SAR - Systems Calibration

Vorlesung: Hochauflösende Radarsysteme
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Calibration

Relates the **SAR image intensity** to radar backscattering coefficients $\sigma$ & $\sigma_0$, providing information about the accuracy of this relationship.

Estimation and removal of all system-related influences results in pure object signatures.

**Goal**

Model the relationship between geophysical parameters & measured backscattering coefficients.

Quantitative analyses & the development & interpretation of models in different geophysical applications require calibrated data.

Quality of these RCS maps is essentially defined by the capability to determine the radiometric characteristics of the radar system. These are the absolute and relative radiometric accuracy and the radiometric stability.
An overall system calibration includes:

- Internal calibration
- External calibration
- Compensation & correction for system errors in amplitude & phase
- Geo-referenced transformation of SAR image data to backscatter coefficients within an estimated error
Efforts performed by Calibration

Compensation of instrument fluctuations
performed by in-flight verification of the instrument against pre-flight results. This internal calibration
yields a stabilized radar instrument & defines the radiometric stability.

Compensation of the antenna pattern
in order to obtain a constant gain across the whole SAR image by
determination of the actual antenna pattern
leading to relatively calibrated SAR data products

Correction for the radiometric bias
by measuring the radar system against standard ground targets
This external calibration yields to an absolute calibrated radar system and
defines the absolute radiometric accuracy.
Processing Chain

- Kinematic postprocessing of GPS flight path data including IMU data
- Antenna data generation
- Computation of motion irregularities
- SAR focusing considering motion irregularities
- Determination of Coregistration Error
- Calculation of interferometric phase and coherence
- Phase unwrapping
- Absolute phase calibration
- Phase to Cartesian coordinate conversion
- Terrain geocoding of amplitude data
- Radiometric calibration
- Mosaic of geocoded products
Radiometric Calibration Base: Radar Equation

\[ P_{\text{rec}} = \frac{P_{\text{tr}} G^2_{\text{Arge}} (\theta_{\text{Hel}}) G^2_{\text{Aaz}} (\theta_{\text{Haz}}) \lambda^3 G_{\text{recel}} G_{\text{proc}}}{(4\pi)^3 R^3 L_s} \sigma_\theta \]

\[ G^2_{\text{Aaz}} (\theta_{\text{Haz}}) = \frac{\theta_{\text{Haz}} + \Delta \theta}{\theta_{\text{Haz}} - \Delta \theta} \int_{\theta_{\text{Haz}} - \Delta \theta}^{\theta_{\text{Haz}} + \Delta \theta} G^2_{\text{Aaz}} (\theta_{\text{Haz}}) d\theta \]  
and  
\[ \sigma_\theta = \sigma \frac{\sin \vartheta_{\text{irge}} \sin \vartheta_{\text{iaz}}}{\delta_{\text{rge}} \delta_{\text{az}}} \]

Proper determination of

\( \theta_{\text{irge}} = \) local incidence in range, \( \theta_{\text{iaz}} = \) local incidence in azimuth;

\( \delta_{\text{rge}} = \) image pixel dimension in range; \( \delta_{\text{az}} = \) image pixel dimension in azimuth

These quantities depend upon:

- real antenna position
- real antenna pointing direction
- pixel position on the ground
External Calibration
On-Ground Calibration Targets with known RCS

\[ \sigma = \frac{4\pi}{3} \frac{a^4}{\lambda^2} \]
\( \sigma = \frac{4\pi a^4}{3 \lambda^2} \)

E–SAR
18–08–89, 2. Track
C – Band, VV
4 Looks
off nadir = 47°

\( \sigma = 1676 \text{ m}^2 \)
Signal to Noise Ratio as a function of range. (660 m flight altitude, 30 deg depression angle.)
Example: Calibration Field for Scan SAR, ENVISAT/ASAR
Measured Azimuth Antenna Patterns of ASAR/ENVISAT
a) Uncalibrated Slant Range Amplitude Data, b) Terrain geocoded, c) Calibration Factor

F. Holecz 1, P. Pasquali 1, J. Moreira 2, D. Nüesch: RIGOROUS RADIOMETRIC CALIBRATION OF AIRBORNE AeS-1 InSAR DATA Proc. IGARSS July 1998, Seattle, USA.
C-band, 8m receive antenna

X-band
6m receive antenna

Baseline 60 m mast

Orbit height: 233 km
Inclination: 57 deg
X-band lookangle: 52 deg

C-band transmit and receive antenna

X-band transmit and receive antenna (12 m)

flight direction
X-SAR/SRTM Error Budget

X-SAR/SRTM Height Error Sources

- Baseline Tilt Angle
- Baseline Length
- Instrument Phase
- Random Phase
- Ambiguity Phase

Performance Requirements

- Relative Height Accuracy (90 %) < 6 m
- Absolute Height Accuracy (90 %) < 16 m

Height Error Examples (Middle of Swath)

<table>
<thead>
<tr>
<th>Error Type</th>
<th>Relative (30 seconds)</th>
<th>Absolute (11 Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>Error</td>
<td>Accuracy</td>
</tr>
<tr>
<td>Baseline Tilt Angle</td>
<td>2 arcsec</td>
<td>3,0 m</td>
</tr>
<tr>
<td>Baseline Length</td>
<td>1,3 mm</td>
<td>0,8 m</td>
</tr>
<tr>
<td>Instrument Phase</td>
<td>4,0 deg</td>
<td>4,2 m</td>
</tr>
<tr>
<td>Total</td>
<td>5,5 m</td>
<td>14,4 m</td>
</tr>
</tbody>
</table>
Calibration Concept

• Estimation of systematic errors
• Monitoring of system parameters and instrument performance
• Characterization of instrument parameters
• Development of calibration models (parameter drifts as a function of time and temperature)
• Ocean as reference height (sea surface height model)
X-SAR/SRTM Calibration Phases

• Preflight concept definition phase including sensor characterization, calibration algorithm development and implementation

• Ground campaigns during the mission

• 6 months commissioning phase: generation of static and dynamic calibration files, analysis and modeling of parameter drifts with temperature and time

• Operational calibration and validation
SRTM Baseline Measurement Breakdown

\[ \mathbf{B} = \mathbf{M}_{\text{ics}}^{\text{WGS}} (\mathbf{A} - \mathbf{P}_i - \mathbf{E}_i) + \mathbf{M}_{\text{ocs}}^{\text{ICS}} (\mathbf{P}_o + \mathbf{E}_o) \]

\[ \mathbf{P} = \mathbf{P}_i^{\text{WGS}} - \mathbf{M}_{\text{ics}}^{\text{ics}} \mathbf{G}_x \mathbf{A} + \mathbf{P}_i + \mathbf{E}_i \]

- **\( \mathbf{B} \)** = Interferometric Baseline Vector
- **\( \mathbf{P} \)** = Phase Center Position Vector
- **\( \mathbf{A} \)** = ICS to OCS Origin Vector
- **\( \mathbf{P} \)** = Location of GPS Antennas in WGS84
- **\( \mathbf{G} \)** = GPS Antenna ICS/OCS Location
- **\( \mathbf{P} \)** = Antenna Area Centroid Location
- **\( \mathbf{E} \)** = Offset Vectors between Area Centroids
  - Antenna Phase Centers
- **\( \mathbf{M} \)** = Rotation Matrices to convert between Coordinate Systems

**Responsibility Color Codes**

- ---- Structure & Mechanics
- ---- AODA
- ---- C-RADAR
- ---- Ground Data Processing
X-SAR/SRTM Receive Channels with Calibration Tone

Outboard Receive Channel 9602 MHz Inboard Receive Channel

6m Antenna & 6 LNA’s

Combiner

Down Conversion

Mast Cables

135 MHz 263 MHz

RF Adaptor Electronics

IF&Demodulator Electronics

12m Antenna

CAL Tone

Radio Frequency Electronics

1052 MHz

I&Q Signals
Correction & Calibration of the X-SAR Data

Critical Parts of the X-SAR Radar electronics

- Phase variation of radar receive signal in six individual paths:
  antenna panel to XCB including LNA’s & phase shifters

- Down-conversion using 263 MHz signal generated in RFE (1052 MHz) & distributed over the mast to XDC, ± 4 deg phase variation at 263 MHz multiplied by 36 in down-conversion

- Phase variation of radar receive signal running at 135 MHz over the mast cable: ± 2deg over a temperature range between -10°C and -50°C

IF & Demodulator Unit, RF Adaptor Electronics, RF Electronics
X-SAR/SRTM Swaths over Bavaria (Calibration site)
X-SAR/SRTM Calibration Sites

D1-D18 1.5 m Corner reflectors Germany
D19-D24 3m Corner reflectors
D25-D27
RU1-Russia-Kitab-1
RU2-Russia-Zelenchukskaya-2
RU3-Russia-Zvenigorod-3
RU4-Russia-Irkutsk-4
RU5-Russia-Bear_Lakes-5
CH1-5 Switzerland-1-5
SA1-2 South-Africa-1-2
NO1-2 Norway-1-2
EG1-3 Aegypten-1-3
BK1-6 Baikal-1-6
KG1-Kirgisien-1-4
IS1-2 MIRBATS-ISRAEL
IS3-673-HILL-ISRAEL
IS4-MITSPE-ZOHAR-ISRAEL
IS5-HIDDEN-HILL-ISRAEL
IS6-SEDE-ZIN/minhat-north-ISRA
IS7-SEDE-ZIN/minhat-south-ISRA
IS8-BEER-SHEVA/goral-ISRAEL
IS9-BEER-SHEVA/hatserim-ISRAEL

\[ \sigma = \frac{4\pi a^4}{3 \lambda^2} \]
Attitude and Orbit Determination Avionics (AODA)

The relative position of both antennas must be known with a precision better than 1 mm!
# AODA System Overview

<table>
<thead>
<tr>
<th>Instruments</th>
<th>Function</th>
<th>Accuracy</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS 2 GPSR &amp; 4 GPSA</td>
<td>C-band areas (ACS and OCS) state vectors - Position (WGS 84) - Velocity (WGS 84) Time tag</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Star Tracker Assembly (STA)</td>
<td>Estimates inertial attitude of ICS STA boresight orientation inertial space</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inertial Reference Unit (IRU)</td>
<td>Propagation of inertial attitudes between STA updates</td>
<td>roll 5.0 pitch 36.0 yaw 5.0</td>
<td></td>
</tr>
<tr>
<td>ASTROS (AEB) &amp; Optical Target Assembly (OTA)</td>
<td>Estimates the relative attitude and position of the OSS -&gt; SAR baseline and support antenna alignment tracks 3 LED targets at 60 m distance</td>
<td>0.8 arcsec</td>
<td>0.8 arcsec</td>
</tr>
<tr>
<td>Electronic Distance Meter (EDM)</td>
<td>Distance measurement to OCS and X-SAR back structure - 2 for ICS to OCS vector length determination (red.) - 2 for ICS to inboard X-SAR area centroid Y &amp; Z offset determination</td>
<td>- 0.5 mm</td>
<td>- 0.5 mm</td>
</tr>
</tbody>
</table>

**Accuracy**
- X: 1m
- Y: 0.05m/s
- Z: 1m
- 0.05m/s
- 1 Hz
Geometric Calibration

**Differential Range Delays**
Using Data itself by **Cross Correlation of Speckle Patterns** between the two Interferometric Channels

**Common Range Delay, Time Tag/Velocity Biases**
Using **Corner Reflectors, Calibration Sites:**
Oberpfaffenhofen, Mojave Desert, Australia

**Baseline Length/Tilt, Orbit, Phase Offsets:**
Estimation from **Short Ocean Data Takes** before & after Ocean-land Crossing or from **Ground Control Points**

**Residual Phase Errors (e.g. Multipath) & System Stability:**
**Long Ocean Data Takes** at the Beginning & End of the Mission
Required data for X-SAR calibration/validation

- NIMA/JPL
- DLR/User
- DLR/User
- X-SAR
- DLR/User
- ERS-1 altimeter data
- TOPEX-POSEIDON data
- GCP data base
- High precision DEMs
- Ocean data takes
- Calibration test sites (CRs)
- Geoid undulations
- GDPS

- AODA-PADR file
- X-SAR HK data
- Tide tables
- Maps
- Cal tone
- GDPS
- X-GDPS

- AODA
- MPOS
- DLR/User
- DLR/User
- X-SAR
INSTRUMENT CALIBRATION

Interferometric phase:

\[ \Phi_{\text{int}} = -(\Phi_1 - \Phi_2) + \frac{1}{6} \sum (\Phi_{\text{CT1}} - \Phi_{\text{CT2,i}}) + 36.5 \Phi_{\text{boom-out}} - 1/6 \sum (\Phi_{\text{ant-LNA,i}} - \Phi_{\text{switch,i}} - \Phi_{\text{XCB-LNA}}) + \Phi_{\text{ant1-testcp}} - \Phi_{\text{RAE-testcp}} - \Phi_{\text{CT-att1}} + \Phi_{\text{CT-}} \]

- caltone estimation
- phase variation of 263MHz signal on boom cable from phase detector
- correction terms from preflight instrument characterization
X-SAR/SRTM Swaths over Bavaria (Calibration site)
Ocean Calibration

- Height error:
  \[ \delta h = h_{\text{meas}} - h_{\text{ground-truth}} \]

- Error contributions from baseline length/tilt, phase and orbit height offsets
  \[ \delta h = [\delta_{h,b} \quad \delta_{h,\alpha} \quad \delta_{h,\phi} \quad \delta_{h,H}] \begin{bmatrix} \delta b \\ \delta \alpha \\ \delta \Phi \\ \delta H \end{bmatrix} \]

- MAP estimation based on prior information provided by AODA problem sufficient SNR at 55deg incidence angle?

Two iterations to determine static and dynamic calibration file
SRTM Calibration: measured Height over Ocean

8500 km

22 m

Institut für Hochfrequenztechnik und Radarsysteme

Quellenangabe
Result: Long Time Stability on DT 146.190

Absolute Accuracy 16 m (99%)

Relative Accuracy 6 m (84%)

8500 km

Azimuth cut of DEM error over a long ocean data take. Absolute accuracy requirement (16 m, 90%) is easily met, the relative requirement (6 m, 90%) only after reduction of thermal noise.
Features/Operation Modes of TerraSAR-X

<table>
<thead>
<tr>
<th>Single/dual polarisation</th>
<th>Large number of:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide range of swath positions (20° - 55°)</td>
<td>- Operation modes</td>
</tr>
<tr>
<td>3 basic operation modes</td>
<td>- Antenna beams</td>
</tr>
</tbody>
</table>
  - Strip Map (26 look angles)
  - ScanSAR (WS à 4 SS)
  - Spotlight (123 look angles)
| Left/right looking SAR | 26 elevation beams |
| Experimental modes | 123 elevation beams à 100 azimuth patterns |
  - Wide band width
  - Along track interferometry

Calibration major challenge costs affordable
TerraSAR Calibration Concept

- Internal Calibration
- PN-Gating Method
- In-Orbit Analysing of Individual TRM’s
- Antenna Pattern
- Precise Model
- Estimation of Actual Antenna Pattern
- Measurements as much as possible
- Sufficient Number of Ground Targets
- Reliable Reference
TerraSAR Calibration Concept & Philosophy

- Calibration
  - Radiometric Characteristics
    - Calibration
  - Stability
    - Internal Calibration
  - Relative Accuracy
    - Antenna Pattern Compensation
  - Absolute Accuracy
    - Bias Correction

Image magnitude → Calibration → Physical units
Challenge of Antenna Pattern Optimisation

- Drifted or failed T/R modules
- Optimization of remaining modules
- Best beam steering

**Diagram:**
- Antenna array
- T/R modules
- Elevation Pattern and Template
  - Side lobe region
  - Main lobe region
TerraSAR Internal Calibration

3 Calibration Pulses:

– 1 Transmit Path 1-2-4-5
– 2 Receive Path 6-4-2-1
– 3 Only RFE/DCE 6-5

controlling the instrument as a whole

individual modules?
TerraSAR Internal Calibration

critical part of TerraSAR-X: is the active antenna, X-Band Front-end (XFE) consisting of 384 transmit/receive (T/R) modules each feeding a radiating sub-array for horizontal and vertical polarisation. Critical elements & parameters of the XFE are monitored. For this three different types of calibration pulses are applied, whereby sets of these pulses are needed at the start and end of each data take. All calibration pulses have the same length and bandwidth (chirp) as is commanded for the mode.

Transmit Signal Path (1-2-3): During imaging transmit pulse is routed from the RF electronics (1) through the transmit/receive (Tx/Rx) distribution network where it is divided up and connected to the T/R modules (2). There it is amplified before being applied to the radiator sub-array (3) for transmission.

• Receive Signal Path (3-2-1): The radar echo received by the antenna is passed to the T/R modules (3), where it is amplified. The signals from all the modules are combined in the Tx/Rx network and fed to the RF Electronics. From there it goes to the Digital Control Electronics (DCE) where it is digitised and formatted, before being stored in the Solid State Mass Memory (SSMM)

Correcting Calibration Path (6-5): Calibration Pulse 3 is for monitoring the receive path through RF Electronics and Digital Control Electronics, excluding the XFE. It is needed for correcting the Calibration Pulse 1 and 2.
PN – Gating Principle

Overall signal:

\[ s_c(t) = \sum_{i=0}^{N_{T/R}-1} c_i(t) \cdot a_i \cdot e^{j\varphi_i} + n_i(t) \]

Complex signal of \( jth \) T/R module:

\[ s_j(t) = a_j \cdot e^{j\varphi_i} \]

Information extraction for one T/R module:
correlate overall signal is with respective PN sequence:

\[ CCF_j(\tau = 0) = \int s_c(t) \cdot c_j(t) \, dt = \hat{s}_j = \hat{a}_j \cdot e^{j\varphi_i} \quad (3) \]

This decoding process removes the PN modulation
the complex correlation peak is an estimation of
amplitude & phase settings of the respective T/R module
Superposition of all T/R Signals

\[ S_c(t) = \sum_{i=1}^{N_{T/R}} s_i(t) \cdot c_i(t) \]

correlation with the inherent Module code \( c_i \)

extraction of individual module signal \( s_i \)

<table>
<thead>
<tr>
<th>bit</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>( \cdots )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_1 \cdot c_1 )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
</tr>
<tr>
<td>( S_2 \cdot c_2 )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
</tr>
<tr>
<td>( S_3 \cdot c_3 )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
</tr>
<tr>
<td>( S_N \cdot c_N )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
</tr>
</tbody>
</table>
PN-Gating

Technique characterizing individual T/R modules while all modules are operating, i.e. a characterization under most realistic conditions.

Phase of each T/R module individually shifted about \( \pm \pi/2 \) between Cal-pulses

i.e.

phase shift keying according to a

PN code sequence

Each T/R module has a different PN code or code shift resp
For larger Number of T/R Modules code length would need to be increased correspondingly to achieve the same errors. But using of an ideally orthogonal code (Walsh sequence f.e.) the cross correlation of two distinct sequences is 0. Thus the code length can be reduced considerably down to 512 for 384 T/R modules.
Antenna Pattern Model

Goal:
Derive all reference pattern required for SAR data processing; i.e. provide an accurate estimation of the actual antenna pattern with a minimum number of costly in-flight antenna pattern measurements.

- **Pre-flight Characterization**: calculating & analyzing antenna patterns of the different operation modes as well as on-ground antenna pattern measurements like those of a single radiation element or individual rows or panels.

- **In-Orbit Verification**: in-flight antenna patterns measured in use of ground receivers & by rainforest measurements (expensive!).

- **Internal Calibration**: PN-gating method, an antenna pattern can be calculated with the actual excitation coefficients of the individual modules.

- **Module Failure Analysis**: in case of contingencies, for example failed T/R modules, an optimization of the excitation coefficients of the remaining modules is intended in order to obtain the best beam of each operation mode.
Antenna Pattern Model

Pre-Flight Characterisation
- Synthesis
- Analysis
- On-Ground Measurements

In-Orbit Verification
- In-Flight Measurement
- Rainforest Measurement

Internal Calibration
- PN-Gating
- Module Stepping

Module Failure
- Antenna Optimisation
- Synthesis

Antenna Pattern Model

Estimation of Actual Antenna Pattern

Reference Pattern for Processing
Essential TerraSAR-X calibration facilities:

- standard ground targets for the bias correction,
- ground receivers for in-flight measurements,
- different analysis and evaluation tools, like antenna pattern model providing an estimation of the actual antenna pattern or
- an appropriated SAR processor, as there are two types of calibration data that have to be processed:
  - SAR images covering deployed calibration targets,
  - special calibration products like PN-gating method
Essential TerraSAR-X calibration facilities

- **Standard ground targets** for bias correction
- **Ground receivers** for in-flight measurements
- **Different analysis & evaluation tools**, like
  - antenna pattern model providing to estimate the actual antenna pattern
  - **SAR Product Control Software (SARCON)** for target analysis of different calibration targets
- **Appropriated SAR processor**, for the two types of calibration data to be processed:
  - SAR images covering deployed calibration targets,
  - Special calibration products like these of the presented
- **PN-gating method.**

A major challenge for calibrating the TerraSAR-X instrument. Is keeping the cost affordable