DLR'S INDEPENDENT VERIFICATION OF THE SENTINEL-1C SYSTEM CALIBRATION

Patrick Klenk, K. Schmidt, J. Giez, A. Pullela, M. Nannini, P. Prats, M. Schwerdt

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2024/11/12

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Introduction & Overview

- **ESA's third** Sentinel-1 (S1) S/C **Sentinel-1C (S1C)** to be launched **this December**
- **Independent system calibration** to be performed **by the DLR SAR Calibration Center** under an ESA contract
- This presentation:
  - Overview of previous DLR Cal/Val activities in support of Sentinel-1 & introduction to DLR Cal field
  - Calibration Approach and activities planned for Sentinel-1C
  - Selected results from just completed commissioning phase rehearsal

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DLR's general SAR System Calibration Concept

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SAR System Requirements

Pixel localization accuracy	Radiometric Stability →	Relative Radiometric Accuracy →	Absolute Radiometric Accuracy
Timing variations after compensation	Temporal system variations	Spatial system variations	Link to absolute radiometric reference

SAR System Calibration Procedures

Geometric Calibration
- Bias estimation and compensation for fast and slow time

Internal Calibration
- Drift compensation (amplitude, phase)
- RF characterization

Pointing Determination
- Elevation
- Azimuth

Antenna Model Verification
- Elevation
- Azimuth

Polarimetric Calibration
- Balance polarization channels (gain, phase)

Absolute Radiometric Calibration
- Derive radiometric bias (absolute calibration factor)

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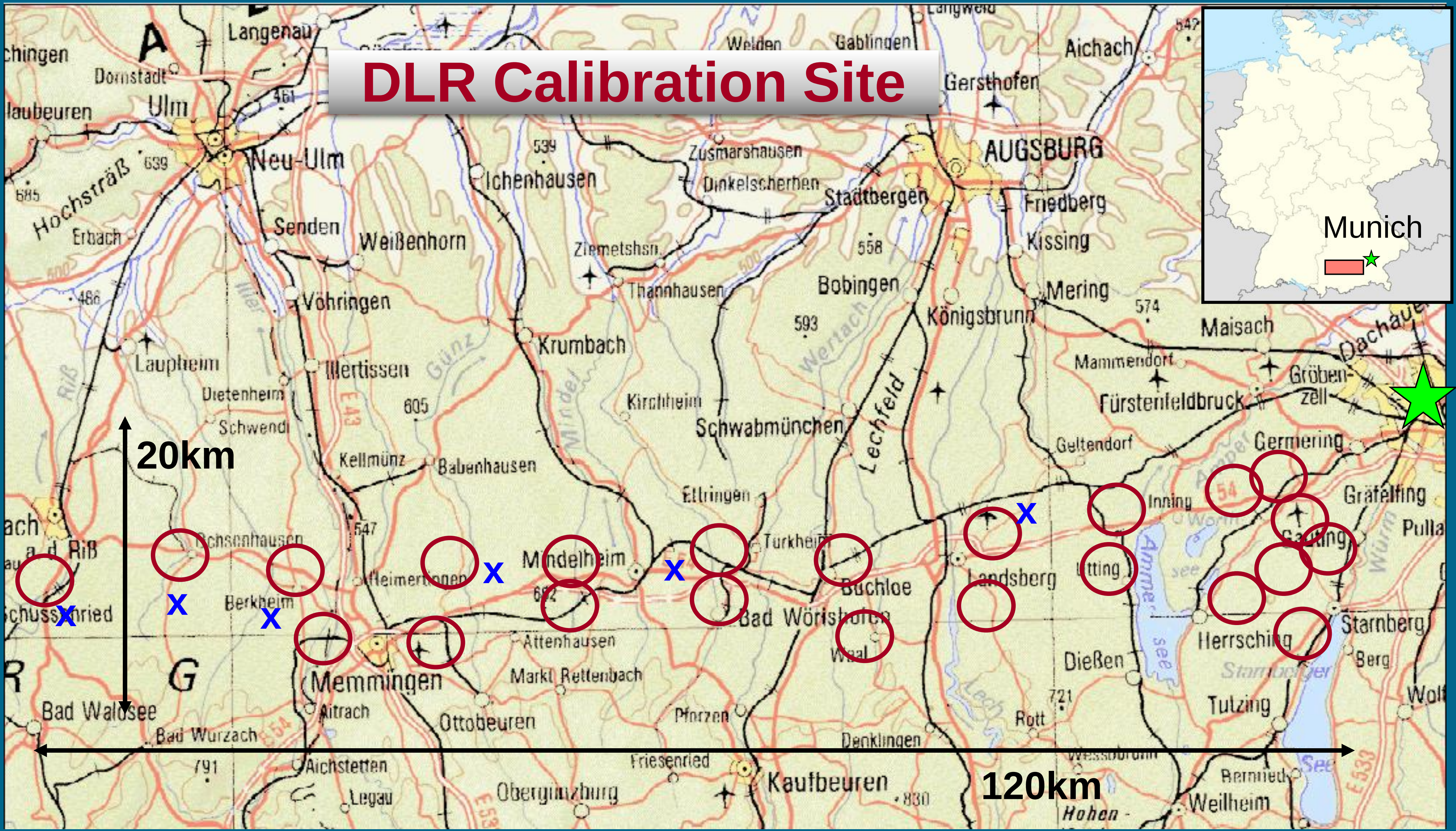
DLR Calibration Site



- **23 corner reflectors (red circles)**
- Including **6 remote controlled targets** (blue crosses)

29 target positions in South Germany (20 km x 120 km)

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DLR's remote controlled Reference Targets

- 3 CR and 3 transponders deploye[...] DLR Calibration Site (area of 120 x 40 km²) [...] rmany
- Deployed and operat[...] entinel-1B since April 2014 => [...] for **Sentinel-1A/B and C**
- Aligned [...] AR missions like SARah or Capella

More details on our innovative reference targets:
See tomorrow's talks by S. Raab and A.M. Büchner

3 Corner Reflectors

- 2.8 m leg length, RCS: 4[...]
- ≤ 1.0 mm mech[...]
- 0.2 dB ab[...]

C-Band Transponders

- 5.405 GHz, 100 MHz BW
- 60 dBm² RCS
- ≤ 0.1 rad. stability
- 0.2 abs. rad. accuracy => **patented** method "**3 TM**"

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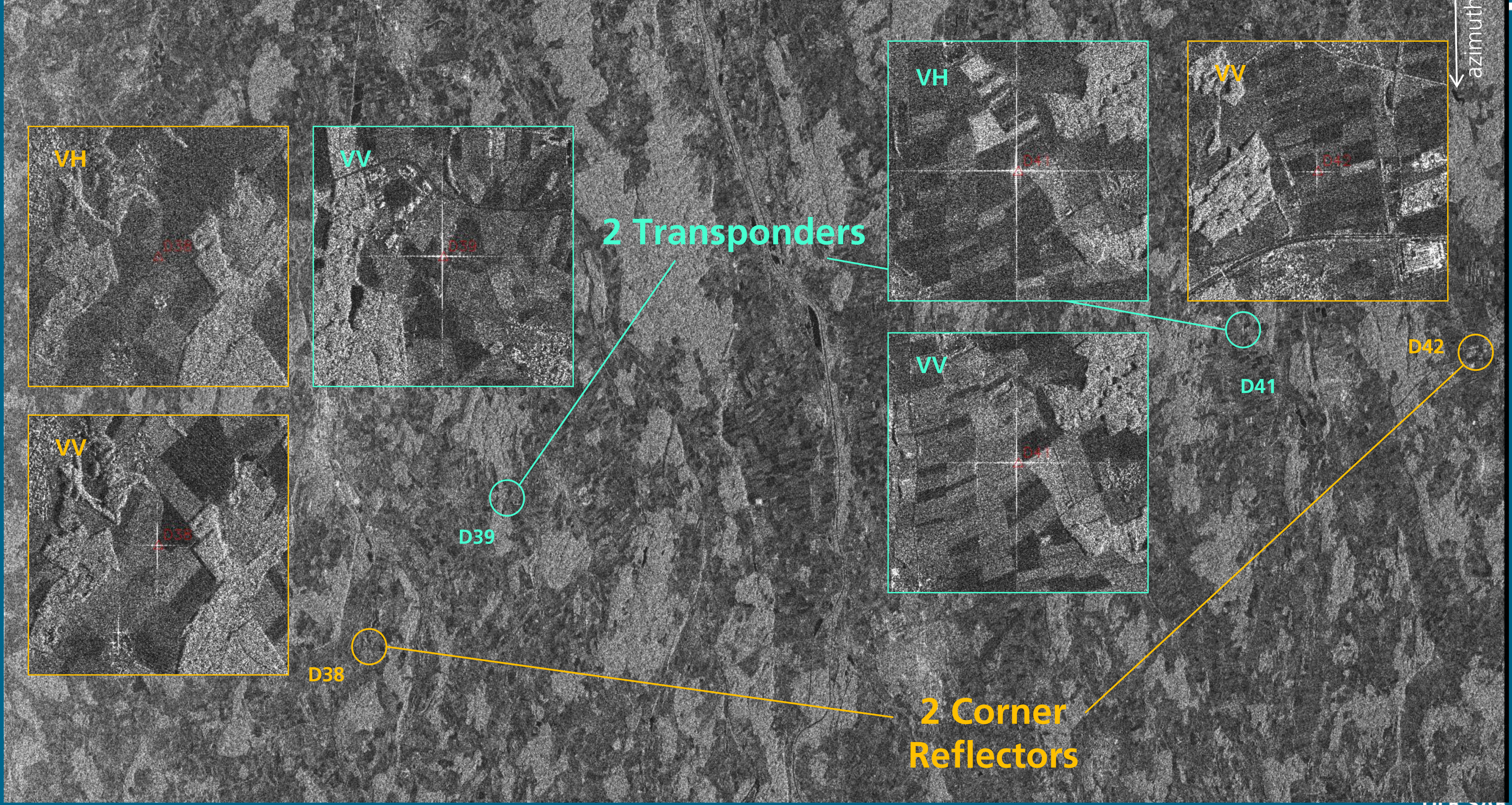
Sentinel-1A SAR Image of DLR Cal-Field - 2014-05-19



- StripMap Mode in Dual Polarization (VV, VH)

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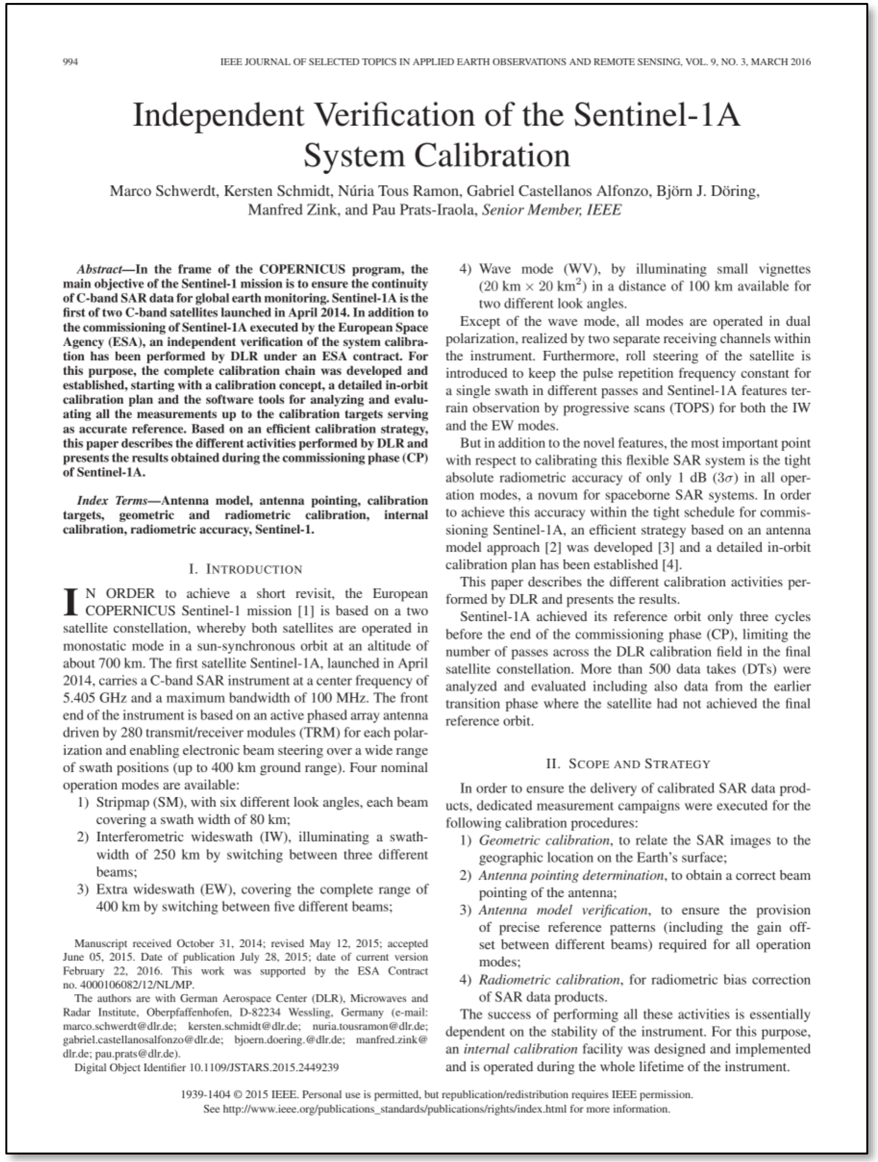
Previous Independent DLR Calibration Campaigns for Sentinel-1

- DLR's independent assessment of end-to-end SAR system calibration on behalf of ESA of S1A in 2014 and S1B in 2016
- Similar scope of independent cal/val activities planned for S1C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Independent Verification of the Sentinel-1A System Calibration

Marco Schwerdt, Kersten Schmidt, Núria Tous Ramon, Gabriel Castellanos Alfonzo, Björn J. Döring, Manfred Zink, and Pau Prats-Iraola, *Senior Member, IEEE*

***Abstract*—In the frame of the COPERNICUS program, the main objective of the Sentinel-1 mission is to ensure the continuity of C-band SAR data for global earth monitoring. Sentinel-1A is the first of two C-band satellites launched in April 2014. In addition to the commissioning of Sentinel-1A executed by the European Space Agency (ESA), an independent verification of the system calibration has been performed by DLR under an ESA contract. For this purpose, the complete calibration chain was developed and established, starting with a calibration concept, a detailed in-orbit calibration plan and the software tools for analyzing and evaluating all the measurements up to the calibration targets serving as accurate reference. Based on an efficient calibration strategy, this paper describes the different activities performed by DLR and presents the results obtained during the commissioning phase (CP) of Sentinel-1A.**

***Index Terms*—Antenna model, antenna pointing, calibration targets, geometric and radiometric calibration, internal calibration, radiometric accuracy, Sentinel-1.**

I. Introduction

IN ORDER to achieve a short revisit, the European COPERNICUS Sentinel-1 mission [1] is based on a two satellite constellation, whereby both satellites are operated in monostatic mode in a sun-synchronous orbit at an altitude of about 700 km. The first satellite Sentinel-1A, launched in April 2014, carries a C-band SAR instrument at a center frequency of 5.405 GHz and a maximum bandwidth of 100 MHz. The front end of the instrument is based on an active phased array antenna driven by 280 transmit/receiver modules (TRM) for each polarization and enabling electronic beam steering over a wide range of swath positions (up to 400 km ground range). Four nominal operation modes are available:

1) Stripmap (SM), with six different look angles, each beam covering a swath width of 80 km;
2) Interferometric wideswath (IW), illuminating a swath-width of 250 km by switching between three different beams;
3) Extra wideswath (EW), covering the complete range of 400 km by switching between five different beams;
4) Wave mode (WV), by illuminating small vignettes (20 km × 20 km^2) in a distance of 100 km available for two different look angles.

Except of the wave mode, all modes are operated in dual polarization, realized by two separate receiving channels within the instrument. Furthermore, roll steering of the satellite is introduced to keep the pulse repetition frequency constant for a single swath in different passes and Sentinel-1A features terrain observation by progressive scans (TOPS) for both the IW and the EW modes.

But in addition to the novel features, the most important point with respect to calibrating this flexible SAR system is the tight absolute radiometric accuracy of only 1 dB (3σ) in all operation modes, a novum for spaceborne SAR systems. In order to achieve this accuracy within the tight schedule for commissioning Sentinel-1A, an efficient strategy based on an antenna model approach [2] was developed [3] and a detailed in-orbit calibration plan has been established [4].

This paper describes the different calibration activities performed by DLR and presents the results.

Sentinel-1A achieved its reference orbit only three cycles before the end of the commissioning phase (CP), limiting the number of passes across the DLR calibration field in the final satellite constellation. More than 500 data takes (DTs) were analyzed and evaluated including also data from the earlier transition phase where the satellite had not achieved the final reference orbit.

II. Scope and Strategy

In order to ensure the delivery of calibrated SAR data products, dedicated measurement campaigns were executed for the following calibration procedures:

1) *Geometric calibration*, to relate the SAR images to the geographic location on the Earth's surface;
2) *Antenna pointing determination*, to obtain a correct beam pointing of the antenna;
3) *Antenna model verification*, to ensure the provision of precise reference patterns (including the gain offset between different beams) required for all operation modes;
4) *Radiometric calibration*, for radiometric bias correction of SAR data products.

The success of performing all these activities is essentially dependent on the stability of the instrument. For this purpose, an *internal calibration* facility was designed and implemented and is operated during the whole lifetime of the instrument.

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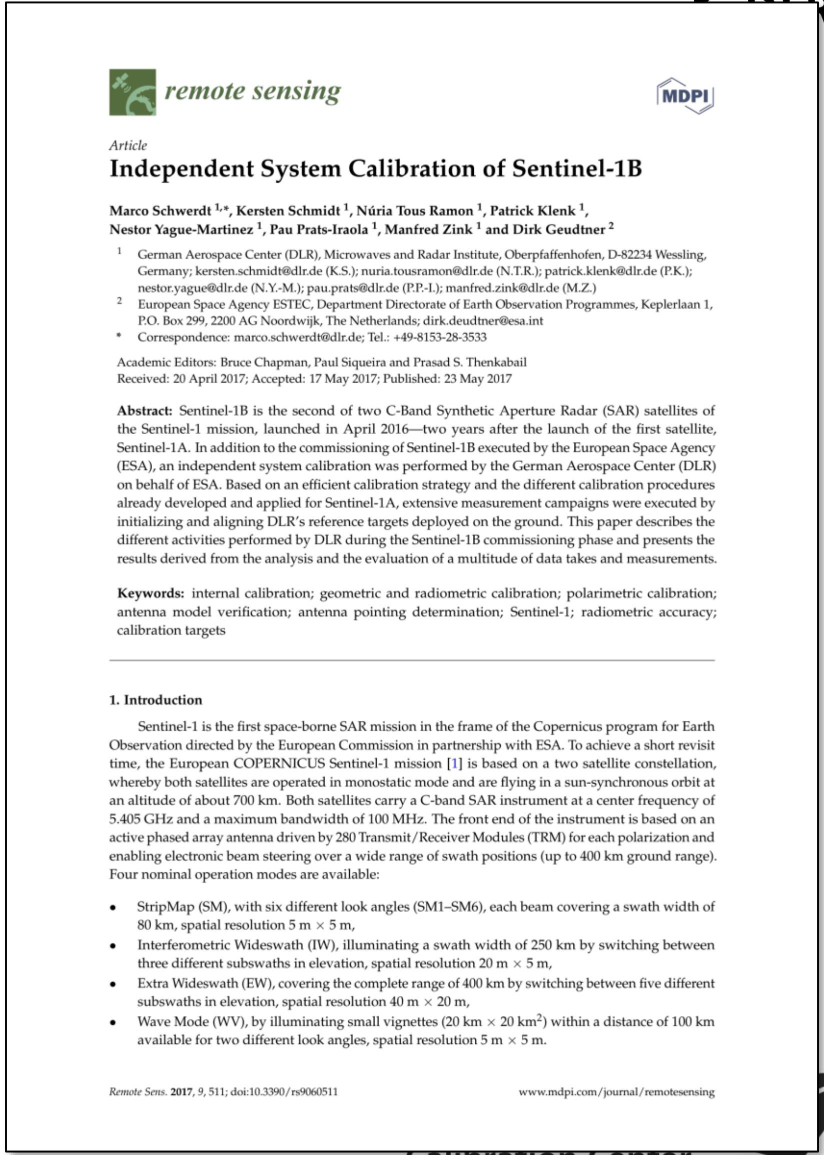
remote sensing
MDPI

Article

Independent System Calibration of Sentinel-1B

Marco Schwerdt [1,*], Kersten Schmidt [1], Núria Tous Ramon [1], Patrick Klenk [1], Nestor Yague-Martinez [1], Pau Prats-Iraola [1], Manfred Zink [1] and Dirk Geudtner [2]

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Abstract: Sentinel-1B is the second of two C-Band Synthetic Aperture Radar (SAR) satellites of the Sentinel-1 mission, launched in April 2016—two years after the launch of the first satellite, Sentinel-1A. In addition to the commissioning of Sentinel-1B executed by the European Space Agency (ESA), an independent system calibration was performed by the German Aerospace Center (DLR) on behalf of ESA. Based on an efficient calibration strategy and the different calibration procedures already developed and applied for Sentinel-1A, extensive measurement campaigns were executed by initializing and aligning DLR's reference targets deployed on the ground. This paper describes the different activities performed by DLR during the Sentinel-1B commissioning phase and presents the results derived from the analysis and the evaluation of a multitude of data takes and measurements.

Keywords: internal calibration; geometric and radiometric calibration; polarimetric calibration; antenna model verification; antenna pointing determination; Sentinel-1; radiometric accuracy; calibration targets

1. Introduction

Sentinel-1 is the first space-borne SAR mission in the frame of the Copernicus program for Earth Observation directed by the European Commission in partnership with ESA. To achieve a short revisit time, the European COPERNICUS Sentinel-1 mission [1] is based on a two satellite constellation, whereby both satellites are operated in monostatic mode and are flying in a sun-synchronous orbit at an altitude of about 700 km. Both satellites carry a C-band SAR instrument at a center frequency of 5.405 GHz and a maximum bandwidth of 100 MHz. The front end of the instrument is based on an active phased array antenna driven by 280 Transmit/Receiver Modules (TRM) for each polarization and enabling electronic beam steering over a wide range of swath positions (up to 400 km ground range). Four nominal operation modes are available:

- StripMap (SM), with six different look angles (SM1–SM6), each beam covering a swath width of 80 km, spatial resolution 5 m × 5 m,
- Interferometric Wideswath (IW), illuminating a swath width of 250 km by switching between three different subswaths in elevation, spatial resolution 20 m × 5 m,
- Extra Wideswath (EW), covering the complete range of 400 km by switching between five different subswaths in elevation, spatial resolution 40 m × 20 m,
- Wave Mode (WV), by illuminating small vignettes (20 km × 20 km^2) within a distance of 100 km available for two different look angles, spatial resolution 5 m × 5 m.

Remote Sens. **2017**, *9*, 511; doi:10.3390/rs9060511 www.mdpi.com/journal/remotesensing

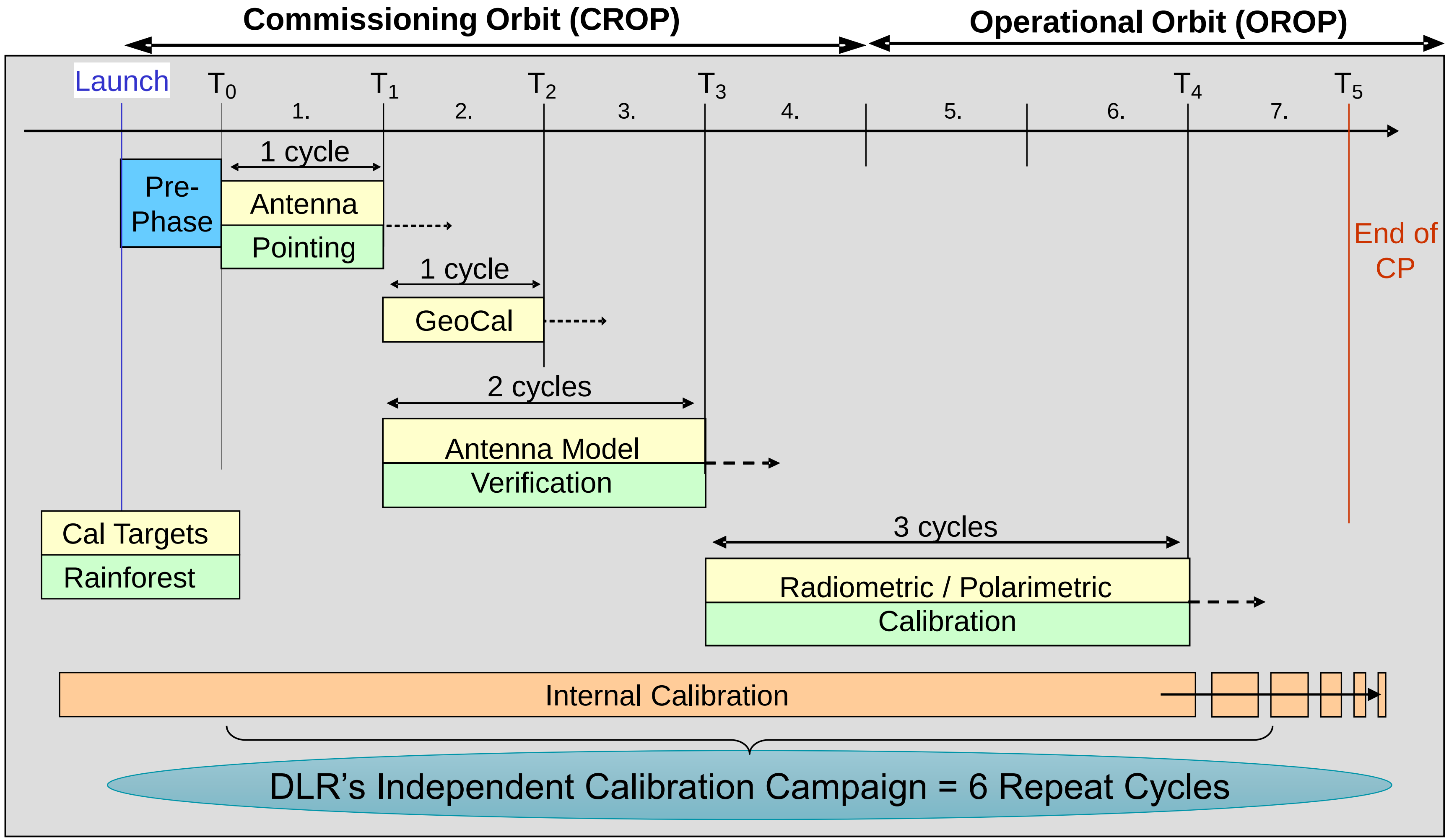
Novel Calibration Aspects for S1C

- Implementation of S1C hardware improvements compared to S1A/B [1] [2] ,
- Simplification of calibration pulse sequence, dropping S1A/B‘s APDNCal and TaCal pulses,
- Adjustments to RF-Characterization (RFC) mode timeline,
- Additional interleaved noise pulses for IW, EW and WV modes [2] .

→ Adjustments with respect to Sentinel-1 A/B necessary, tools adapted

[1] P. Potin et al, “Sentinel-1A/-1B Mission and Performance Status, Sentinel-1C/-1D Improvements,” in EUSAR 2022, pp. 141–146.
[2] E. Schied et al, “The Sentinel-1 C & D SAR Instrument,” in EUSAR 2018, June 2018, pp. 632–635, 2018.

Sentinel-1C In-Orbit Calibration Plan



- Dedicated in-orbit calibration plan for S1C CP activities includes multiple acquisitions over the DLR calibration field
- Initial CP activities (four cycles) with 30 degree orbit phasing to S1A, rest in 180 degree phasing

- **First acquisition** over **DLR Cal field** will be in **CW 1/2 2025**
- **24 S-1C acquisitions in CROP**
- **18 S-1C acquisitions in OROP**

} **42 S1C acquisitions** in **first six cycles** (01-04 2025)

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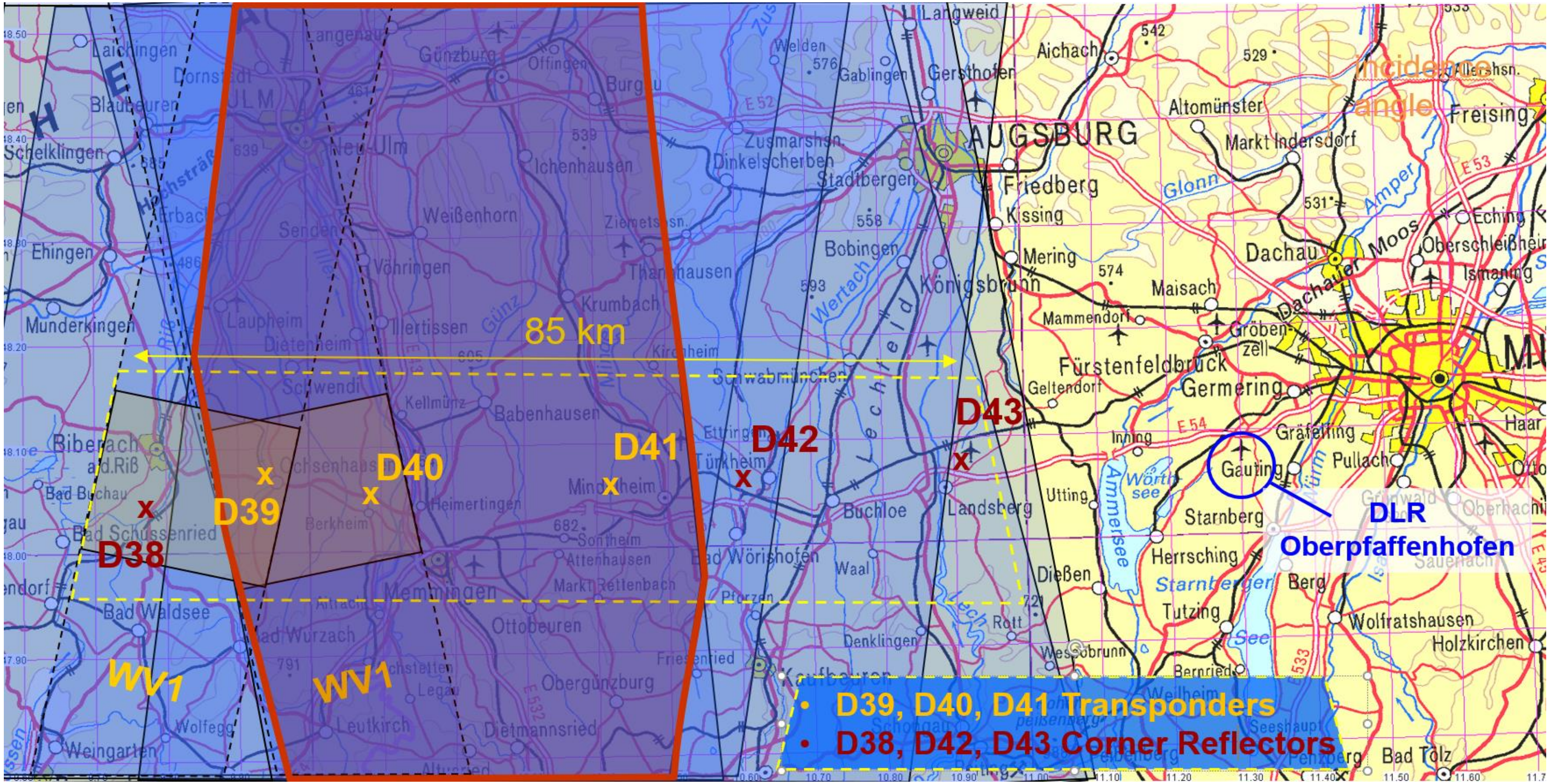
Sentinel-1 Coverage over the DLR Cal field



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Demonstrating Commisioning Readiness: S1C Rehearsal #1

- Rehearsal main goal: Demonstration of tool readiness for CP activities
- ESA provided set of rehearsal data (simulated / modeled based on S1A&B / OGC based)
- DLR conducted series of corresponding tests with those data
- **All defined tests have been passed successfully**
- In the following, we show **select results** from**:**
    - Ical module tests
    - ACM-RF module tests
    - Image Quality / Point Target Analysis tests
    - InSAR Analysis tests

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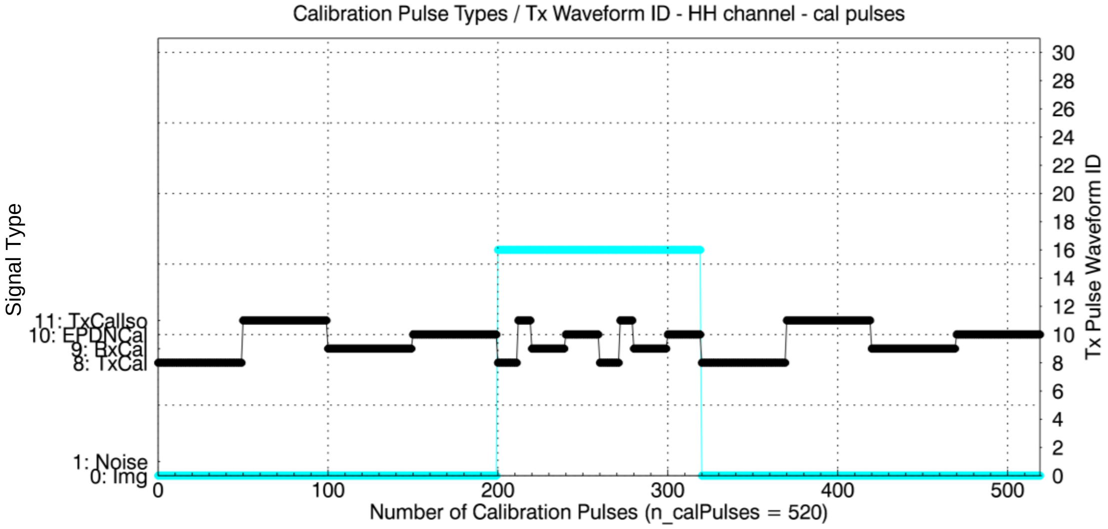
ICAL Module Tests Overview (I)

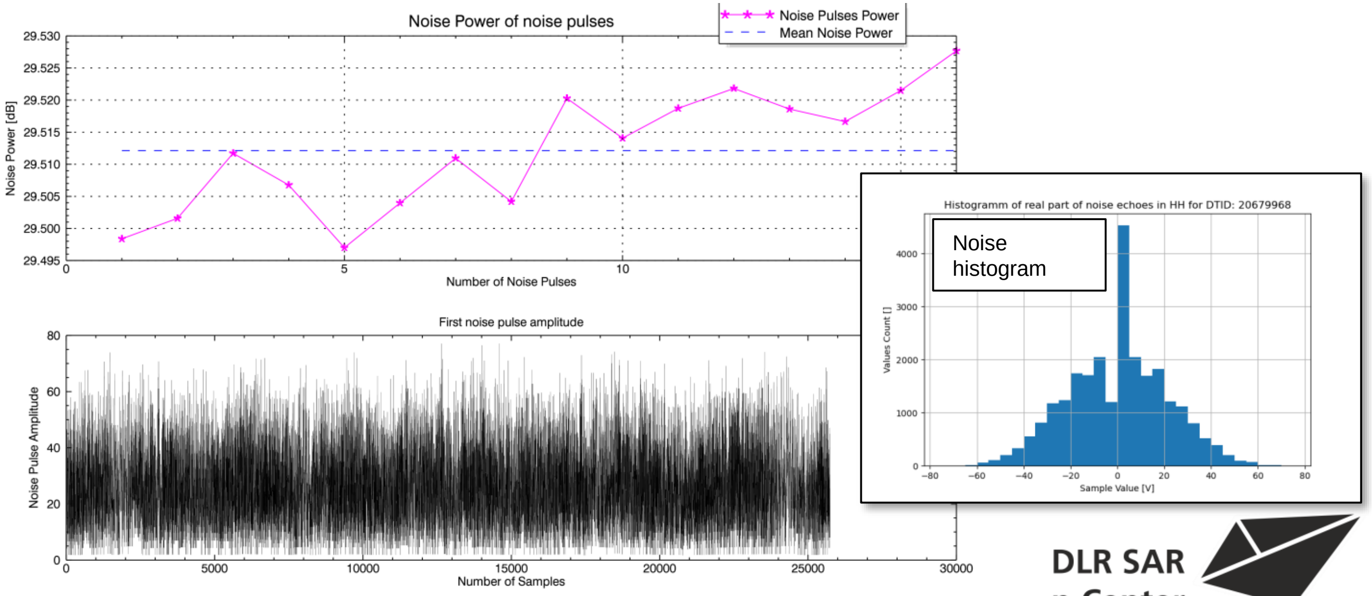
- Expected number of calibration/noise pulses extracted successfully
- All extracted radar parameters and timing information match the RDB
- Noise pulse decompression successful, histograms evaluated

Tests conducted	Outcome/ Status
Header Check of Constant Parameters	OK
Header Check of Counters and Data Length	OK
Timeline Check	OK
Mode Parameters Extraction	OK
Check of Noise Pulses	OK

RFC DT pulse timeline



Evaluated noise power



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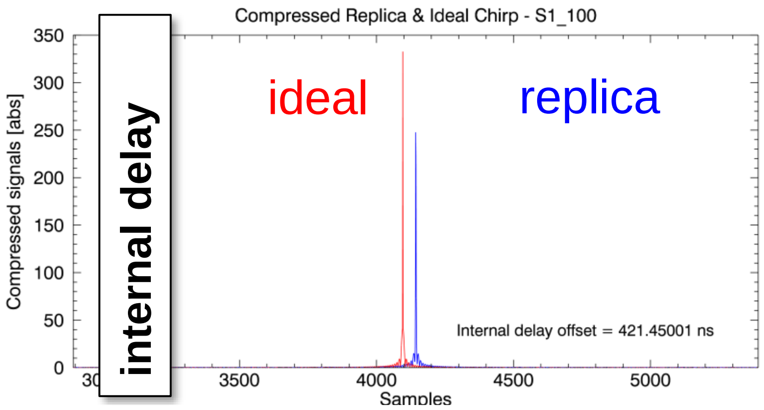
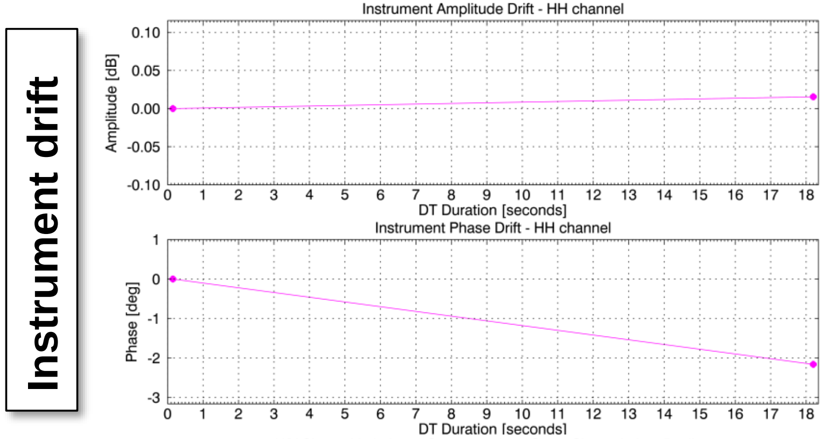
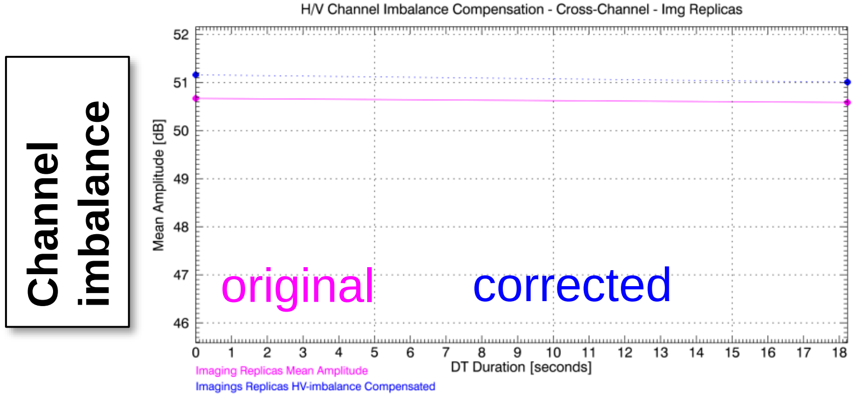
ICAL Module Tests (II)

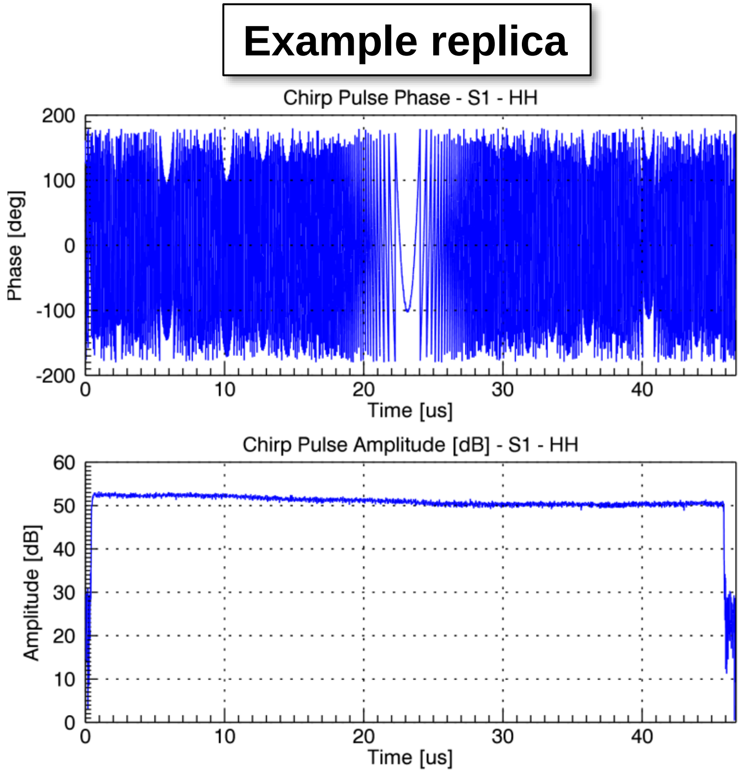
- Calibration pulses detected and extracted
- Replica successfully generated
- Raw data corrections applied
- Result products generated:
  - Internal Delay
  - Instrument Drift
  - Channel imbalance

Tests conducted	Outcome/Status
Check of Calibration Pulses	OK
Replica Extraction	OK
IQ-Correction	OK
Spurious Signal Correction	OK
Rx Gain Correction	OK
Calibration Pulse Decoding	OK
Internal Delay Extraction	OK
Channel Imbalance Calculation	OK
PG-Product Extraction + Drift Monitoring	OK









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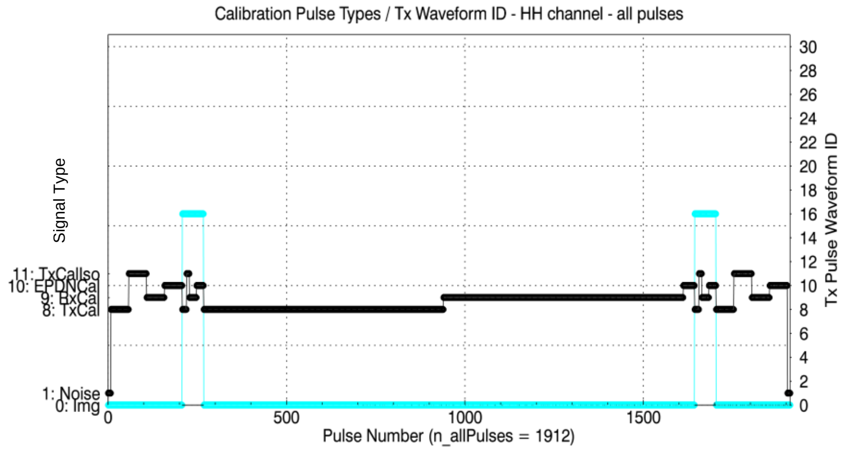
RFC Module Test Results Example

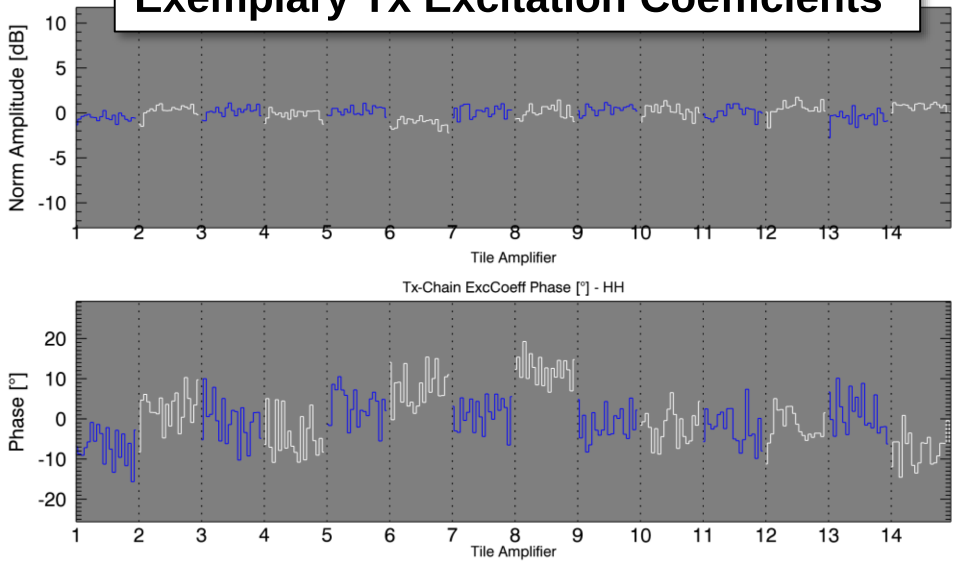
- Number of calibration and noise pulses match expectations
- Extracted header information verified against RDB
- Calibration pulses extracted successfully
- Tx/Rx excitation coefficients generated successfully
- Error matrices (deviation of calculated excitation coefficients vs. ICDB reference values) generated successfully

Tests conducted	Status
Header Check of Constant Parameters	OK
Header Check of Counters and Data Length	OK
Timeline Check	OK
Mode Parameters	OK
Check of Calibration Pulses	OK
Calibration Pulse Decoding	OK
Excitation Coefficient Derivation	OK
Error Matrix Calculation	OK

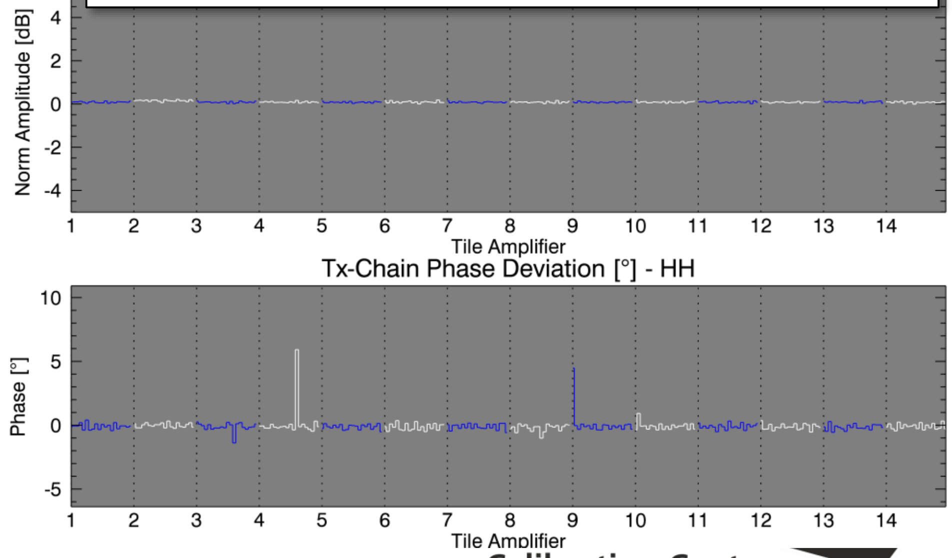
RFC DT pulse timeline



Exemplary Tx Excitation Coefficients



Exemplary Tx Amp/ Phase Deviations



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ACM Test Report Overview

ACM Module functionalities tested

Main Procedures Rainforest Module:

- Pointing determination in EL
- Antenna Pattern Verification in EL
- NESZ estimation over Pacific Doldrums

Main Procedures Ground Receiver Module:

- Pointing determination in AZ
- Antenna Pattern Verification in AZ

Main Procedure NESZ Module:

- Estimation of NESZ over low backscatter

Module	Test	Result
ACM-RF	Ingestion of L1 Product and display image	PASS
ACM-RF	Ingestion of L1 Product annotation and extraction of the reference antenna pattern	PASS
ACM-RF	Derive and display masking	PASS
ACM-RF	Estimation of antenna patterns from rainforest measurements in Stripmap mode	PASS
ACM-RF	Estimation of antenna patterns from rainforest measurements in Interferometric Wide-Swath and Extra-Wide-Swath mode	PASS
ACM-RF	Pointing estimation from rainforest measurements	PASS
ACM-GR*	Ingestion of Ground Receiver Measured Data	PASS
ACM-GR*	Ingestion of Orbit and Attitude Product	PASS
ACM-GR*	Estimation of antenna patterns in azimuth	PASS
ACM-GR*	Pointing estimation in azimuth	PASS
ACM-NESZ	Ingestion of L1 Product	PASS
ACM-NESZ	Estimation of NESZ over area of low backscatter	PASS

*No GR recordings available for current DLR Trsp interface

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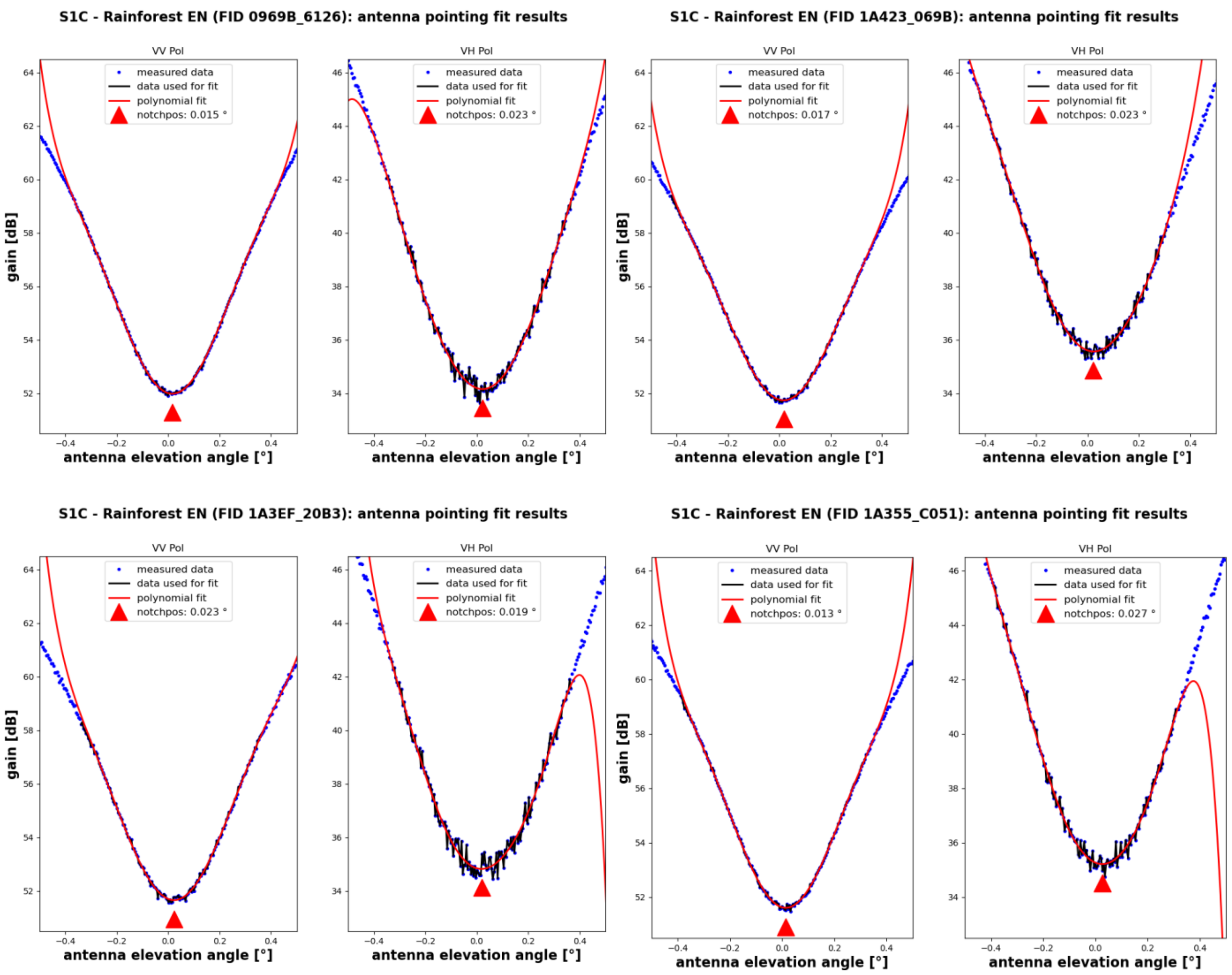
ACM Rainforest Module Elevation Notch based Pointing Estimations

- All provided elevation notch test datasets were evaluated successfully
- Estimated pointing values shown in the graphics on the right



S1C_EN_SLC__1SDV_20150724T100442_20150724T100500_006951_00969B_6126
S1C_EN_SLC__1SDV_20170328T230215_20170328T230234_015898_01A355_C051
S1C_EN_SLC__1SDV_20170330T102935_20170330T102944_015920_01A3EF_20B3
S1C_EN_SLC__1SDV_20170330T224552_20170330T224611_015927_01A423_069B

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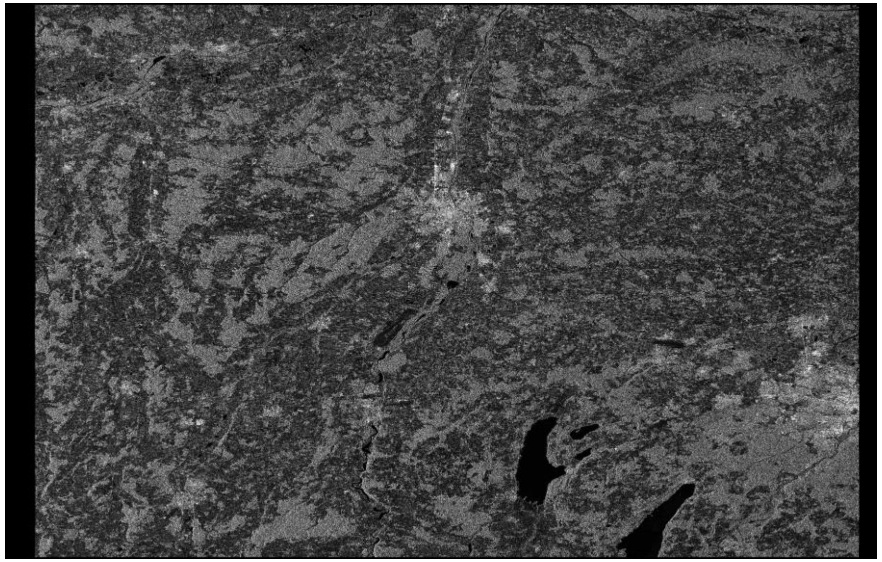
CALIX Test Report – Point Target Evaluations

Main Procedures:

- L1 format verification
- Visual inspection of SAR image and target impulse responses
- Evaluation of target responses w.r.t.
  - Image quality
  - Geometric parameters
  - Radiometric parameters
  - Polarimetric parameters



SAR scene over DLR calibration field

Test	Result
Verify the correct reading of the Sentinel-1 L1 product annotation files.	PASS
Verify the correct reading of the image file of the Sentinel-1 L1 product	PASS
Verify geocoding and location of reference targets within the SAR image.	PASS
Determine image quality parameters by evaluating IRFs	PASS
Determine geometric parameters	PASS
Determine radiometric parameters	PASS
Determine polarimetric parameters	PASS

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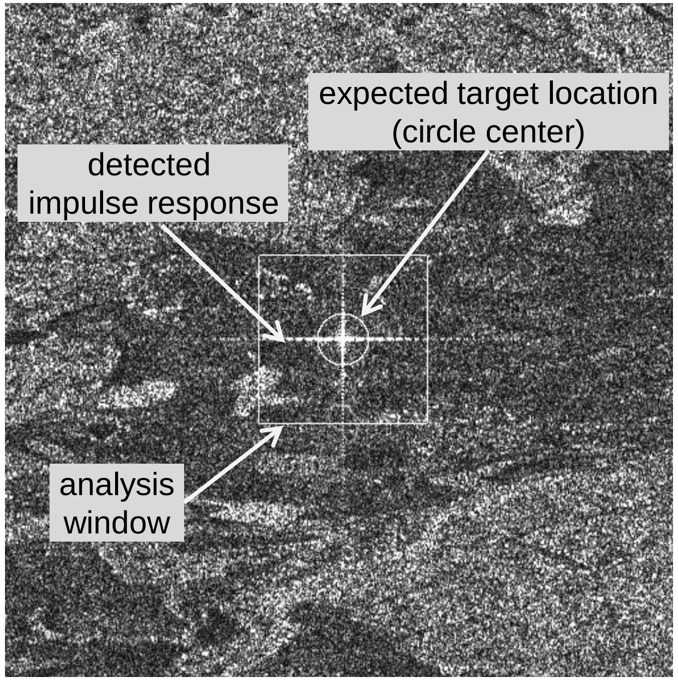
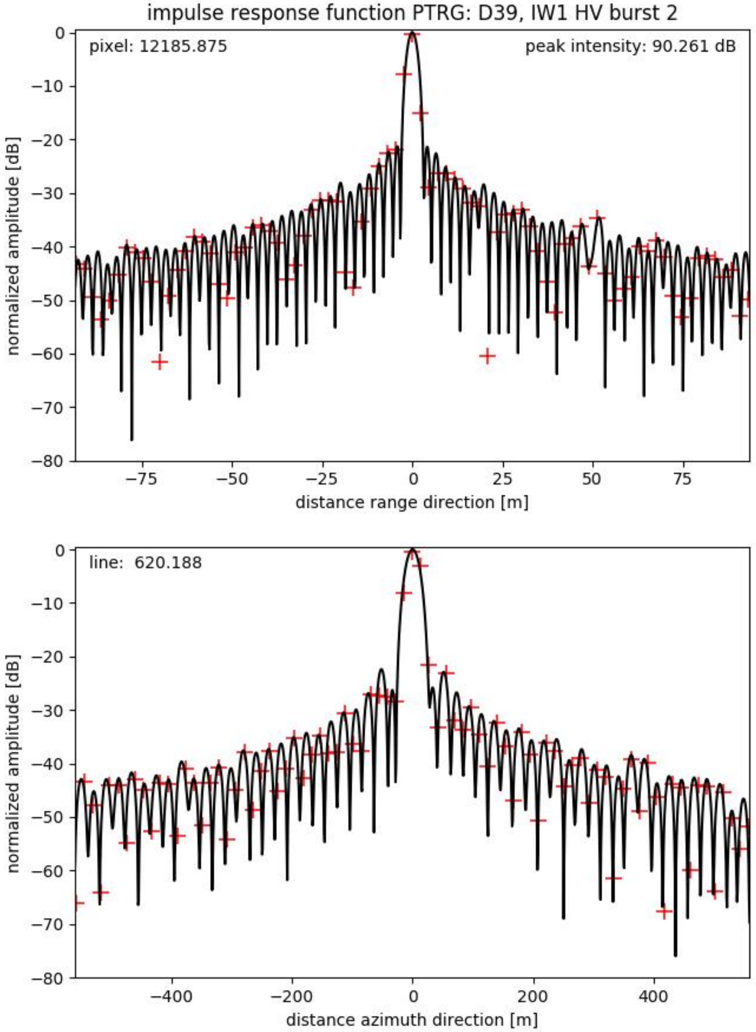
Inspection and Evaluation of Point Target Responses

Target: D39
Polarization: HV
Subswath: IW1





IRF Key Parameters Table	Value HV pol
	PT_Id=D39
IRF Ground Range Spatial Resolution (m)	4.748
IRF Slant Range Spatial Resolution (m)	2.675
IRF Azimuth Spatial Resolution (m)	21.773
IRF Range ISLR (dB)	-15.931
IRF AzimuthISLR (dB)	-17.481
IRF Range PSLR (dB)	-21.263
IRF Azimuth PSLR (dB)	-22.382
IRF ISLR 2d (dB)	-13.732
IRF Look Angle (deg)	30.510
IRF Incidence Angle (deg)	34.294
IRF Measured Radar Cross-Section (dB)	60.840
IRF Relative (Measured-Nominal) RCS (dB)	0.030

S1C_IW_SLC__1SDH_20150704T170712_20150704T170731_006664_008E63_3A6F.SAFE

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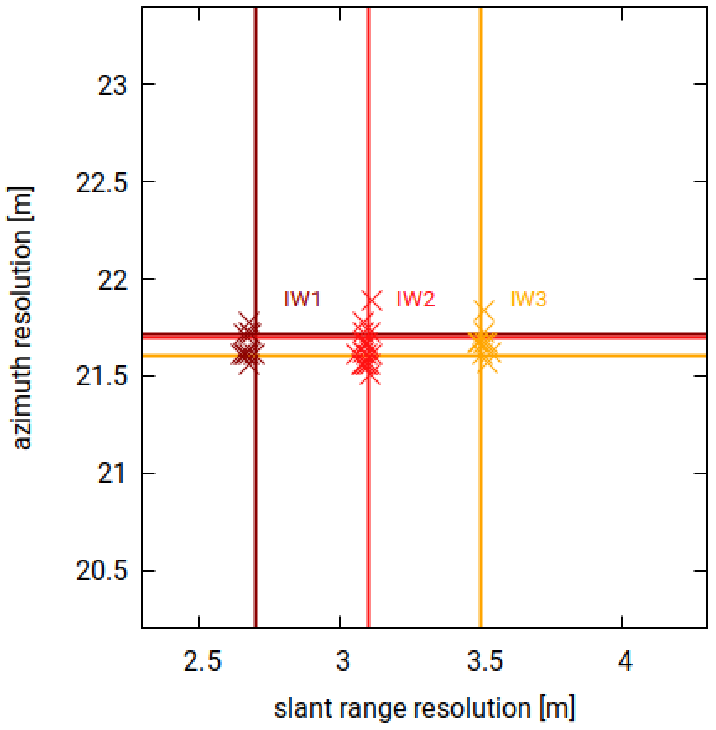
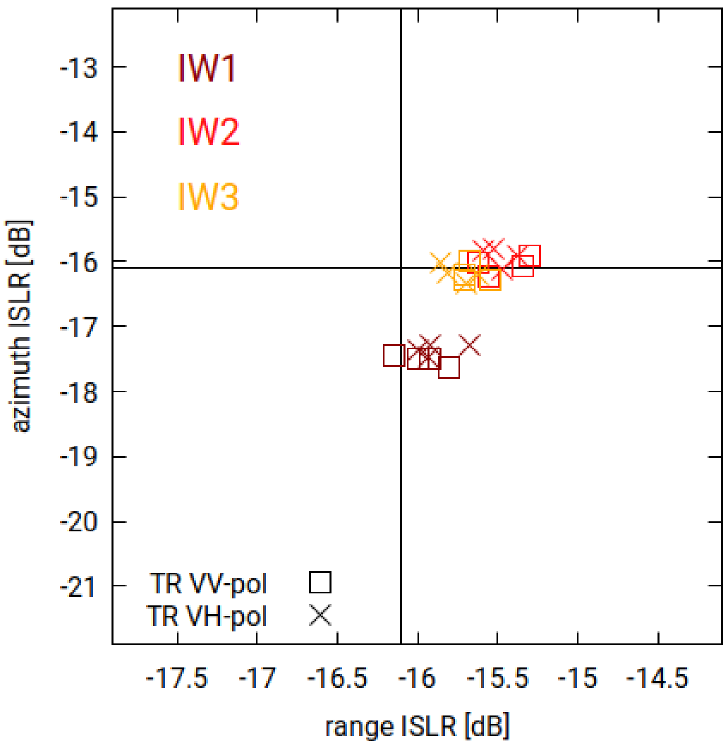
Evaluation of Image Quality Parameters

Mode: IW
Targets: Transponders of DLR calibration field

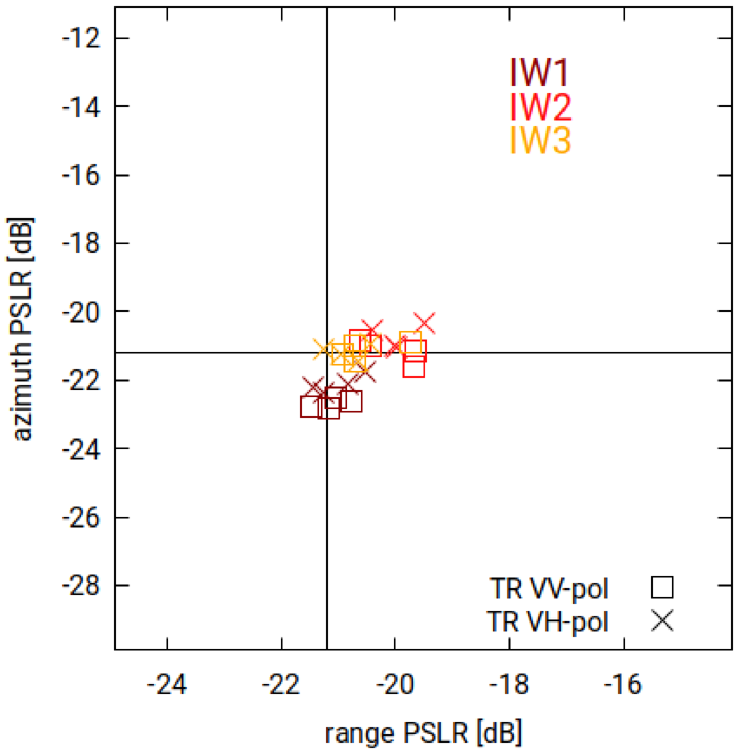
Geometric resolution



Integrated sidelobe ratio



Peak-to-sidelobe ratio



- Measured results (points) corresponds to product definition (lines)
- Slightly lower (better) ISLR and PSLR for IW1 for azimuth direction (y axis)

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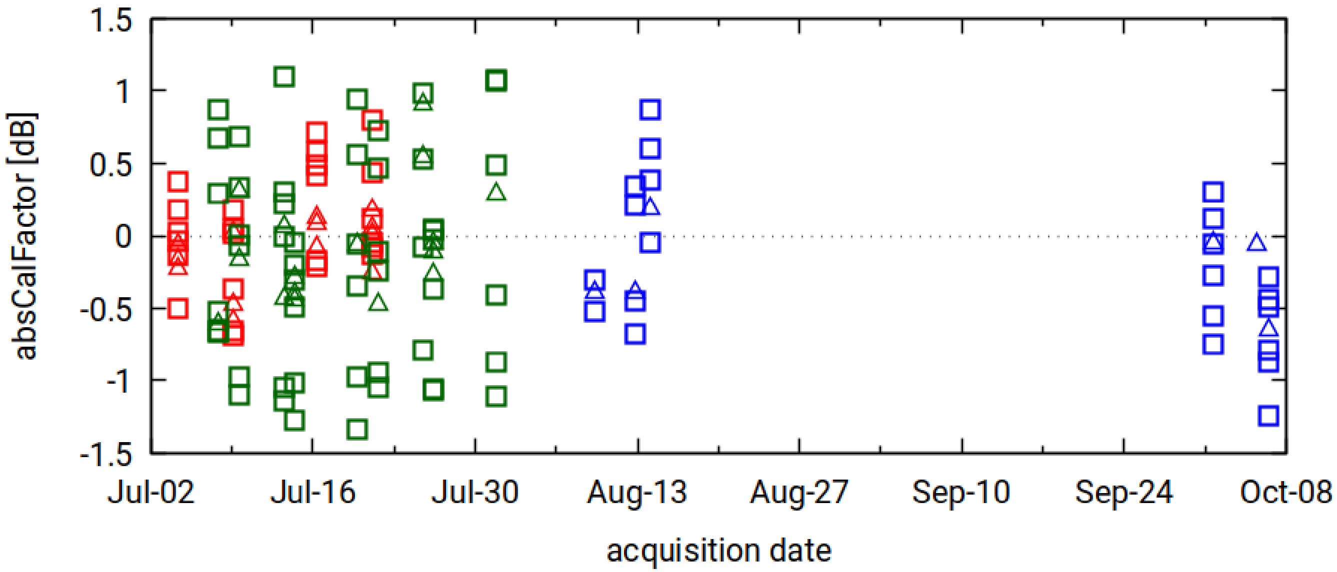
Radiometric Analysis



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S1C_IW_SLC__1SDV_20150716T170709_20150716T170736_006839_00936E_0B67.SAFE
S1C_IW_SLC__1SDV_20150720T052607_20150720T052628_006890_0094E4_47B6.SAFE
S1C_S6_SLC__1SDV_20151001T171522_20151001T171541_007962_00B213_4D5F.SAFE
S1C_S1_SLC__1SDH_20150811T054236_20150811T054255_007211_009DC6_087D.SAFE
S1C_S3_SLC__1SDH_20150809T170711_20150809T170730_007189_009D2B_B899.SAFE
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S1C_EW_SLC__1SDH_20150706T054233_20150706T054254_006686_008F07_7AD5.SAFE
S1C_EW_SLC__1SDV_20150709T171519_20150709T171540_006737_00906A_7EE0.SAFE
S1C_EW_SLC__1SDV_20150711T165859_20150711T165920_006766_009149_AE50.SAFE
S1C_EW_SLC__1SDV_20150713T053425_20150713T053446_006788_0091FE_53D2.SAFE
S1C_EW_SLC__1SDV_20150718T054234_20150718T054255_006861_00940C_4471.SAFE
S1C_EW_SLC__1SDV_20150721T171520_20150721T171541_006912_00957C_79AB.SAFE
S1C_EW_SLC__1SDV_20150723T165900_20150723T165921_006941_009646_9AE8.SAFE
S1C_EW_SLC__1SDV_20150725T053426_20150725T053447_006963_0096FF_5456.SAFE
S1C_EW_SLC__1SDV_20150730T054235_20150730T054256_007036_009902_DA1B.SAFE

Acquisition modes

IW mode EW mode Stripmap mode

Targets from DLR calibration field

△ Corner reflector
□ Transponder

- Non-biased absCal factor consistent for all three modes
- Slightly higher variation for EW mode compared to IW mode

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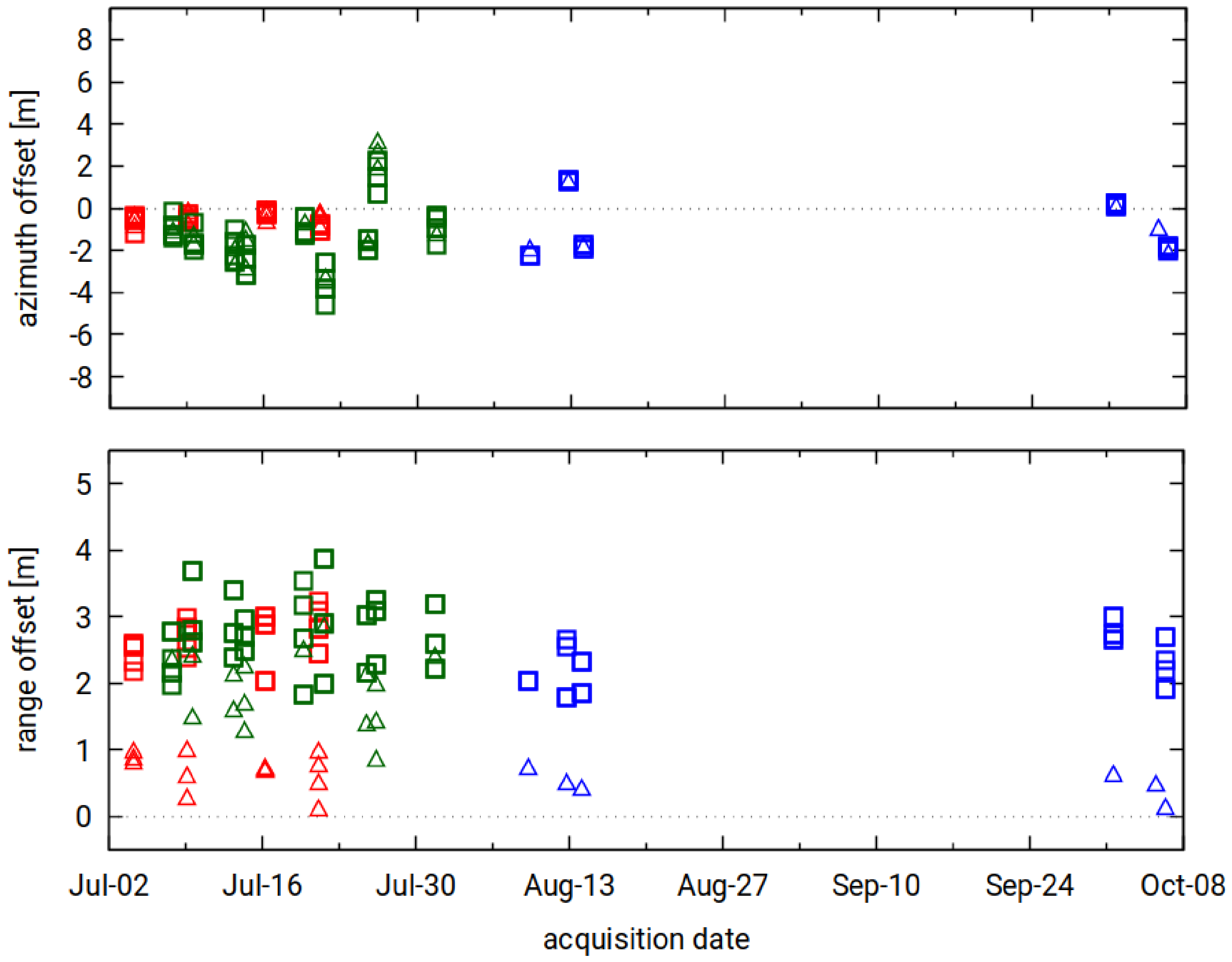
Geometric Analysis

Timeline of requested products from DLR calibration field



Targets from DLR calibration field

△ Corner reflector
□ Transponder

Acquisition modes
IW mode EW mode Stripmap mode

- Small residual for azimuth and range offsets as expected
- Slightly higher variation for azimuth offsets for EW mode due to lower resolution
- Slightly higher range bias for transponders (transponder's internal delay is not fully compensated)

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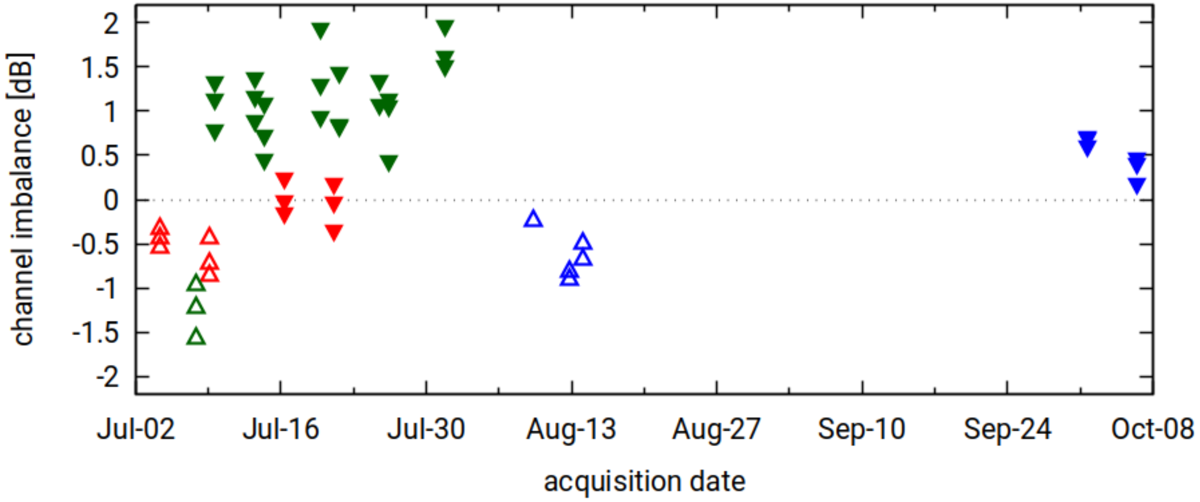
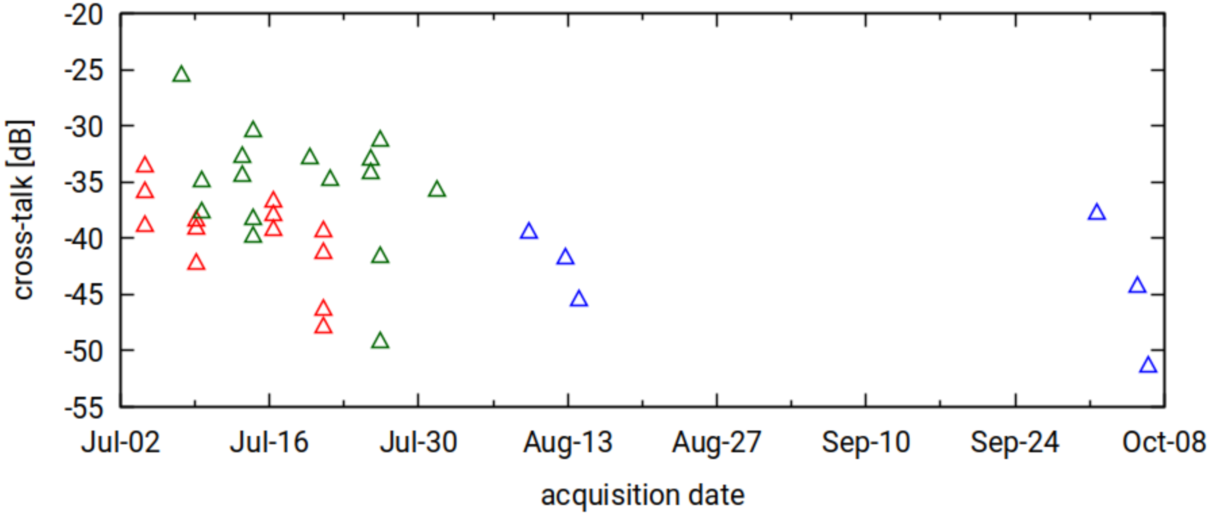
Polarimetric Analysis





Acquisition modes
IW mode EW mode Stripmap mode

Channel Imbalances from transponder responses between
△ HH / HV
▼ VV / VH

- Expected results similar to previous analysis
- Higher imbalances found for EW mode (similar to findings at S1B CP)

Cross-talk derived from DLR corner reflectors
- Expected results similar to previous analysis
- Below -30 dB for IW and Stripmap mode
- Slightly higher for EW mode due to coarser resolution

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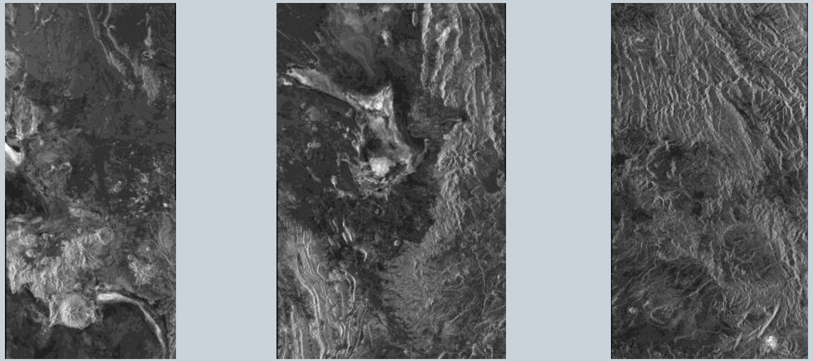
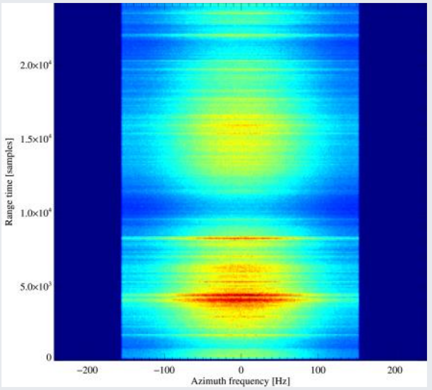
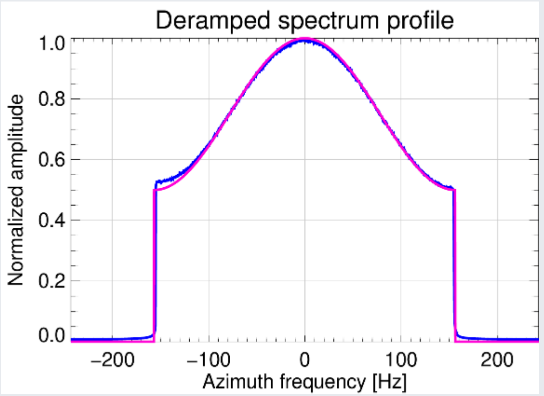
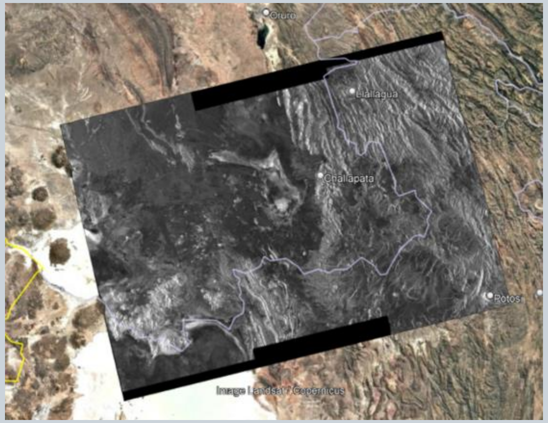
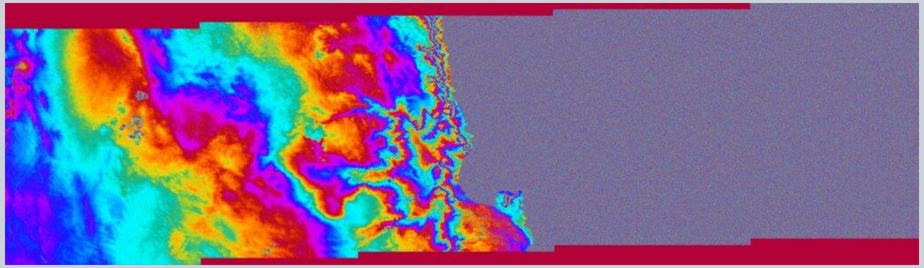
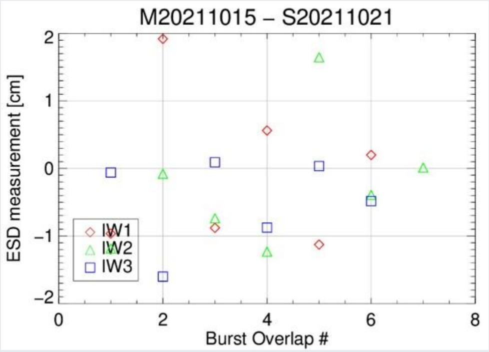
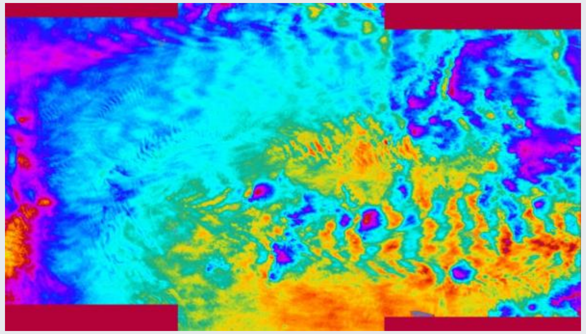
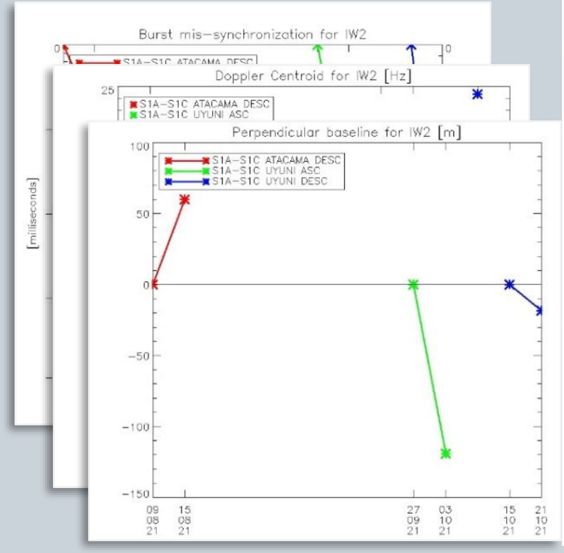
InSAR analysis - TAXI Test Report

Test ID	Description	Output		Success
TC-TAXI-01 TC-TAXI-02	L1 product ingestion	Quick-Looks		✓
TC-TAXI-03	Demodulation and TOPS deramping function	2D and averaged Deramped spectrum	 	✓
TC-TAXI-04	Geocoding and mosaicking (TOPS only) reflectivity image	Properly geocoded image		✓

InSAR analysis - TAXI Test Report

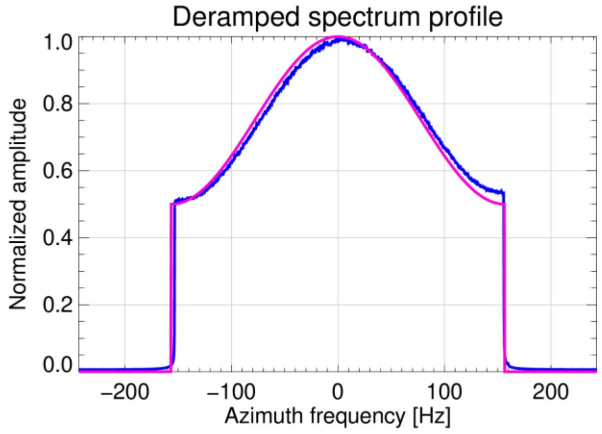
Test ID	Description	Output	Success
TC-TAXI-05	Generation of the interferogram between two S1C acquisitions	Interferogram and Coherence 	✓
TC-TAXI-06	Generation of the interferogram between S1A and S1C	ESD output, Interferogram and Coherence  	✓
TC-TAXI-07	Interferometric compatibility	Burst mis-sync Doppler Centroid Perp. Baseline Baselines 	✓

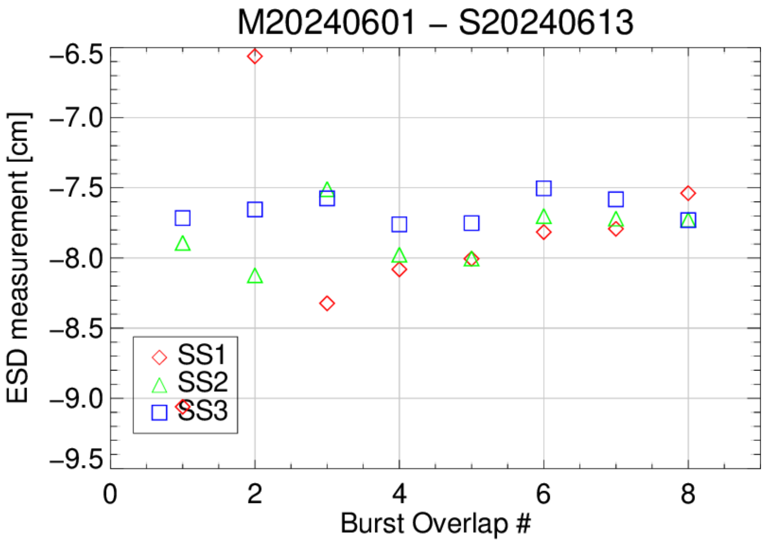
		Range		
Perp. Baseline [m]		Near	Mid	Far
Azimuth	Early	61	59	56
	Mid	62	59	56
	Late	62	59	57
Parallel Baseline [m]		Near	Mid	Far
Azimuth	Early	19	27	32
	Mid	19	27	32
	Late	19	27	33
AT Baseline [m]		Near	Mid	Far
Azimuth	Early	-13	-15	-16
	Mid	-14	-15	-16
	Late	-14	-15	-16
Baseline [m]		Near	Mid	Far
Azimuth	Early	64	64	66
	Mid	65	64	64
	Late	66	66	65

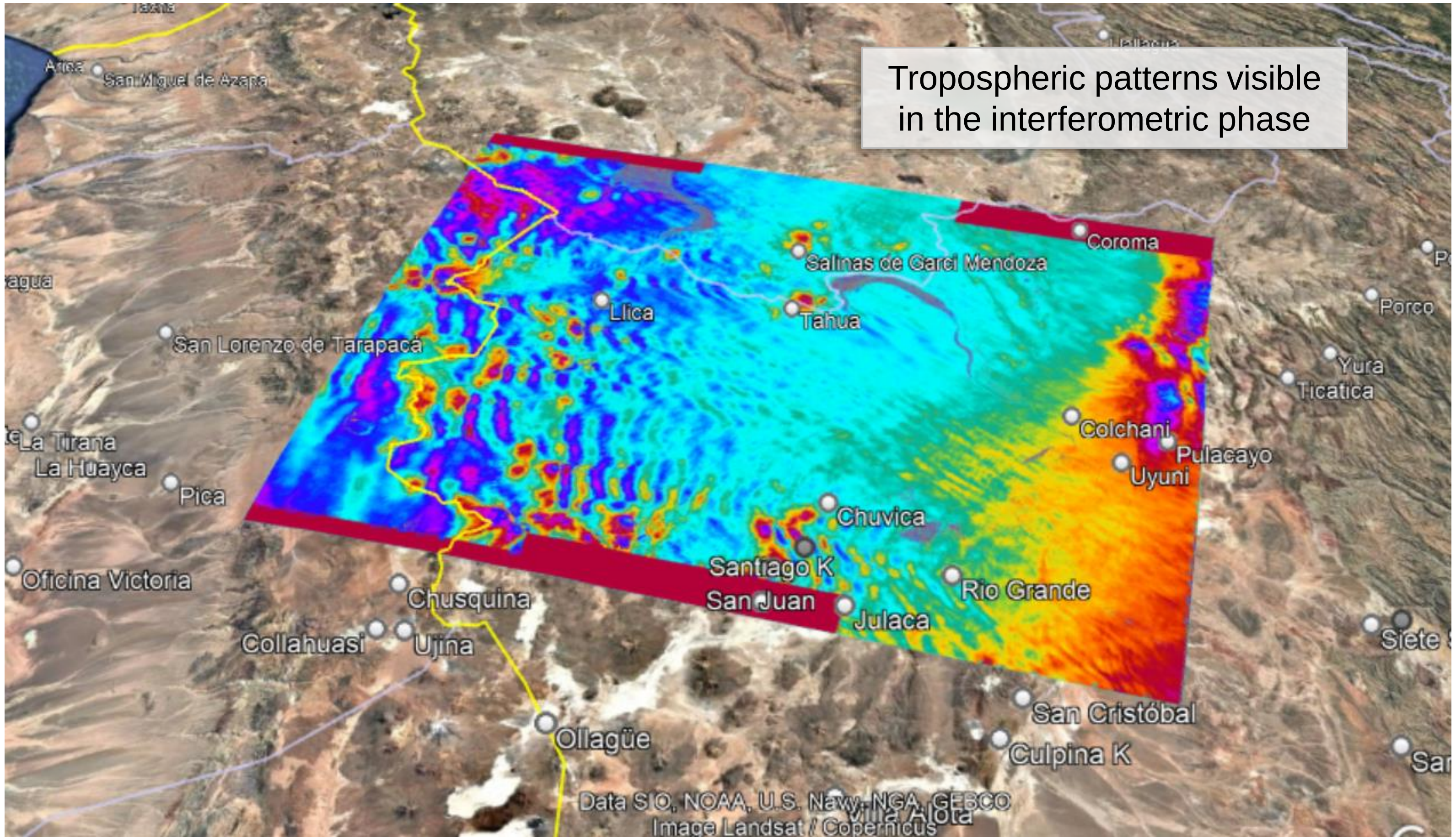
InSAR analysis - TAXI Test Report

Results generated from simulated S1C data provided on October 24

Primary date: 20240601
Secondary date: 20240613







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Conclusion

DLR

- **Sentinel-1C** will be the **third Sentinel SAR system** to be independently calibrated by DLR on behalf of ESA
- S1C CP rehearsal just **successfully** completed – review meeting next week
- **DLR's Cal/Val team is well-prepared** for supporting a successful S1C commissioning phase.

- **Further Questions? Contact me @ Patrick.Klenk@dlr.de or find me here:**

researchgate.net

linkedin.com

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