Final Results of DLR’s Independent Sentinel-1B System Calibration

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Objective and Respective Tasks

➢ The objective of the DLR’s task is to obtain an **independent assessment** for the **calibration** of Sentinel-1B (similar to S-1A).

➢ In addition to the S-1B commissioning phase executed by ESA, the **Institute** has planned, implemented and executed a **complementary calibration campaign**.

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**SAR System Calibration**

- **Geometric Calibration**
  - Range Delay Offset
  - Azimuth Shift

- **Internal Calibration**
  - Amplitude/Phase Drift
  - RF Characterization

- **Pointing Determination**
  - Elevation
  - Azimuth

- **Antenna Model Verification**
  - Elevation
  - Azimuth

- **Absolute Radiometric Calibration**
  - Absolute Calibration Factor

- **Polarimetric Calibration**
  - Distortion (Imbalance, Cross Talk)
  - Faraday Rotation

- **Corner Reflectors**
- **Transponders**
  - Corner Reflectors
  - Transponders
  - Distributed Target

- **Pixel Localization Accuracy**

- **Radiometric Stability**

- **Relative Radiometric Accuracy**

- **Absolute Radiometric Accuracy**

- **External Calibration**
Challenge to calibrate Sentinel-1

- **4 different Modes** operated at least over 10 Years
- Dual Polarization
- Wide Range of Swath Positions (18°-47°)
- **Tight Performance** in all Modes

1.0dB (3σ) Commissioning Phase 3 Months

Efficient Calibration Strategy
S1 Coverage across DLR Cal-Field

- **Goal**: One absolute calibration factor based on DLR antenna model approach
- **suitable set** of 7 beams covering low, mid and high incidence angles, 1 beam/mode

External Calibration reasonable

- SM1, SM2, IW1, EW3, SM5, IW3 and WV1

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**at least 4 Targets per Pass**

- 2 x low
- 2 x mid
- 2 x high

**incidence angle**

**85 km**

**WV1 asc Day 10**

**Goal**: One absolute calibration factor based on DLR antenna model approach

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**External Calibration reasonable**

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**D39, D40, D41 Transponder**

- **D38, D42, D43 Corner Reflector**

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**Oberpfaffenhofen**

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**DLR SAR Calibration Center**
DLR’s remote controlled Reference Targets

- Deployed and successfully operated for Sentinel-1 since April 2014
- Being checked permanently
- Can be aligned for further spaceborne SAR missions

3 Corner Reflectors
- 2.8 m leg length => 49.2 dBm² RCS
- ≤ 1.0 mm mech. tolerance
- **0.2 dB (1σ) abs. rad. accuracy**

3 C-Band Transponders
- 5.405 GHz, 100 MHz BW, 60 dBm² RCS
- ≤ 0.1 rad. stability
- **0.2 dB (1σ) abs. rad. accuracy**
In-Orbit Calibration Plan

- **Launch**
- **Pre-Phase**
  - **Antenna Pointing**
  - **GeoCal**
  - **Antenna Model Verification**
- **Cal Targets**
  - **Rainforest**
- **Internal Calibration**
- **DLR’s Complementary Calibration Campaign = 6.5 Repeat Cycles**

- **First S1B acquisition** over **DLR Cal field** on **15th June 2016**
- **36 S-1B acquisitions**
- **30 S-1A acquisitions**

**66 acquisitions were successfully executed and analyzed in 2.5 months** (15.6.2016 – 25.8.2016)
S-1B Instrument Drift of a Long IW DT (25 min)

EFE Temperature [deg]

Amplitude Drift < 0.25dB

Phase Drift ~ 15 deg

• Stable Performance even for long Data Takes
• Residual drift can be compensated for by Internal Calibration

Δ Temp ≈ 20°C
S-1B RF Characterization of individual T/R Modules

• First In-Flight Monitoring by means of the PCC Method verifies the RF Performance of individual T/R Modules

In-Flight measured Excitation Laws of 280 TRMs

- Tile #5 Row #7,8
- 2 TRMs non-operational (< 1 %)
- no impact on antenna performance

• RF characterization over 2.5 months shows very stable Sentinel-1B front end (color of asterisk indicates an individual TRM)

In-Flight measured Excitation Laws of 280 TRMs

- Amplitude Setting < 0.2dB
- Phase Setting < 3deg

2.5 months RFC acquisitions

RFC Measurement Execution Time [date]
Antenna Pointing Determination: Notch Pattern Evaluation

Evaluation of transponder measured azimuth notch patterns for determining antenna azimuth pointing

- Elevation dependent azimuth squint
- Indicates mispointing both in pitch and yaw

Evaluation of elevation notch patterns acquired over the Amazon rainforest for Determining antenna elevation pointing

- After star tracker realignment: Average copol roll mispointing around -15 mdeg
Antenna Pattern Verification in Azimuth: Stripmap Beam recorded by DLR Transponder

- Inputs
  - Precise orbit and attitude
  - Transponder position and pattern
  - GPS measurement times
  - Satellite parameters

Ground Receiver Position Vector

Mispointing corrected

- 28 mdeg Azimuth Squint

Accuracy within main beam $\Delta \leq 0.05$ dB
- Results comparable for S1, 2 & 5
  $\rightarrow$ transmit azimuth beam pattern highly accurate
Antenna Model Verification in Elevation

- Instrument is operated in TOPS mode
- EW elevation beams measured across the Amazon rainforest
- Miss-pointing correction applied during analysis
- For co-pol **beam-to-beam gain offset** between subswaths up to **0.5 dB**
- **Gain slope** almost **1 dB** for co-pol

Check **antenna patterns** and **normalization** during SAR data processing as for S1A
S-1 Pass across DLR Cal-Field

- Independent Sentinel-1A and Sentinel-1B system calibration executed during CP in 2014 and 2016 respectively
- Calibration support for routine operation of Sentinel-1A since November 2014
Residual offset in range **+1.1 m**, in azimuth **-1.8 m**

⇒ can be compensated for by shifting the SAR data

**Pixel localization accuracy** (1σ, Req. 0.83 m SM, 3.33 m IW)

- in range for all modes < **0.6 m**
- In azimuth < **0.9 m** (SM), < **1.5 m** (IW)

- Range delay offset based on near real time (NRT) orbit
- And compensated for
  - instrument delay and
  - atmospheric delay
Absolute Radiometric Calibration

- **Absolute calibration factor** derived from the IRF of each DLR target and for different modes and beams
- **Offsets** of absolute calibration factor up to 2.0 dB
  - For stripmap mode an incorrect beam-to-beam gain offset compensation was identified and will be removed
Similar mean values for HH, HV, and VV polarization, but VH channel has an offset of up to 0.5 dB.

Radiometric accuracy of S-1B for IW products 0.36 dB (1σ)*

(*0.05 dB stability, 0.067 dynamic range error, 0.2 dB target accuracy, w/o atmospheric losses)
Channel Imbalance in Gain

- Derived by transponder IRF
- Channel imbalance up to 1.2 dB between cross- and co-pol channel
- High channel imbalance for low and high look angles
  similar **smiling effect** (elevation dependent) as for S-1A

- H and V on transmit show opposite behavior
- But changing the sign of one pair yields the same curve for both polarization on transmit, e.g. (HV – HH) and (VV-VH)
  \( \Rightarrow \) imbalance is independent of transmit polarization and rather determined by the receiving channels (V-H)
Channel Imbalance in Phase

- Stable phase imbalance of $+150^\circ$ for VV - VH and $-150^\circ$ for HH - HV
  - will be corrected during SAR data processing ($\text{PG}_{\text{ref}}$)
- Phase imbalance independent of transmit polarization
- Phase imbalance determined by receiving channels: $\text{Rx}_V - \text{Rx}_H$
- For low elevation angles small phase slope of about $8^\circ$ (residual uncertainty after phase pattern compensation ?)
Cross-talk using Corner Reflectors

- Cross-pol signal is suppressed by trihedral corner reflector
- **Ratio** between cross- and co-pol is used to determine the cross-talk of the SAR instrument

Cross-talk for all modes

< - 35 dB

(SM < -45dB)
Summary & Recommendations

- **Efficient calibration strategy** has been developed for Sentinel-1 (precise antenna model, relying on 1 absolute calibration factor)

- **DLR calibration field** (South Germany) has been **successfully operated** for S-1A since launch in **April 2014** and now also for S-1B: enclosing an area of **20 km x 85 km** and 6 test sites with the **latest generation** of DLR’s remote controlled reference targets

- **High stability** of the Sentinel-1B instrument even for long DTs

- **TRM performance** is **confirmed** (4 non-operational TRMs have no impact < 1.5%)

- **Several effects** were observed and investigated, corresponding **recommendations** were derived (e.g. derive ExLaw reference values in-flight, apply actual failure matrix, pointing correction, etc.), at least two major **effects** should be investigated further on:
  - **Channel imbalance** in gain shows **smiling effect** (similar as S-1A)
    => check **receiving patterns** and their **application** during **SAR data processing**
    (performance of transmit patterns successfully verified)
  - **Offset** between **stripmap** up to **2.0 dB** (EW up to 0.5 dB): normalization issue

- **Absolute radiometric accuracy** of Sentinel-1B in **IW mode** shows the strong requirement of **1.0 dB** ($3\sigma$) can in principle be achieved in all modes.