Polarimetry and Interferometry Applications

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Goal

Point out exemplary some Application Possibilities of the Interferometric & to some extent Polarimetric Techniques & Systems considered & presented in the forgoing respective Lectures in order to deepen & fasten the Auditories Understanding & Comprehension

★

Offer a Glance into a Selection of Representative Activities in the Domains of Scientific, Commercial, & Operational Applications of Interferometry & Polarimetry
Applications for Digital Height Models

- Safety for Air Traffic
- Disaster management
- Telecommunications
- Infrastructure planning
- Hydrology

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### Application Areas and Specific User Requirements

**Driver for research & development of all SAR Technique, Technology & Systems**

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<th>Military</th>
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<tr>
<td>Polarization</td>
<td>quad</td>
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<td>Dual/quad</td>
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<td>Incidence Interval</td>
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<tr>
<td>Spatial Resolution</td>
<td>3m-30m</td>
<td>10 m</td>
<td>3m – 10m</td>
<td>3m – 10m</td>
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<td>Variable</td>
<td>Variable</td>
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<tr>
<td></td>
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<td></td>
<td>40 km – 100 km</td>
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<td>Tomography</td>
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SAR Interferometry Applications & User

- Creation of Land Deformation Maps with Millimetre Accuracy
- Generation of Digital Elevation Models with Meter Accuracy,
- Improved Target Recognition by Creation of 3D Images of Targets
- Improved Land Use Classification by exploiting Coherence Measurements,
  Measurement of Current Fields & Moving Target Indication
- Economical & Operational Importance for Constructors (Building a Tunnel can cause Unwanted Deformation),
- Governments (Dike Monitoring, Disaster Monitoring),
- Military (Target Detection, Identification, Classification, Area Exploration
- Governments & Companies creating Georectified SAR Imagery (Need for Topographic Maps), etc.
SAR Polarimetry Applications

Polarimetry offers Maximal Information an Electromagnetic Wave can carry. Most Modern Civil & Military Applications require full Polarimetric Systems.

Polarization will Improve exemplary:

- Ice Detection & Classification,
- Man Made Target Detection & Classification,
- Crop Monitoring & Classification etc..

Commercial Aspects are widely in the Foreground
Polarimetry

Polarization is the Orientation of the Electric Vector \( (E) \) in an Electro Magnetic Wave, frequently "Horizontal" \((H)\) or "Vertical" \((V)\) in conventional imaging radar systems. Polarization is Established by the Antenna.

Complete State of scattered Electromagnetic Wave described by the Scattering Matrix \( S \), which connects the Received Field Vector \( E_r \) with the Transmitted Field Vector \( E_t \). (Börner)

\[
\begin{bmatrix}
E^r_H \\
E^r_V
\end{bmatrix}
= \begin{bmatrix} S \end{bmatrix}
\begin{bmatrix}
E^t_H \\
E^t_V
\end{bmatrix}
= \begin{bmatrix}
S_{HH} & S_{HV} \\
S_{VH} & S_{VV}
\end{bmatrix}
\begin{bmatrix}
E^t_H \\
E^t_V
\end{bmatrix}
\]

Scattering Matrix Decomposition into 3 Components (Example Sperical Basis):

\[
[S] = e^{j\varphi} \left\{ e^{j\varphi_s} k_s [S_{sphere}] + k_d [S_{dipole}] + k_k [S_{helix}] \right\}
\]
Scattering Matrix

\[ \vec{E} = \vec{E}_0 \frac{e^{-\alpha r}}{kr} e^{-j(\omega t + \varphi)} \]

\[ \alpha = jk + \gamma \]

\[ E_{scat}^H = S_{HH} E_{inc}^H + S_{HV} E_{inc}^V \]

\[ E_{scat}^V = S_{VH} E_{inc}^H + S_{VV} E_{inc}^V \]

\[ \vec{E}_{scat} = \begin{pmatrix} E_{scat}^H \\ E_{scat}^V \end{pmatrix} = \begin{pmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{pmatrix} \begin{pmatrix} E_{inc}^H \\ E_{inc}^V \end{pmatrix} = (S) \vec{E}_{inc} \]

\[ S_{i,k} = \sqrt{\sigma_{i,k}} e^{j\varphi_{i,k}} \]
Basis Matrices

A generic Matrix is decomposable into Basis Matrices

\[
\begin{bmatrix}
S_{HH} & S_{HV} \\
S_{VH} & S_{VV}
\end{bmatrix}
\]

\[
\begin{bmatrix}
a + b & c \\
c & a - b
\end{bmatrix} = a \begin{bmatrix} 1 & 0 \\
0 & 1
\end{bmatrix} + b \begin{bmatrix} 1 & 0 \\
0 & -1
\end{bmatrix} + c \begin{bmatrix} 1 & 0 \\
0 & 1
\end{bmatrix}
\]

\[
a + b = S_{HH} ; a - b = S_{VV}
\]

\[
a = S_{HH} + S_{VV} ; b = S_{HH} - S_{VV} ; c = S_{HV} = S_{VH}
\]

Scattering Vector \( \vec{k} = (a,b,c) = (S_{HH} + S_{VV} ; S_{HH} - S_{VV} ; S_{HV}) \)
Pauli Distribution

**Single Bounce, odd**

Rough Surface Plate, Sphere, Dihedral;

\[ \mathbf{S}_{\text{odd}} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \]

**Double Bounce, even**

Tilted Dihedral;

\[ \mathbf{S}_{\text{even}} = \begin{bmatrix} \cos 2\alpha & \sin 2\alpha \\ \sin 2\alpha & \cos 2\alpha \end{bmatrix} \]

**Volume Scattering, diffuse**

Vegetation

\[ \mathbf{S}_{\text{diff}} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \]

Scattering Vector \( \vec{k}_{\text{scat}} = (k_{\text{odd}}, k_{\text{even}}, k_{\text{diff}}) = (S_{\text{HH}} + S_{\text{HV}}, S_{\text{HH}} - S_{\text{HV}}; 2S_{\text{HV}}) \)
Polarimetric Image of the E-SAR System in L-Band

\[
S_1 = \begin{bmatrix}
1 & 0 \\
0 & 1
\end{bmatrix},
S_2 = \begin{bmatrix}
\cos 2\alpha & \sin 2\alpha \\
\sin 2\alpha & \cos 2\alpha
\end{bmatrix},
S_{\text{diffus}} = \begin{bmatrix}
0 & 1 \\
1 & 0
\end{bmatrix}
\]
Example for three-dimensional ‘POL-IN-DEM’ information

E-SAR, L - Band

Vegetation with vertical Structures

Δ- Polarization (HH-VV)

Scattering Matrix

Coherent Decomposition in orthogonal Parts

Vegetation with vertical Structures

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Combination of Polarimetry and Interferometry

\textit{SAR Polarimetry (PolSAR)}

Allows the decomposition of different scattering processes occurring inside the resolution cell.

\textit{SAR Interferometry (InSAR)}

Allows the location of the effective scattering center inside the resolution cell.

\textit{Polarimetric SAR Interferometry (Pol-InSAR)}

Potential to separate in height different scattering processes occurring inside the resolution cell.

- \textit{Sensitivity to the vertical distribution of the scattering mechanisms}
- \textit{Allows the investigation of 3D structure of volume scatterers}
The Combination of Polarimetry and Interferometry

SAR Polarimetry ← Phase sensitivity → SAR Interferometry

Sensitive to scatterers shape, orientation and dielectric properties
Allows decomposition of different scattering processes occurring inside the resolution cell

Established technique for terrain topography estimation allows
Location of scattering centers inside the resolution cell

Polarimetric SAR Interferometry
Potential to separate in height different scattering processes occurring inside the resolution cell.

Sensitivity to the vertical distribution of the scattering mechanisms

Allows the investigation of 3D structure of volume scatterers recovering co-registered textural plus spatial properties simultaneously

Central Part: Coherence
Applications for Digital Elevation Models DEM)

Example: Air traffic Safety

“Virtual Cockpit”

• Precise Information about Aircraft Position by GPS

• Precise Information about Topography below from global, consistent DEM (SRTM)
Hydrology: Water Flow Simulation

Globe-30 DEM

SRTM DEM
Example: Polarimetric Ice, Water, & Land Classification

HH Ice Type

HV Ice Edge

H/A/α Maximum Likelihood Classification Results After Five Iterations

Courtesy Mc Donald Dettwiler & Associates
www.rsi.ca/rsic/ice/eoadp.asp
Military Use of Interferometry and Polarimetry

“The war is father of everything”

Task of Military Reconnaissance Systems

“Assist the Military Leaders in the Early Detection of Crisis Prevention & Crisis Management Efforts, Support the Top Military Leadership to plan and prepare military operations and Support Deployed Forces in the Timely Collection of Current Intelligence Information”.

(Col. F. Kriegel on ”European Satellites for Security” in Brussels, June 2002),

One of the Biggest Tasks For Tactical & Strategic Consideration to get Things Timely, Safely & Efficiently at the Battlefield.

Interferometry & Polarimetry driven intensively by Military Requirements. For Target Detection, Recognition, Identification & Classification full polarimetric information is indispensable.

Decomposition Theorems excellently suited for Target Exploration under Vegetation Layers due to Foliage Penetration Capability of dm-Waves etc.
Polarimetric & Interferometric SAR indispensable

for Collecting Terrain Information like Engineering Resources, Trafficability, Obstacles, Visibility, Camouflage, Concealment Potential, Information on Camping Ground, Water Supply etc.

Systems mounted on Aircrafts, UAV’s, & Satellites allow actual updating of already existing Maps or establishing of new Feature Maps in Real Time.

Example: DEM’s

Military Topographic Maps are most important for Terrain Evaluation.

Aircraft & Helicopter Missions in mountainous ore even hilly Terrain can be supported in Advance & during the Mission with DEM of respective Areas.

Soil Moisture Maps help to identify the best Way for off Road Movements etc. (necessary also for establishing Communication Links etc).

US NIMA has financed the SRTM Mission

illuminating the Importance of DEM’s for Military Purposes.
Flight over unknown Area
Technical Applications
SRTM Systems Operation Geometry

Outboard Coordinate System (OCS)
Inboard Coordinate System (ICS)

Look Angle
Incidence Angle

B

Flight Direction
Time

- 50 km
- 58 km
- 62 km
- 80 km
- 225 km

Courtesy JPL

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Quellenangabe

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Quellenangabe
Technical Applications
SRTM Systems Operation Geometry

Time

Flight Direction

45 km

- 80 km

- 50 km

- 62 km

- 58 km

- 225 km

- 50 km

PRF 1700

1 3 4 4

1 5 5 0

PRF

1 3 4 4
Tomography
**Principle of Tomography**

1. **Illumination Source**
   - Projects multiple beams from different angles.

2. **Image Reconstruction Algorithm**
   - Processes the data from multiple angles.

3. **Simulation**
   - Shows the results of the reconstruction with different angular steps:
     - 45° Steps
     - 5° Steps
     - 1° Step

**Slice Image**

This diagram illustrates the process of tomography, where an object is illuminated from various angles to reconstruct a 3D image.
Polarimetric E-SAR Image, L-Band

1) spruce forest
2) buildings
3) cars
4) corner reflector

SAR Tomography
SAR-Tomography

2-dimensional image of a cut (τομή) through a 3-dimensional Objekt

Multiple parallel repeat-pass POL-IN-SAR imaging

Multiple horizontal Flights
Scattering Mechanisms along Yellow Line at different Altitudes & Polarizations. Buildings Roof is Bright: Bright HH and VV Single Bounce is the Corner Reflector. Double Bounces at Parts of the Buildings Roof & the Lower Parts of Trunks, Volume Scattering dominates in Tree Crowns & Under Story

Airborne Polarimetric SAR Tomography

Upper image: Polarimetric color composite (L-band) of a tomographic slice in the height/azimuth-direction

- HH+VV
- HH-VV
- 2*HV

Lower image: Schematic view of the imaged area
Use of Interferometry for Building Measurements

Using Terrain Elevation Data from Interferometry in Combination with Gray Value Images & Object Shadows Allows Building Mapping

**Accuracy** of Buildings Mapped from Sensor with 30 cm Pixels about ± 3 Pixels or ± 1 m.

2 Overlapping Data Sets are Definitely Needed.
Resulting Minimum Bounding Rectangles fit to point clouds detected automatically from maximum combined height map for different view combinations.

area 200 m x 150 m

Footprints from shadows, reconstructed from two perpendicular views, right + top. Overlaid are the computed optimum rectangles to fit the Point clouds. The area covers approximately 200 m x 150 m.

<table>
<thead>
<tr>
<th>View Combination</th>
<th>Area Error (RMS)</th>
<th>Height Error (RMS)</th>
<th>detected Buildings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom</td>
<td>± 205 m²</td>
<td>± 2,1 m</td>
<td>21</td>
</tr>
<tr>
<td>Left + Right</td>
<td>± 276 m²</td>
<td>± 2,6 m</td>
<td>12</td>
</tr>
<tr>
<td>Left + Bottom</td>
<td>± 422 m²</td>
<td>± 1,6 m</td>
<td>14</td>
</tr>
<tr>
<td>Left + Right + Bottom</td>
<td>± 207 m²</td>
<td>± 1,4 m</td>
<td>16</td>
</tr>
<tr>
<td>Left + Right + Top + Bottom</td>
<td>± 120 m²</td>
<td>± 1,4 m</td>
<td>15</td>
</tr>
</tbody>
</table>

Resulting rms error of area & maximum height, result of applying the automated building detection algorithms to different view combinations. “Maximum height” is used to avoid the confusion resulting from sloping roofs. Leberl F. W., Regine Bolter, From Multiple View Interferometric Radar to Building Models, Proc. EUSAR 2002
Procedure for the extraction of building models from a combination of SAR images and associated interferometric data [6]

Traffic Monitoring
Velocity Measurements with Interferometric SAR
Ambiguous Determination of Pixel Velocity

Azimuth Displacement:

\[ V_{ve} = 3.6 F_{gr} \left( \frac{V_{ae} x}{r_0} + n \frac{PRF \lambda}{2} \right) \]

Along Track Interferometry:

\[ V_{ve} = - \frac{V_{ae} \lambda}{4\pi B} (\Phi + n2\pi) \]

- **B**: ATI Baseline;  
  - **F_{gr}**: Slant to Ground Range Factor;  
  - **n**: Ambiguity Number;  
  - **PRF**: Pulse Repetition Frequency;  
  - **r_0**: Slant Range Distance;  
  - **x**: Doppler Displacement;  
  - **V_{ve}**: vehicle velocity;  
  - **V_{ae}**: aircraft velocity;

- **\lambda**: wavelength;  
  - **\Phi**: Measured ATI Phase;  
  - **3.6**: Conversion Factor m/s to km/h;
Airborne Moving Target Indication

Amplitude SAR Image

Motorway A 92 between Munich City and Munich Airport: not all vehicles are visible

Courtesy Joao Moreira, MFFU Summerschool 2001
Along-Track Interferometric Phase Image

Motorway A2 between Munich City and Munich Airport: **all** vehicles are visible

1. Azimuth Displacement
2. ATI

Courtesy Joao Moreira, MFFU Summerschool 2001
Determination of the Car Direction from the Sub-Look Images

Look 1

Look 2

moving to aeroplane

moving away from aeroplane

Courtesy Joao Moreira, MFFU Summerschool 2001
Sub-Look Images

(1)

(2)

(3)

(4)

Courtesy Joao Moreira, MFFU Summerschool 2001
Acquisition of the Motorway

Traffic situation on the motorway A92 11. Nov. 1999 - 08:57:31 h

Motorway A92 between Munich City and Munich Airport

Courtesy Joao Moreira, MFFU Summerschool 2001
Traffic Flow into town/ leaving town

Measurements at Rosenheimer Straße, Munich

Time of data take in local time at 11 November 1999
Moving and Not Moving Vehicles
(parking cars are excluded)

Measurements at Rosenheimer Straße, Munich

Courtesy Joao Moreira, MFFU Summerschool 2001
Space-borne Moving Target Indication with SRTM

Along Track Interferometry Capability

Due to Antenna Displacement
Coherence loss indicates the presence of a moving target. The larger low coherent areas are Lakes.

Coherence map featuring a 3 km long section of the Autobahn Munich – Nuremberg. The black dots are cars displaced from the red road due to their velocities.

[Breit et. al., Traffic Monitoring using SRTM, Proc. IGARSS 2003]
Results of the Validation Experiment
Comparing 3 Measurement Methods

<table>
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<th>InSAR data evaluation</th>
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<td>Velocities resulting from measured azimuth displacement (130.6 pixel)</td>
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<td>Radial Velocity from Displacement</td>
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<td>Ground Velocity from Displacement</td>
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<tr>
<td>Velocities resulting from ATI Phase (127°)</td>
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<td>Radial Velocity from ATI Phase</td>
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<tr>
<td>Ground Velocity from ATI Phase</td>
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<td>Velocity resulting from GPS Measurement</td>
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<tr>
<td>Ground Velocity</td>
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MTI- Interferometry, SRTM/X-SAR (Bamler, DLR)

Left: Motorway A9, Munich – Nuremberg, Germany, arrow: SRTM track. Right: SRTM/X-SAR image, motorway blue, red arrows vehicles with their velocities (yellow)
Ocean Current Measurements with SRTM Along Track Interferometry

Line-of-sight current field derived from the SRTM data (left) & obtained from KUSTWALD for the tidal phase 20 minutes before SRTM overpass (right); grid resolution is 100 m × 100 m; data points with valid currents from SRTM and KUSTWAD are shown only.

Romeiser et. al. Validation of SRTM-Derived Surface Currents IEEE Proc. IGARSS 03,
Scatter diagram showing the distribution of SRTM-derived vs. KUSTWAD-derived current components in the SRTM look direction, as well as corresponding statistical quantities, for the tidal phase 20 minutes before the SRTM overpass.

Romeiser et. al. Validation of SRTM-Derived Surface Currents IEEE Proc. IGARSS 03,
Mining Induced Subsidence by means of Differential SAR- & Permanent Scattering Interferometry
Determination of Subsidence Effect caused by Ground Water Withdrawal in a Brown Coal Mining Area with D - InSAR using Permanent Scatterers as Reference Points.

Goal

Clarify Correlation between Ground Water Withdrawal, Tectonics & Subsidence on Surface by means of both Differential SAR Interferometry & Permanent Scatterer Technique

D – InSAR: 28 ERS-1 Images registered to the same Master Image

- Perpendicular Baselines: 23 m --- 500 m (--- 1158m).
- 17 D-InSAR Interferograms showed Concentric, nearly Elliptic Fringes, each corresponding to 28 mm Line of Sight Movement.
- For PSI 11.000 Permanent Scatterers were identified & within a reference network selected for more point wise information
- From May 1995 to December 2000 the area affected by groundwater withdrawal sank continuously with 5 cm/year.
Results: Both techniques lead to the same subsidence rates of about 5 cm/year. Even over a time span of 1401 days reliable results were achieved with both methods. The estimated values could be verified by ground measurements of the land surveying office NRB, Germany.
Soil Moisture & Biomass Estimation using Polarimetric Scattering Theory
## User Requirements

<table>
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<th></th>
<th>BIOMASS</th>
<th>SOIL MOISTURE CONTENT</th>
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<td><strong>Spatial Resolution</strong></td>
<td>1/2 ha = 5000m²</td>
<td>70x70m</td>
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<tr>
<td><strong>Temporal Resolution</strong></td>
<td>4 Years</td>
<td></td>
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<tr>
<td>Average Tree Height Change:</td>
<td>3m -- 4 m per Year</td>
<td>Seasonal observation</td>
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<tr>
<td>Differential Height Accuracy:</td>
<td>1 m</td>
<td>&gt; 2 per Year</td>
</tr>
<tr>
<td><strong>Required Accuracy</strong></td>
<td>Tree height estimation: 10%</td>
<td>Volumetric Moisture</td>
</tr>
<tr>
<td></td>
<td>Mean forest height on Earth: 20 m</td>
<td>10% - 20 %</td>
</tr>
<tr>
<td></td>
<td>Height Accuracy: 2 m</td>
<td></td>
</tr>
</tbody>
</table>
State of the Art for Soil Moisture Estimation

accuracy moisture content & surface roughness of bare surfaces: 10 - 20%, moisture content ranging from 0 up to 40 [vol. %]

roughness scales up to ks < 1.

Uncertainties during measuring the surface parameters lead to inaccuracies.

Main Problem

Presence of Vegetation Cover Limits Algorithm Performance Drastically
Scattering Decomposition Techniques lead to Improvements but do not solve the problem

Possible Solutions

Dual-Frequency Polarimetry (for example: L- and P-band)
Combination of Mono- and Bi-Static Polarimetric Measurements
Combination of Polarimetric and Interferometric Measurements
Assumption: Surface Scatterer
Entropy $H < 0.4$ & $\alpha < 0.40^\circ$

$$[C] = \lambda_1 e_1 e_1 + \lambda_2 e_2 e_2 + \lambda_3 e_3 e_3 = [C_1] + [C_2] + [C_3]$$

$$[C_i] = \vec{k_i} \rightarrow \vec{k_i} + \text{ with } \vec{k_i} = \lambda_i e_i = [HH_i, \sqrt{2HV_i}, VV_i]$$

$[C_1]$ represents deterministic anisotropic surface scattering

$[C_2]$ & $[C_3]$ correspond to double-bounce and/or multiple scattering components respectively.

In this sense: $|HH_i|$, $|VV_i|$, and $|HV_i|$ values represent the scattering amplitudes corresponding to the surface scattering only.

The disturbing double-bounce (if present) and multiple scattering effects affecting the original $|HH|$, $|VV|$, and $|HV|$ have been filtered out.
The Polarimetric Eigenvector Decomposition Technique

Covariance Matrix \([C]\) & Scattering Vector \(\vec{k}\)

\[
[C] = \begin{bmatrix}
\langle HH \rangle^2 & \sqrt{2} \langle HHHV^* \rangle & \langle HHVV^* \rangle \\
\sqrt{2} \langle HVHH^* \rangle & 2 \langle HV \rangle^2 & \sqrt{2} \langle HVVV^* \rangle \\
\langle VVHH^* \rangle & \sqrt{2} \langle VVHv^* \rangle & \langle VV \rangle^2
\end{bmatrix}
\]

\[
\vec{k} = [HH, \sqrt{2} HV, VV]^T
\]

Decomposition of \([C]\) leads to three 3 x 3 Independent Rank 1 Covariance Matrices \([C_i]\)

\[
[C] = \lambda_1 \vec{e}_1 \vec{e}_1 + \lambda_2 \vec{e}_2 \vec{e}_2 + \lambda_3 \vec{e}_3 \vec{e}_3 = [C_1] + [C_2] + [C_3]
\]

\[
[C_i] = \vec{k}_i \vec{k}_i^+ \quad \text{with} \quad \vec{k}_i = \lambda_i \vec{e}_i = [HH_i, \sqrt{2} HV_i, VV_i]
\]

\(\lambda_1 > \lambda_2 > \lambda_3\): real non negative eigenvalues of \([C]\); \(\vec{e}_i\) (i = 1, 2, 3): eigenvectors. 
\([C_i]\) orthogonal & independent
Soil moisture Map: mv in Vol %

Hajnsek et. al., Terrain Correction for Quantitative Moisture and Roughness Retrieval… Proc. IGARSS’00,
Institut für Hochfrequenztechnik und Radarsysteme
Soil Surface Roughness Map $k_s$
Measured versus Estimated Soil Moisture

![Graph showing measured versus estimated soil moisture](image)

- **Elbe RMS**
  - 0-4 cm: 8
  - 4-8 cm: 3
  - corr.: 0.7/0.8

- **Weiherbach RMS**
  - 0-4 cm: 7
  - 4-8 cm: 6
  - corr.: 0.2/-

Hajnsek et al., Terrain Correction for Quantitative Moisture and Roughness Retrieval... *Proc. IGARSS’00*, Institut für Hochfrequenztechnik und Radarsysteme
Which is the Optimum Frequency Band ???

**C-band**
- **Pro:** Established Technology
- **Pro:** Limited Penetration Capability in Dense Vegetation
- **Pro:** Temporal Decorrelation (repeat pass implementation)
- **Contra:** ks range to small for a variety of natural surfaces

**L-band**
- **Pro:** Established Technology
- **Pro:** Higher Penetration Capability
- **Pro:** Wide Spectrum of Applications
- **Contra:** ks range covers most natural surfaces

**P-band**
- **Pro:** Approved Penetration Capability in Tropical Forest
- **Contra:** Long Term Temporal Decorrelation (repeat pass implementation)
- **Contra:** Spatial Resolution (Limited Bandwidth)
- **Contra:** Non-Established Technology
- **Contra:** Limited Application Spectrum

*Open Question:* Does L-band see the ground in tropical forest???
Interpretation of Coherence Maps
Results from SIR-C
Multifrequency Interferogram Magnitudes, Mt. Etna

SIR-C

Co-registered slant range SAR images. **Ground range:** 66.8 km x 9 km

X-band: 16000 pulses & 1024 range bins, L- and C-band: 2048 range bins
Coregistered Interferograms with flat earth, Mt. Etna, SIR-C

Coregistered Set of Interferograms
Coregistered Multifrequency Interferograms, Mt. Etna, after Flat Earth Removal

Ground range: 66.8 km x 9 km.

X-band: 16000 pulses & 1024 range bins, L- and C-band: 2048 range bins
Coregistered Coherence Maps, Mt. Etna, SIR-C

Ground range: 66.8 km x 9 km.

X-band: 16000 pulses & 1024 range bins, L- and C-band: 2048 range bins

Institut für Hochfrequenztechnik und Radarsysteme
Phase of the Interferogram without "Flat Earth" Component

X-band

C-band

L-band

Test Site: Mt. Etna / Sicily, Italy
Multifrequency Phase Unwrapping

Wrapped Phases with $E_f$

Unwrapped Phases without $E_f$

$E_f \cdot \frac{\lambda_x}{\lambda_c}$

Scaling to X-Band for Comparison Purposes
Multifrequency Phase Fusion Scheme

\[ F = \frac{1}{\gamma_X + \gamma_C \left( \frac{\lambda_X}{\lambda_c} \right)^2 + \gamma_L \left( \frac{\lambda_X}{\lambda_L} \right)^2} \]
Effect of Filtering

unfiltered

filtered
Multifrequency evaluation: Unwrapped Phase Profiles

Filtering before phase unwrapping

Pixel Size: 21 m
3200 Pixel ~ 67 km

2π ~
## Main Features considered in the Fusion Algorithm

<table>
<thead>
<tr>
<th>Features</th>
<th>X-Band</th>
<th>C-Band</th>
<th>L-Band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Coherence over areas with dense vegetation</td>
<td>high</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td>Coherence over areas with sparse vegetation</td>
<td>low</td>
<td>medium</td>
<td>high</td>
</tr>
<tr>
<td>Coherence over areas with dense vegetation</td>
<td>low</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td>Height standard deviation</td>
<td>2,5 m</td>
<td>4,5 m</td>
<td>19 m</td>
</tr>
</tbody>
</table>
D\Phi = 12^\circ; \quad \gamma_L = \gamma_L = 0,9

SNR > 10 \text{ dB}

\vartheta = 49^\circ; \quad B = 54 \text{ m}; \quad \xi = 41^\circ

R = 316 \text{ km}

D\Phi = 2\pi

Dz_\lambda = \lambda 2,23 \text{ km}

Dz_L = 512 \text{ m}

Dz_c = 111,5 \text{ m}

Dz_x = 66,9 \text{ m}
Coherence and Phase Error Examples from SIR-C

<table>
<thead>
<tr>
<th>SNR</th>
<th>Phase Error $\Delta \Phi \ (\text{rms})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 dB</td>
<td>$\pm 40^\circ$</td>
</tr>
<tr>
<td>15 dB</td>
<td>$\pm 21^\circ$</td>
</tr>
<tr>
<td>20 dB</td>
<td>$\pm 13^\circ$</td>
</tr>
<tr>
<td>25 dB</td>
<td>$\pm 9^\circ$</td>
</tr>
<tr>
<td>30 dB</td>
<td>$\pm 4^\circ$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ambiguity Ratio</th>
<th>Phase Error $\Delta \Phi \ (\text{rms})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 dB</td>
<td>$\pm 50,7^\circ$</td>
</tr>
<tr>
<td>-10 dB</td>
<td>$\pm 12,8^\circ$</td>
</tr>
<tr>
<td>-20 dB</td>
<td>$\pm 4,02^\circ$</td>
</tr>
<tr>
<td>-50 dB</td>
<td>$\pm 0,13^\circ$</td>
</tr>
</tbody>
</table>

Good coherence between 2 passes
- X-Band: < 1 day
- C-Band: < 3 days
- L-Band: < 30 days

Good coherence between 2 passes
X-Band: < 1 day
C-Band: < 3 days
L-Band: < 30 days
Coherence Classification, Mt. Etna, Sir-C Data

Coherency Classification Map based on X-C and L-band.

- High and dense vegetation
- Low and sparse vegetation
- Fresh ash and scoria
- Old ash and scoria mantle
- Old covered lava flows
- Clear lava flows
- Fresh lava flows

Test site: Mt. Etna / Sicily