SENTINEL-1 IN-ORBIT CALIBRATION APPROACH

**A. Østergaard[(1)], I. Navas-Traver[(1)], P.Snoeij[(1)], M. Brown[(1)],
B. Rommen[(1)], D. Geudtner[(1)], D. Bibby[(1)], R. Torres[(1)],
E. Schied[(2)], F. Rostan[(2)], M. Schwerdt[(3)], M. Zink[(3)],
A. Bauleo[(4)], R. Croci[(4)] and A. Pietropaolo [(4)]**

[(1)] ESA-ESTEC, NL-2201 Noordwijk, The Netherlands
[(2)] EADS Astrium GmbH, D-88039 Friedrichshafen, Germany
[(3)] DLR, German Aerospace Center, Microwaves and Radar Institute, 82234 Wessling, Germany
[(4)] Thales Alenia Space Italy, 00131 Rome, Italy

ABSTRACT

ESA is developing the Sentinel-1 European Radar Observatory, a constellation of two polar orbiting satellites that provide C-band SAR products for operational applications. The Sentinel-1 mission has been designed to comply with stringent radiometric stability and accuracy requirements. To ensure these requirements are achieved, the mission relies on an efficient and robust strategy for in-flight calibration.

This consists of (a) pulse-coded Internal Calibration pulses that achieve leakage cancellation and robust estimation and separation of different types of leakage signals and (b) an Antenna Model that estimates very accurately the antenna radiation patterns based on the instrument configuration and pre-launch measurements.

Usage of calibration data and the Antenna Model supports maintaining the long-term absolute radiometric accuracy and enables a graceful degradation of performance in the event of unrecoverable failures of individual transmit/receive modules.

During the commissioning phase, calibration also relies on precise external calibration transponders and measurements with notch patterns over the rainforest and transponders for accurate pointing determination.

1. Introduction

The European Sentinel-1 satellite constellation, which carries C-Band Synthetic Aperture Radars, forms part of the Copernicus satellites. The Sentinel-1 constellation is expected to provide near daily coverage over Europe and Canada, global coverage at least every 6 days – all vast improvements with respect to the existing SAR systems [1, 2].

The Sentinel-1 end-to-end system, including both satellites and the ground segment, is specifically designed to acquire systematically and provide routinely, sustainable and reliable data and information products for Ocean, Land and Emergency services. These cover operational applications such as the observation of the marine environment, including oil spill detection and sea-ice monitoring, the surveillance of maritime transport zones, as well as the mapping of land surfaces including vegetation cover (e.g. forest) and in support of disaster and crisis situations [1].

The satellite constellation is designed and developed under ESA contract, with Thales Alenia Space Italy as prime contractor, developing also the key TRMs for the S-1 SAR antenna, and with Astrium GmbH being responsible for the C-SAR instrument.

The driving requirements for the SAR system are the tight performance with an absolute radiometric accuracy of 1dB (3σ) and 0.5dB (3σ) stability for all operational modes.

In Figure 1 an artist impression of the Sentinel-1 Satellite is shown.

Figure 1. Sentinel-1 satellite

The 12.3 m long S-1 SAR antenna is painted white for thermal reasons and is pointed towards the surface of the earth.

Following the experience gained with ERS and ENVISAT it is necessary for the in-orbit calibration to

Proc. 'ESA Living Planet Symposium 2013', Edinburgh, UK
9–13 September 2013 (ESA SP-722, December 2013)

have a set of precision radar transponders to act as point targets which can be automatically programmed and accessed during the Sentinel-1 commissioning phase and during the mission lifetime in order to achieve and maintain the absolute radiometric accuracy requirement.

The SAR Instrument has to support a variety of SAR operational modes shown in Figure 2. Stripmap, Interferometric Wideswath, Extra Wideswath and Wave all requiring the implementation of multiple antenna beams with differently shaped radiation patterns and scanning capability in along- as well as in across-track direction. Thus, by switching the instrument over a multitude of different beams, progressive scanning in azimuth is possible in order to reduce the scalloping effect (TOPS) [3] and by scanning in elevation a wide range of swath positions can be covered (up to 400 km ground range). All modes, except for the Wave Mode (only HH or only VV), can be operated in dual polarization using two simultaneously receiving channels (HH/HV or VV/VH). Within the timeline of each of the above modes the Internal Calibration is performed to closely ensure compliance to the radiometric stability requirement.

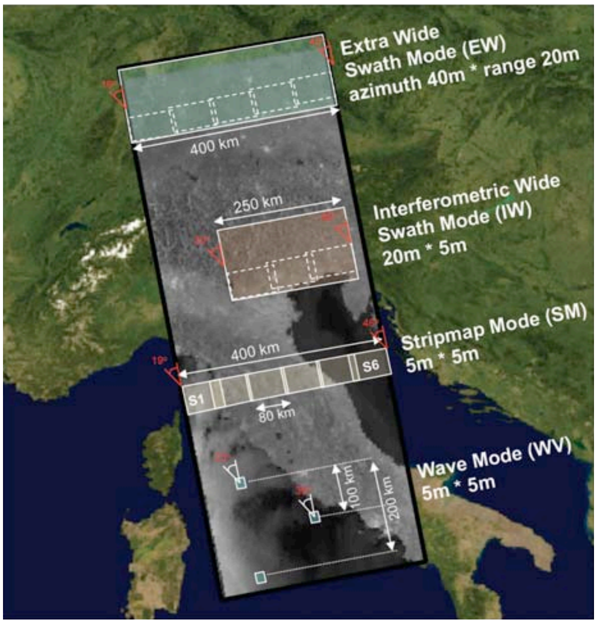

Figure 2. Sentinel-1 SAR Imaging Modes

The Sentinel-1 SAR takes advantage of its RF characterisation mode to accurately monitor any possible drifts or complete failures of TRMs. Thus, it is possible to determine the Tx- and Rx- excitation coefficients of the individual waveguide arrays in order to accurately predict the radiation pattern used for the various SAR modes.

This paper will describe the strategy and the sequence of activities of the in-orbit calibration and validation of the Sentinel-1 satellite.

2. Sentinel-1 SAR Instrument

The C-SAR Instrument of the Sentinel-1 mission is split in two major sub-systems:

- The SAR Electronics Sub-system (SES)
- The SAR Antenna Sub-system (SAS)

The radar pulse is generated at baseband by the chirp generator, up-converted to C-band and pre-amplified within the SES before it is distributed to the SAS.

The S-1 SAR antenna is organised in 14 tiles each carrying 20 dual polarised sub-arrays realised in slotted waveguide technology. The Tx chirp pulse is distributed via the passive Azimuth Power Distribution Network across the antenna to each tile. In each tile the Tx chirp pulse is further amplified in a Tile Amplifier (TA-A and TA-B for redundancy) before it is distributed in the passive Elevation Power Distribution Network feeding 40 active Transmit Receive Modules (TRMs). A pair of active Transmit Receive Modules (TRMs) directly feeds one dual polarised sub-array. Thus across the antenna 280 TRMs feeds the vertically polarised sub-arrays and another 280 TRMs feeds the horizontally polarized sub-arrays.

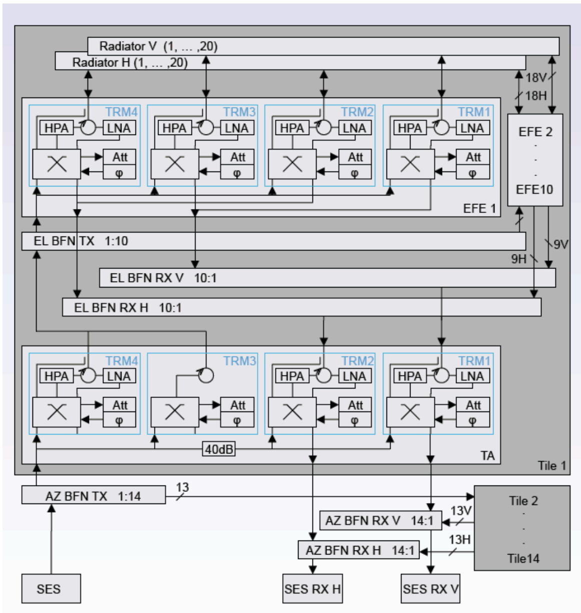

Figure 3. Sentinel-1 RF Block Diagram

Likewise the horizontally and vertically polarized echoes are received by the sub-arrays and Low Noise Amplified in the TRMs before they are combined in separate Elevation and Azimuth distribution networks and sent to the SES for down-conversion and ADC/IQ demodulation in two separate co- and cross-polar receiving chains.

The SAS Tile forms the smallest functional entity of the SAR Antenna Subsystem, encompassing also two Tile

Controller Units (TCU A and TCU B for redundancy) and two Tile Power Supply Units (TPSU 1 and TPSU 2) each feeding half a tile of the TRMs (and both Tile Amplifiers).

The TCUs commands the beam switching of the SAR antenna by properly switching the amplitude and phase settings of the Tx and Rx chains of each individual TRM at PRI rate. Furthermore, the TCU contains ground characterisation tables of each individual TA/TRM allowing for autonomous temperature compensation.

Within the each TRM a stable calibration coupler in combination with certain switching circuitry enables the necessary signal routing for measuring a number of calibration signals as required for the Internal Calibration and for the RF Characterisation mode [4].

Each sub-array can be regarded as a dual-polarized unit made up by two parallel slotted resonant waveguides, actually one for each polarization (HP, VP). The vertical polarisation (VP) is excited by offset longitudinal slots in a ridge waveguide, while the horizontal polarisation (HP) is generated by transverse narrow wall slots excited by inserted tilted wires. This concept stands out because of its high efficiency and high polarization purity [5].

3. CALIBRATION APPROACH

The in-orbit Sentinel-1 SAR system end-to-end calibration and verification activities are required to take place within a three months Commissioning Phase.

The in-orbit calibration and verification relies on the Internal Calibration for short and long term stability, on External Calibration for Antenna Pointing, for Geometric Calibration, for Radiometric Calibration and for Polarimetric Calibration. Finally, it relies extensively on the so-called Antenna Model that enables:

- Shifting most of the antenna characterization from the commissioning phase to pre-launch activities.
- Relative Radiometric Calibration and correction for graceful degradation of TRMs and/or TRM/TPSU failures (SAR RF Characterisation) to be performed without the need for external targets.
- The use of only one unique absolute calibration factor (for all beams and for all positions with beams).
- That only a limited set of operational beams needs to be measured/verified, thus saving valuable time during the Commissioning Phase.

With all the above in place, the sequence of in-orbit calibration and verification activities involve the following:

- Functional Verification of L0 and L1b Data Products
- Internal Instrument Calibration and RFC (monitoring overall instrument drift as well as drifts/errors on unit level)
- SAR Antenna Pointing (Electrical and/or mechanical alignment)
- Geometric Calibration (Timing)
- Antenna Model Verification (for a reduced number of beams)
- Radiometric or Absolute Calibration
- Polarimetric Calibration (Inter-channel gain and phase balance)
- Interferometric (InSAR) Verification (Synchronisation over repeat orbits)

In the following section the above calibration and verification activities are further detailed.

4. DETAILED ACTIVITIES

The Level 0 SAR data products will be verified with respect to:

- Fixed parameter header check of SAR data packets
- Dynamic Header and Timeline check
- Raw data packet verification
- Packet time monitoring
- Flexible Dynamic Block Adaptive Quantisation (FDBAQ) compression performance verification
- PVT and attitude ancillary data check
- Monitoring of Telemetry
- ADC overflow and Doppler Centroid

The Level 1b SAR data products will be verified with respect to the SAR instrument performance:

- Impulse Response Function (IRF)
- Resolution in azimuth and range
- Point target ambiguity ratio (PTAR)
- Peak-to-sidelobe ratio (PSLR)
- Integrated sidelobe ratio (ISLR)
- Noise Equivalent Sigma Zero (NESZ)

The Internal Calibration [4] relies on monitoring the overall PG (or transmit power times receive gain) product for the SAR instrument. The PG product is obtained from a set of Internal Calibration measurements which are necessary to cover all elements in the Tx and the Rx chain exactly once while keeping the signal levels well above the noise floor but also within the linear range at all stages of the receive chain. The PG product is obtained by forming the proper fraction (in the Fourier domain) of the Internal Calibration signals. This fraction of calibration signals is compressed (i.e. correlated with a replica chirp) in the ground processing. The complex peak of the compressed signal provides the PG value (amplitude and phase). The Sentinel-1 Internal Calibration scheme covers all Tx and Rx polarization states (i.e. HH, HV, VV, and VH).

The RF Characterisation mode relies on measuring the same signal paths, but these are repeated a number of times using an elaborate phase coding of the signals sent through the individual TRMs to enable an inversion algorithm determining their individual transmit and receive excitation coefficients. The S-1 SAR antenna is designed to meet stringent criteria for the active return losses of the envisaged operational beams of the SAR instrument. A pulse coded calibration (PCC) scheme relying on so-called Hadamard matrices as proposed in [6] was considered as the theoretical basis for the RF Characterisation mode of the SAR, but the Hadamard matrices does not explicitly consider the active return loss as seen by the S-1 SAR antenna during the RF Characterisation mode. The PCC was therefore elaborated using a so-called triangular scheme [7] allowing measurement of the excitation coefficients of the individual TRMs while simultaneously achieving an improved active return loss. As for the Hadamard matrices this elaborated PCC scheme acts to suppress leakage and ideally cancel deterministic errors (errors in the phase gain map) other than for the individual excitation coefficient being decoded.

Determination of the Antenna Pointing relies on accurate orbit and attitude information from the platform for the mechanical pointing of the antenna. The (additional) electrical pointing in azimuth is determined from commanding the antenna to radiate an azimuth notch beam and to measure this beam using the receive-only function of the S-1 transponder. Further, the Doppler centroid estimation, which is computed from science data, can support the estimation of the azimuth pointing. The elevation pointing is then determined from commanding an elevation notch beam and mapping e.g. over the rain forest and correlating the gamma profile with the antenna notch beam. Pointing accuracies below 0.01° can be achieved.

The Geometric Calibration aims at associating the SAR image to the ground surface being imaged. Its (slant-) range accuracy is mainly affected by the internal delay of the instrument and by tropospheric propagation effects. Shift in azimuth is due to differences in SAR time and true orbit time. Accuracy well within the required 2.5m (3σ) can be achieved [8].

The Antenna Model is based on a rigorous electromagnetic formulation including all polarisation and mutual coupling effects. The active element patterns of each individual sub-array have been measured in the new PNFS facility in Friedrichshafen during an extensive measurement campaign in October and November 2012. During measurements, the active SAR antenna was maintained at a constant temperature equilibrium thus enabling that the autonomous amplitude and phase compensation, which is performed under control of the TCUs as a function of the internal temperatures of the TAs and EFEs, could be frozen [9].

For validation the entire SAR antenna was commanded using the appropriate excitation coefficients to radiate and to receive by a number of operational beams, which was then measured in the PNFS. Direct comparison of these operational beams with the corresponding pattern predictions by the Antenna Model formed the basis for the on ground validation.
In Figure 4 an example of the Tx*Rx (2-way) IW1 beam in vertical polarisation is shown. The vertical red lines indicate the boundaries of the corresponding swath/coverage area used for the IW1 beam.

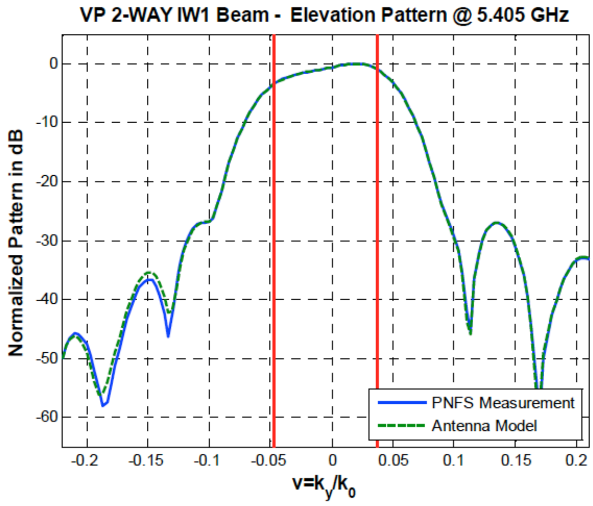

Figure 4. IW1 beam

In Figure 5 a zoom of the coverage area is shown, along with a plot of the gain difference between the two beams. The normalized pattern scale and the pattern difference scale are shown on opposite sides.

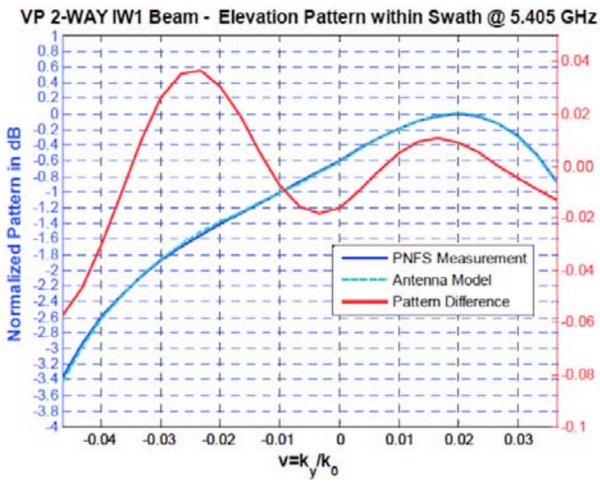

Figure 5. IW1 beams and differences

The 0.1dB pattern difference requirement for the two-way beams is expressed as the RMS error integrated over the corresponding swath width of the operational beam. A plot of the corresponding performance of the validated beams (vertical polarisation only) is shown in Figure 6, along with the performance of a number of Stripmap, Interferometric Wideswath and Extra Wideswath beams. The 0.4° and 0.8° legends denote beams scanned in azimuth.

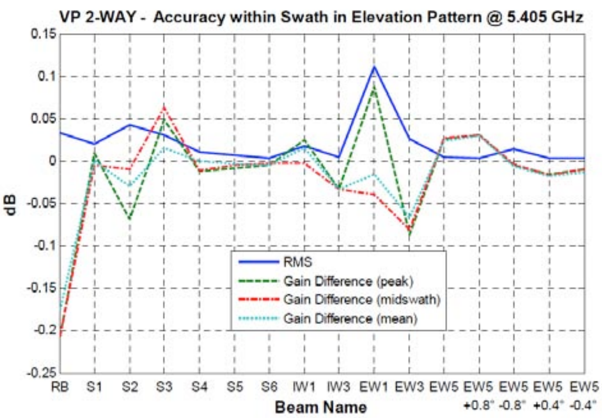

Figure 6. RMS pattern and gain difference.

With precise antenna pointing, geometric calibration and known transmit and receive excitation coefficients from the RF Characterisation mode, the Antenna Model can accurately be verified.

This verification encompasses:

- Tx*Rx Elevation Antenna Pattern derived from the Gamma profile of a homogenous scene.
- Tx*Rx Beam-to-beam gain offset in elevation derived from the Gamma profile of a homogenous scene.
- Tx Azimuth Antenna Pattern measured by ground receivers (S-1 transponders). Also, for TOPS modes (IW and EW) modes this is possible, by proper selection of scanned beams linking the ground receiver time to the timeline of the instrument.
- Tx*Rx Azimuth Antenna Pattern derived from range-compressed SAR data acquired over homogenous scene.

Applying both Internal Calibration and the antenna model relative radiometric calibration for all SAR data products can be performed without any measurements against reference point targets. Furthermore, the antenna model can provide the gain offset between the different operational beams.

Consequently, only one absolute calibration factor has to be derived from deployed reference targets. This factor is valid for all operation modes and beams. The determination of this calibration factor is equivalent to the Absolute Radiometric calibration. It relies on two key elements. The first one is the accurate Internal Calibration based on the elaborated PCC technique for monitoring and characterizing the whole instrument down to individual TRMs. The second one is the precise Antenna Model. The number of measurements and consequently the number of passes required is mainly driven by the radiometric accuracy budget. As targets precise ground transponders and known distributed targets are used.

Polarimetric Calibration involves the analysis of Internal Calibration measurements to determine the inter-channel gain imbalance and phase, as well as it is based on external measurements over radar reference targets for co-registration of channels by estimation of the peak of the IRF location enabling verification of the co-registration offset.

Interferometric (InSAR) verification involves verifying the phase stability and burst synchronisation of the SAR system over repeat orbit cycles, and the maintenance of the orbital tube (i.e. interferometric baseline). Phase stability analysis is performed for bursts overlapping areas including inter-burst (same subswath) and inter-subswath areas for point targets.
Burst synchronisation quality analysis is performed considering the burst start time difference and azimuth image co-registration results, and resulting overlap of the Doppler spectra. Finally, SAR interferograms and coherence maps will be generated and assessed.

5. IN-ORBIT CALIBRATION SCHEDULE

The in-orbit calibration schedule is shown is Figure 7, where each time period T0 through T4 corresponds to 12 days. The extended periods for the Radiometric Calibration and the In-SAR Verification are required to accommodate several revisit measurements over transponders and over scenes with distributed targets to cover almost all modes/swaths and polarisations and for averaging purposes.

6. CONCLUSION

Extensive on ground measurement and validation campaigns have been carried out, confirming the Instrument Stability through the Calibration and the RF Characterisation mode, but also to meet the very demanding requirements for the Antenna Model. These on-ground validation activities have confirmed an unprecedented accuracy of the Antenna Model, and have allowed to shift time consuming validation activities from the Commissioning Phase to pre-launch.
The above achievements form the basis for a successful and very time limited Commissioning Phase, planned to take place within a three months period.
A further, but important advantage of the RF Characterisation mode together with the Antenna Model is that it enables to predict accurately the differences in the patterns of the operational beams should any drift or

failures occur during the lifetime of the mission. Therefore, the quality of the products can be maintained

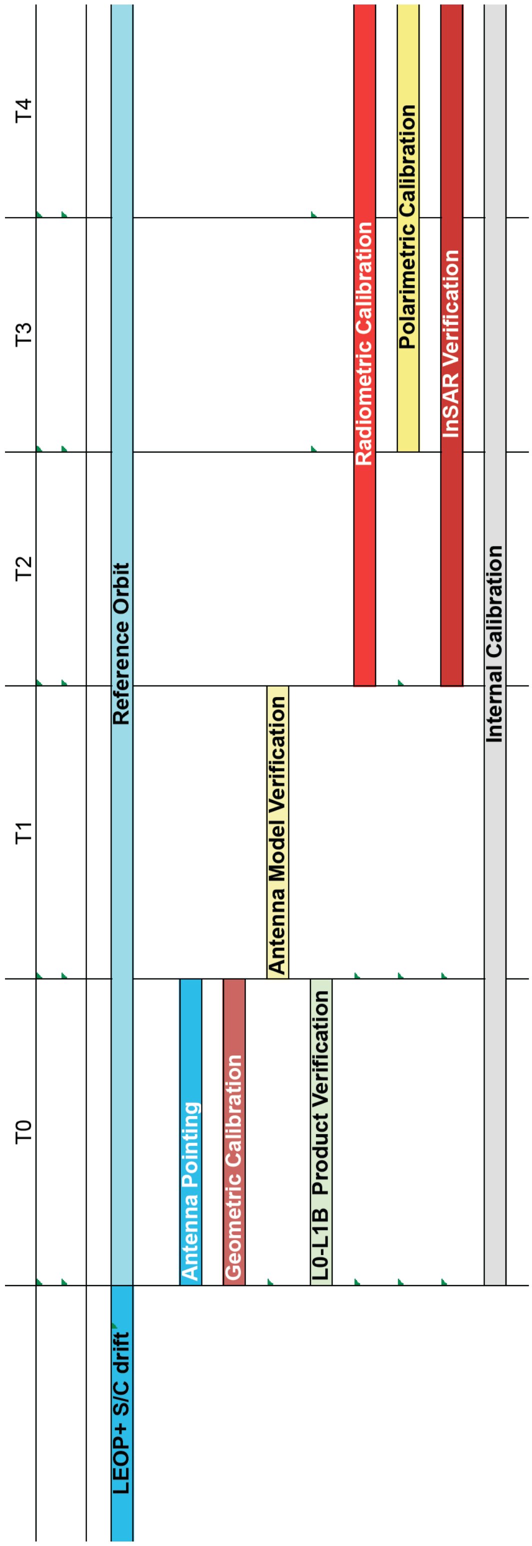

Figure 7. In-Orbit Calibration Schedule

throughout the mission lifetime and re-optimisation the beam excitations coefficients can be accommodated if deemed necessary to comply with e.g. ambiguity requirements.

With the presented in-orbit calibration approach a time and cost effective plan is in place for the launch of the Sentinel-1 SAR.

7. REFERENCES

[1] GMES Sentinel-1 Mission Requirements Document: Issue 1 revision 4. ES-RS-ESA-SY-0007, 2007. http://esamultimedia.esa.int/docs/GMES/GMES_SENT1_MRD_1-4_approved_version.pdf

[2] Torres, R., Snoeij, P., Geudtner, D., Bibby, D., Davidson, M., Attema, E., et al., “GMES Sentinel-1 mission”, Remote Sensing of Environment, Vol. 120, pp. 9–24, 2012.

[3] Francesco De Zan and Andrea Monti Guarnieri, “TOPSAR: Terrain Observation by Progressive Scans”, IEEE Transactions on Geoscience and Remote Sensing, Vol. 44, No. 9, September 2006, pp. 2352-2360.

[4] E. Schied, F. Rostan, A. Østergaard, I. Navas Traver and P. Snoeij. “The Sentinel-1 C-SAR Internal Calibration”, EUSAR 2010, 8th European Conference on Synthetic Aperture Radar, Aachen, Germany, June 7-10, 2010.

[5] Grafmüller, B.; Herschlein, A. and Fischer, C.: The TerraSAR-X Antenna System, Proc. IEEE Intl. Radar Conference, Arlington, Virginia, USA, 2005.

[6] D. Hounam, M. Schwerdt and M. Zink, “Active Antenna Module Characterisation by Pseudo-Noise Gating,” 25th ESA Antenna Workshop on Satellite Antenna Technology, 2002.

[7] A. Østergaard, I. Navas Traver, P. Snoeij, E. Schied, F. Rostan and R. Croci, “Pulse Coded Calibration of the Sentinel-1 SAR Phased Array Antenna Optimised for Low Active Return Loss”, Radar 2012, International Conference on Radar Systems, 22-25 October 2012, Glasgow, UK.

[8] Marco Schwerdt, Benjamin Bräutigam, Markus Bachmann, Björn Döring, Dirk Schrank, and Jaime Hueso Gonzalez, “Final TerraSAR-X Calibration Results Based on Novel Efficient Methods”, IEEE Transactions on Geoscience and Remote Sensing, Vol. 48, No. 2, February 2010, pp. 677-689.

[9] A. Hees, P. Koch, F. Rostan, M. Huchler, R. Croci, and A. Østergaard, “Sentinel-1 SAR Antenna Subsystem - Final RF Pattern Test Campaign”, 35^{th} Antenna Workshop, 10-13 September 2013, Noordwijk, The Netherlands.