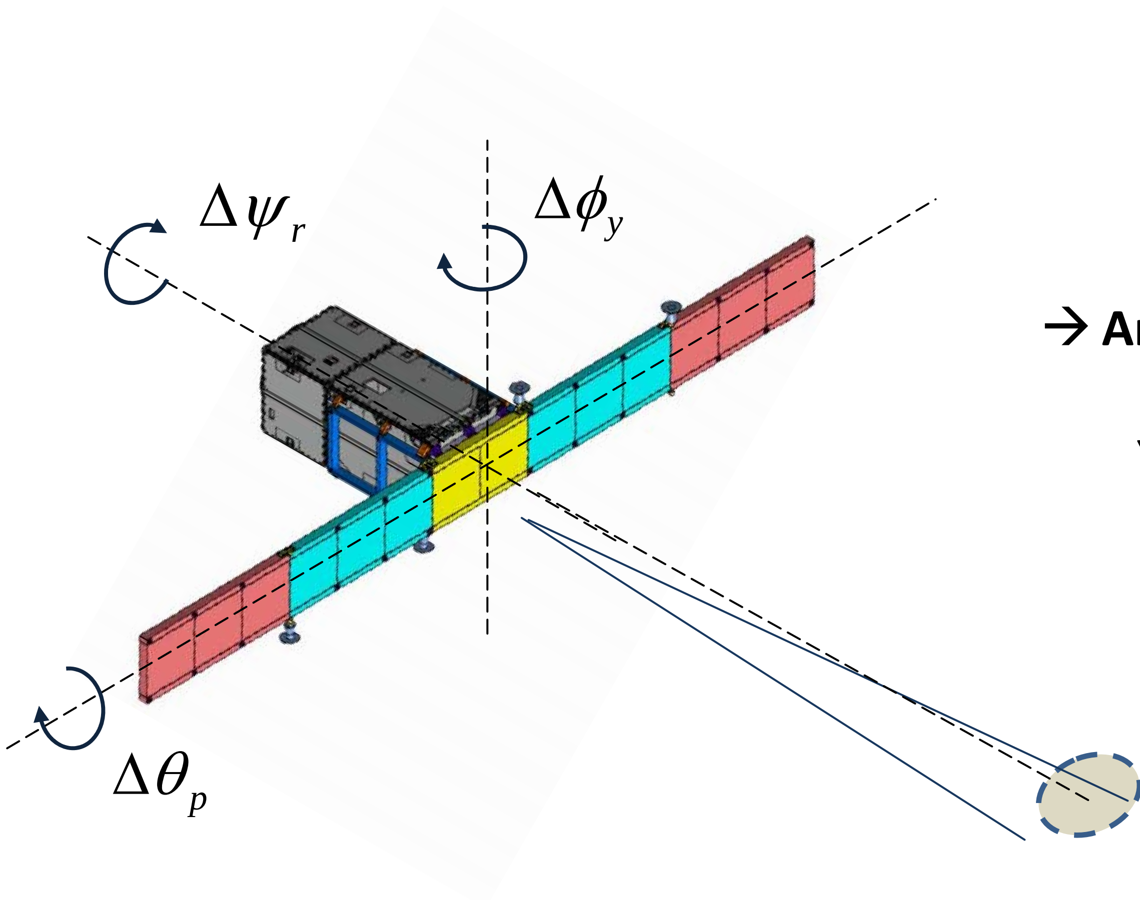
→ **Antenna beam width**

Azimuth: $$\phi_a = \frac{\lambda}{L_\phi} \cong 0.23^\circ$$

Elevation: $$\theta_a = \frac{\lambda}{L_\theta} \cong 3.43^\circ$$

Performance evaluation

Sentinel-1: antenna stability



→ **Antenna pointing stability**

Yaw ($\Delta\phi_y$): ± 0.01 deg

Pitch ($\Delta\theta_p$): ± 0.01 deg

Roll ($\Delta\psi_r$): ± 0.01 deg

Performance evaluation

Beamwidth

→ **Gridded trihedral RCS**

→ RCS assumed equal to the flat trihedral (Ruck, 1970)

$$\sigma_{gt}(\theta,\phi) \approx \frac{4\pi}{\lambda^2} l^4 \left(v - \frac{2}{v} \right)^2, \qquad v(\theta,\phi) = \cos\theta + (\sin\phi + \cos\phi)\sin\theta$$

→ **Dihedral RCS** (derived from Hayashi, 2006)

$$\sigma_{di}(\theta,\phi) \approx \frac{4\pi}{\lambda^2} a^2 b^2 \sin^2\left(\frac{\pi}{4} - \phi \right) \frac{\sin^2(u)}{u^2}, \qquad u(\theta,\phi) = \frac{2\pi}{\lambda} l \cos\theta \sin\phi$$

→ **Beam width**

→ Elevation plane (θ): GT and DIH have large beam width

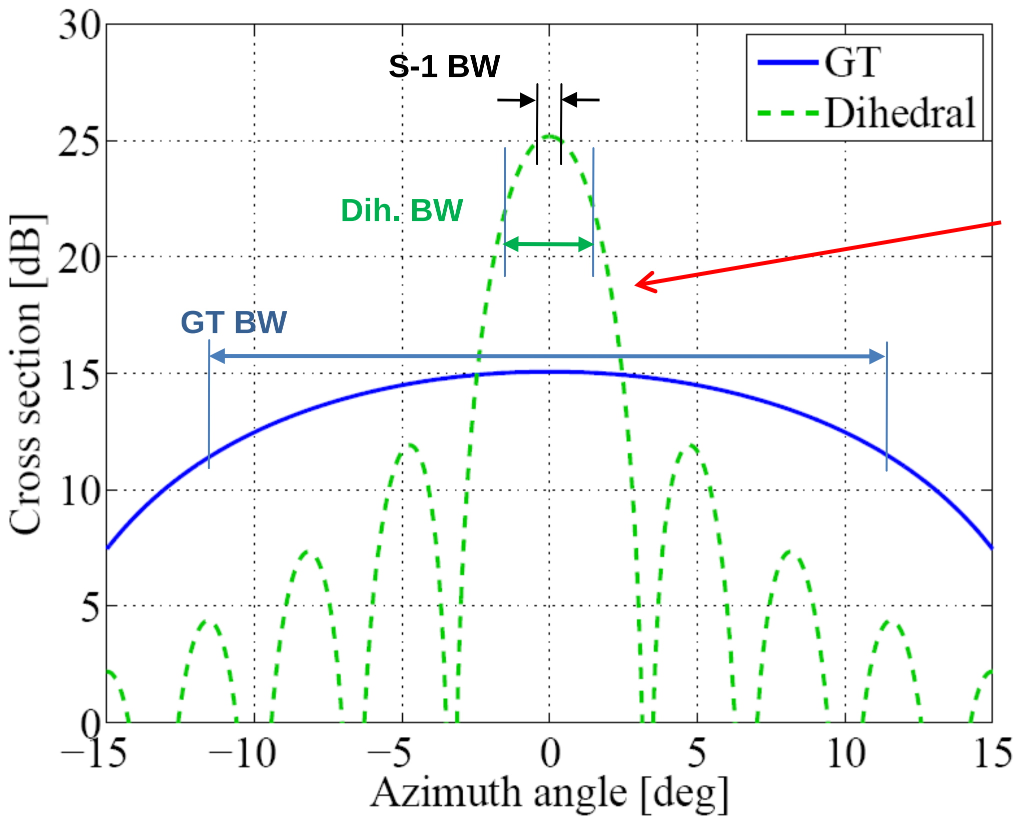
→ Azimuth plane (ϕ)?

Performance evaluation

Beam width on azimuth plane

→ First criterium for S-1: $BW_{S-1} = \phi_a + \Delta\phi_y < BW_{trg}$

→ Plot for $\theta = 30^\circ$ and $l = 10\lambda$



Dihedral is difficult to point ☹

Performance evaluation

Polarimetric noise

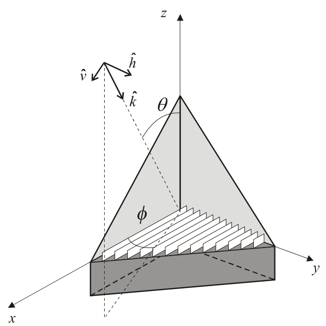
→ **Average polarimetric noise:**

→ Coherent averaging of scattering vectors from different angular positions: $\underline{k} = \begin{pmatrix} S_{HH} \\ S_{HV} \\ S_{VH} \\ S_{VV} \end{pmatrix}$

→ Compared with the requirement on the cross-talk level: $\delta_{req} = -30\ dB$

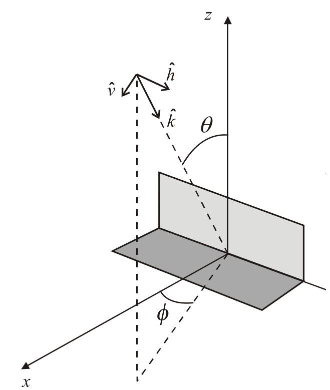
→ **Second criterium:**

$$\delta < \delta_{req}$$



Average on azimuth beam width + yaw stability and pitch stability

$$\delta(\theta_{ref}) = 1 - \underline{k}(\theta_{ref}, 0) \cdot \left(\frac{1}{N_\theta N_\phi} \sum_i \sum_j \underline{k}(\theta_i, \phi_j) \right)^*$$



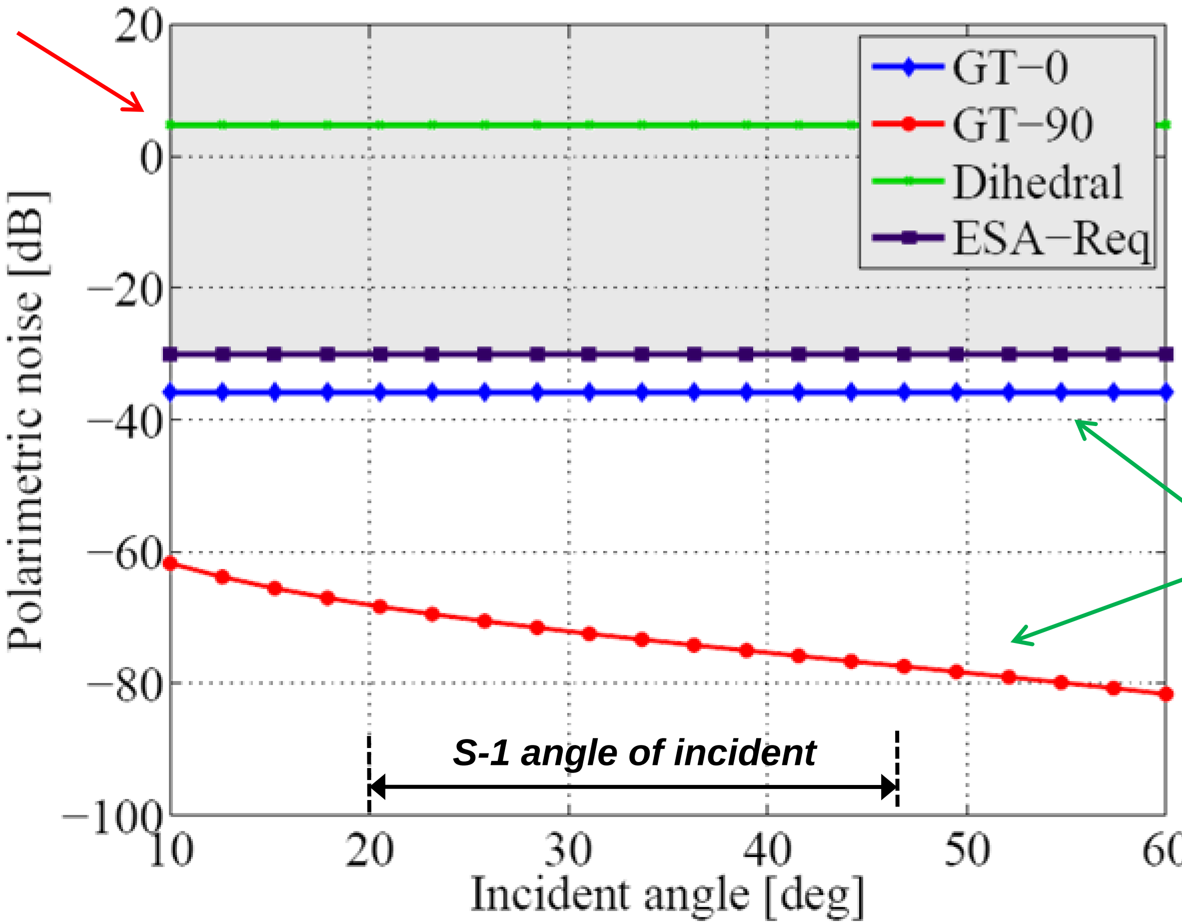
Average on roll stability

$$\delta = 1 - \underline{k}(0) \cdot \left(\frac{1}{N_\psi} \sum_i \underline{k}(\psi_i) \right)^*$$

Performance evaluation

Polarimetric noise

Dihedral noise above the requirement ☹



Requirement -30 dB

Gridded trihedrals noise below the requirement ☺

Estimation of distortion parameters

Comparison of the two approaches

Pro
Con

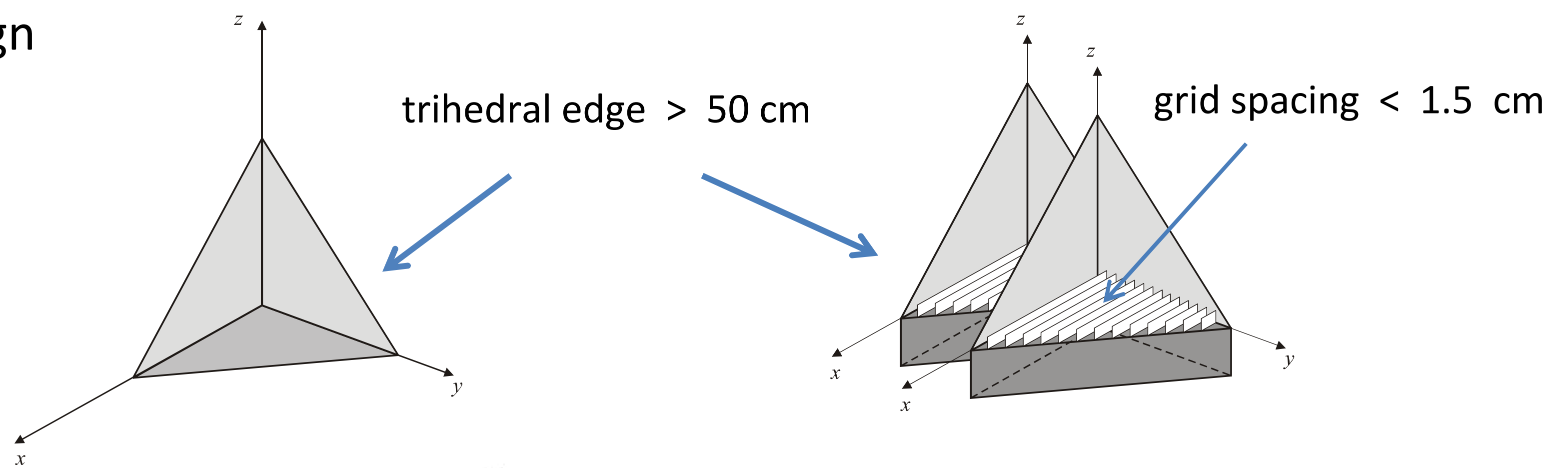
Distributed target + Trihedral + Oriented dihedral ☹	Trihedral + 2 gridded trihedral ☺
Trihedrals and dihedrals are simple to construct (Pro)	Gridded trihedrals require accurate construction of the grid (Con)
Oriented dihedral has a narrow beam width and it is difficult to orient (Con)	Gridded trihedrals have large beam width (Pro)
The dihedral has high polarimetric noise due to roll pointing error (Con)	The average polarimetric noise is below the cross-talk requirement (Pro)
Trihedrals and dihedrals are slightly affected by rain (Pro)	The microwave absorber layer can be affected by rain (Con)
Require the identification of azimuthally distributed targets in the SAR image (Con)	Do not use azimuthal symmetry assumption (Pro)

Dual-Pol calibration

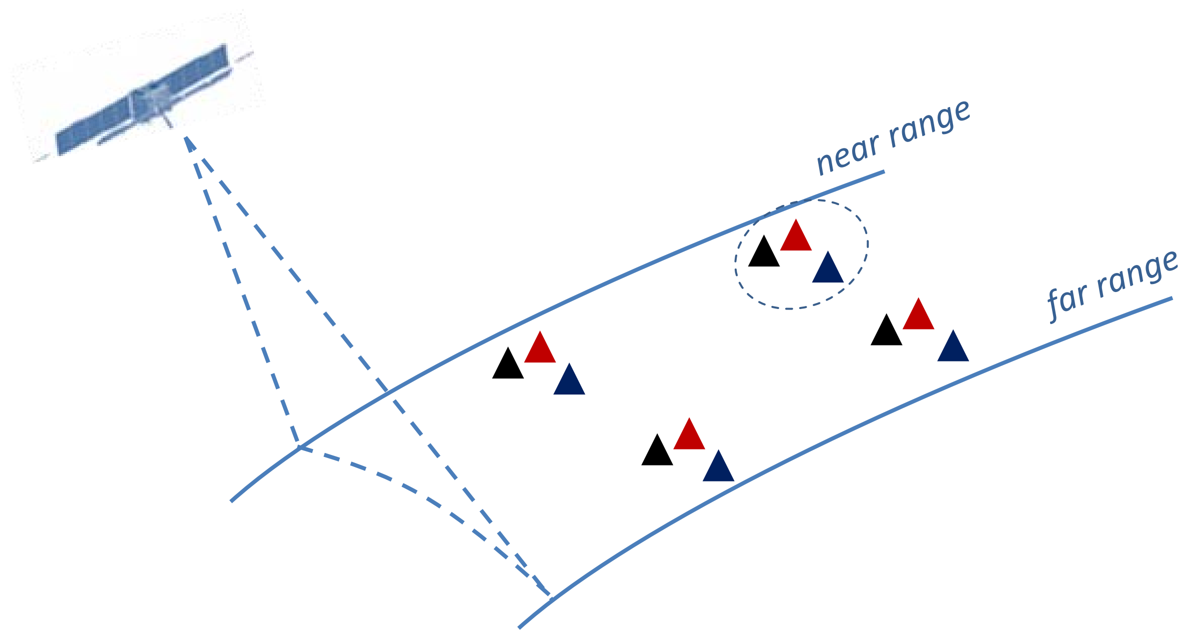
Possible approach for Sentinel-1 using passive targets

Trihedral + 2 gridded trihedral

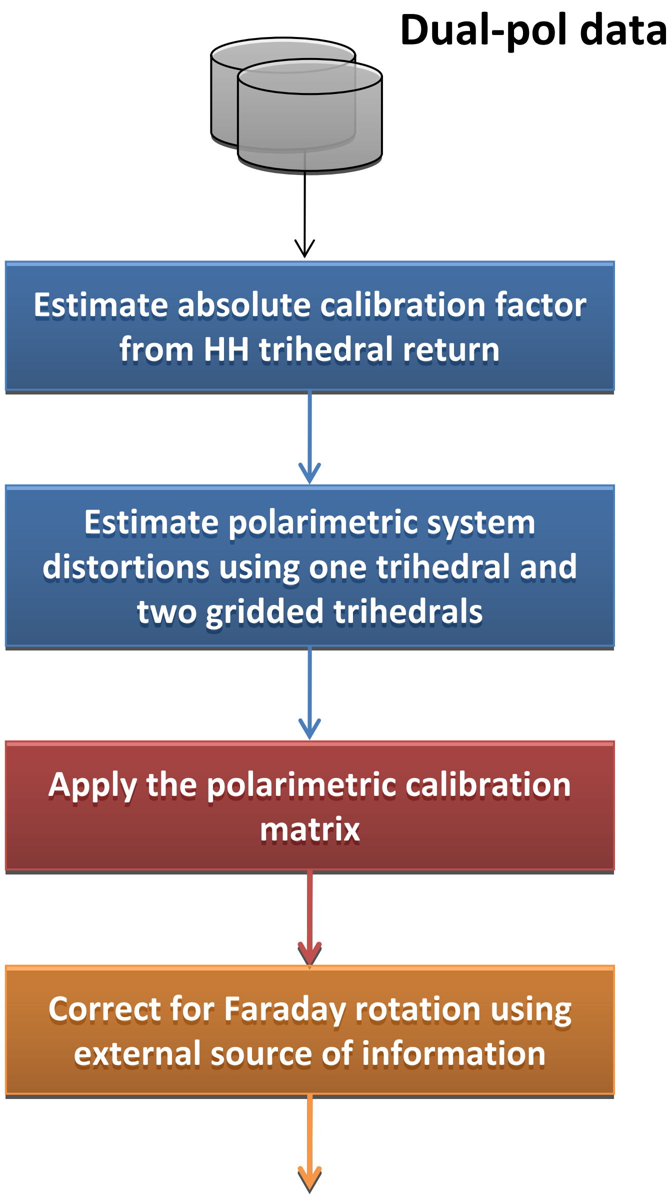
→ Design



→ Location



Dual-Pol Data Calibration



→ Polarimetric calibration matrix

$$\begin{pmatrix} S_{HH}^{\mathrm{cal}} \\ S_{VH}^{\mathrm{cal}} \end{pmatrix} = \underbrace{\frac{1}{\delta_1\delta_2 - f}\begin{pmatrix} f & -\delta_2 \\ -\delta_1 & 1 \end{pmatrix}}_{\text{calibration matrix}} \begin{pmatrix} M_{HH} \\ M_{VH} \end{pmatrix}$$

→ The transmitting x-talk δ_3 is important for evaluating the reliability of dual-pol measurements

$$S_{HH}^{\mathrm{cal}} = S_{HH} + \delta_3 S_{HV}$$
$$S_{VH}^{\mathrm{cal}} = S_{VH} + \delta_3 S_{VV}$$

→ Faraday rotation can be corrected as optional step from external source (e.g. TEC data)

Conclusions

→ Dual-pol distortion model

– Contains 1 transmitting x-talk and 3 receiving distortion parameters

→ Estimation of distortion parameters from dual-pol data

– 1 trihedral and 2 gridded trihedrals are required
– Gridded trihedrals provide large beam width and polarimetric noise within the requirement

→ Calibration procedure

– Performed for each beam and for each mode
– Faraday rotation can be corrected as optional step