TerraSAR System Calibration

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ABSTRACT

The ESA Earth Observation TerraSAR-L system features a L-band Synthetic Aperture Radar and strives for very high radiometric performance for spatial resolutions of 5 meters and swaths up to 200 km, in strip-map and ScanSAR operations, full-polarimetric capabilities, repeat-pass ScanSAR interferometry and a Wave Mode. Such levels of radiometric performance require the use of instrument calibration mechanisms. The rich capabilities of the L-SAR instrument in terms of antenna beams, polarisations and modes would make the traditional calibration approach, used for ERS and ENVISAT, a too expensive and time-consuming process.

In addition, the L-SAR instrument is based on an 11 x 2.9 m active phase array antenna, with 160 transmit/receive modules arranged in 16 rows and 10 columns. With traditional calibration schemes, any deviation of the antenna characteristics, for instance by losing sub-arrays throughout the spacecraft lifetime, would cause significant degradation of the radiometric performance as these schemes would not be capable to correct the sensing data as efficiently as for the nominal fully operating system. Moreover, in order to maintain a comparable radiometric performance, a full re-characterisation of the on-board instrument should be carried out every time that a given number of sub-arrays change their characteristics.

The experience gained thought the development and calibration of the ENVISAT ASAR and the lessons learnt during the commissioning period have been used to establish a novel calibration approach based on very accurate on-ground pre-launch characterisation data, a set of post-launch external measurements to be performed during the initial commissioning period, periodic in-flight internal characterisation data, and the internal calibration data to be taken during and together with the sensing data.

This concept is conceived to achieve a very high radiometric quality but reducing as much as possible the in-flight characterisation, that requires deployment, maintenance and data collection of transponders, and the need of long-lasting antenna beam characterisation using repetitive passes over the rainforest, for each antenna beam.

THE TERRASAR-L MISSION

ESA’s TerraSAR-L mission is designed for a lifetime of 5 years featuring a 14-day repeat cycle in a Sun-synchronous dawn-dusk orbit, with global imaging coverage, tight orbit control, high precision orbit determination and a 20-minute of high resolution and radiometric performance data per orbit [1]. These high radiometric performance requirements together with the operational concept and the systematic data-take approach of the mission, requires the implementation of a very effective calibration concept.

TerraSAR-L calibration is intended to provide data with the information needed to achieve the required performance of radiometric accuracy better than 1dB (3σ), with a short in-flight commissioning time reduced to three months, and capable to cope with active antenna graceful degradation throughout the mission lifetime with the same radiometric performance. Moreover, the concept reduces the effort and cost of the in-flight characterisation that requires deployment, maintenance and data collection of transponders; and the need of long-lasting antenna beam characterisation using repetitive passes over the rainforest that, in the case of ASAR, required more than 5 *good* samples for each antenna beam, for 8 antenna beams and more than six months.

The TerraSAR spacecraft is based on the novel Snapdragon configuration that simplifies the payload design and AIT. The main payload is an L-band SAR instrument based on an 11 x 2.9 m active phase array antenna with 160 transmit/receive sub-arrays laid down in 16 rows and 10 columns. The instrument operates Strip-map and ScanSAR modes, with full-polarimetric Strip-map capabilities, repeat-pass ScanSAR interferometry and a Wave Mode, with a bandwidth up to 85 MHz.

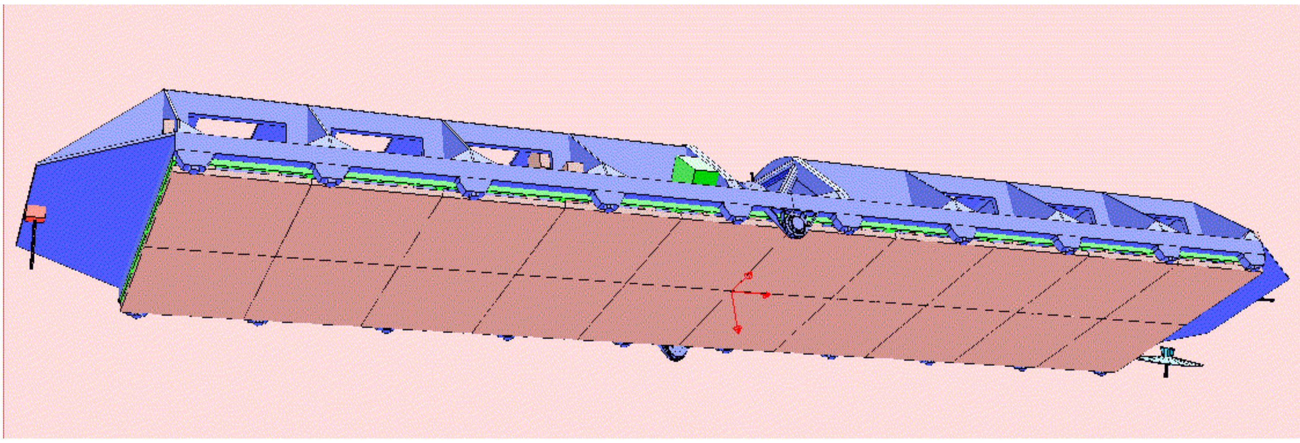

Figure 1: Snapdragon Configuration

CALIBRATION STRATEGY

The end-to-end system calibration strategy is based on calibrating as much as possible pre-launch, which particularly applies to Instrument and Processor calibration, and:

- Validate rather than verify on ground and verify rather that validate in orbit
- Build a reliable and accurate characterisation data and implement internal monitoring of instrument variables in orbit

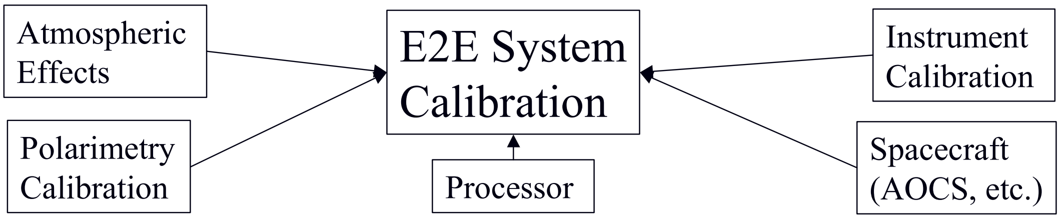

Figure 2: TerraSAR-L Overall Calibration

Obviously, the use external targets is necessary for atmospheric and polarimetric calibration. However, the effect from the instrument can be decoupled from the atmospheric and polarimetric uncertainties if it is characterised previously.

The system calibration implementation is based on:

- on-ground *pre-launch characterisation*,
- post-launch *external measurements* during the initial commissioning period,
- periodic in-flight *internal characterisation*,
- and the *internal calibration* during and together with the sensing data.

This calibration concept requires extra hardware to be built in the system, specific to routing the calibration signals through the instrument. This additional hardware consist of:

- Calibration network to be built on the antenna to loop back the internal calibration signals
- Auxiliary transmitter and receiver to cope with the non-operational levels of the calibration signals
- Switching hardware (switches, circulators, etc.)

The calibration hardware introduces additional uncertainty to the calibration scheme, as it is also subjected to variations. This uncertainty is reduced by pre-launch characterisation of this hardware and monitoring the stability of the auxiliary transmitters and receivers by a specific calibration pulses.

WHAT IS CALIBRATION?

In-orbit calibration requires having the knowledge to the requested accuracy of the following parameters at the time of radar sensing for a data take:

- Antenna Radiation Patterns,
- Antenna Pointing (i.e. the reference frame of the radiation pattern),
- Absolute Gain (i.e. instrument and atmospheric effect) for absolute radiometry,

- Polarimetric characteristics (i.e. crosspolarisation and imbalance effects)
- Variations of these parameters during the data taking: The short-term Instrument Stability Tracking

With the exception of the atmospheric effect on propagation loss and polarimetric imbalances, the rest of the parameters fall in the category of instrument calibration.

The antenna radiation patterns and pointing are assumed to be stable in short term and are solely dependent on the sub-array characteristics, T/R module status and a successful antenna deployment. The absolute gain is assumed to vary slightly throughout the data take because of temperature effects and limitations of temperature compensation schemes

INSTRUMENT CALIBRATION

Antenna Patterns

The calibration of the antenna beams will be based on an *Antenna Model* that will be developed and validated during the on-ground pre-launch test activities. This Antenna Model will be built from accurate Embedded Sub-array Patterns and T/R module characterisation. This characterisation will be based on the Module Stepping tests to be taken under the same operating conditions and well correlated to the embedded sub-array tests.

Once the latest updated T/R module data is provided, the antenna pattern of every beam is generated automatically by the Antenna Model when the corresponding beam coefficients are applied.

Antenna Pointing

The antenna pointing, i.e. the antenna boresight alignment with respect to the AOCS system of coordinates, is a consequence of the alignment of the various systems of coordinates during on-ground spacecraft integration, the in-orbit deployment of the instrument, and the radiating conditions of the phased array antenna.

The Antenna Model will be built with respect to the system of coordinates of the on-ground deployed antenna and will be capable to determine the antenna pointing for every beam with respect to this system of coordinates. The spacecraft AIT alignment will provide the alignment of the antenna reference system to the AOCS system and, therefore, to the in-flight attitude at any nominal mode during operations. The AOCS performance is defined:

- Knowledge of the orientation of the spacecraft up to an accuracy of 0.002º per axis, and
- AOCS orientation capability of 0.010º per axis

For the TerraSAR-L snapdragon configuration, the in-orbit deployment may cause some deviations with respect to the assumed nominal antenna system of coordinates (e.g. planarity, etc.) that would affect the pointing of the antenna beams. In this TerraSAR-L specific case, this would, nevertheless, affect the azimuth but not the elevation pointing of the beams. Therefore, a different approach can be taken for elevation and azimuth pointing:

<u>Elevation</u>
The elevation pointing will be derived from the Antenna Model referred to the AOCS reference system. During commissioning the process of derivation of the antenna pointing will be verified by using the antenna pattern verification with repeat passes over the rainforest.

<u>Azimuth</u>
Similarly to the elevation pointing, the azimuth pointing will also be derived from the Antenna Model referred to the AOCS reference system, and also verified during the commissioning period. However, in order to consider the deviations from the nominal deployment and the planarity stability, a special in-orbit pointing calibration test might be performed periodically. This test would use Pointing Calibration Beams that would verify the assumptions from the Antenna Model and would account for the deployment deviations. This pointing calibration test would be based on the monopulse approach (i.e. by switching between a uniform-phase beam, sum, and a beam with the antenna longitudinal half turned 180 in phase, difference) over the rainforest.

Antenna Gain

The absolute instrument gain will be obtained from different sources from the pre-launch on-ground instrument tests to the in-orbit calibration tests. These various procedures will have different accuracies that will be correlated:

a) Pre-launch antenna beam tests in the NF antenna range. The absolute gain will be measured together with the antenna beam patterns for the uniform-illuminated beam and some of the other beams. It is not expected to achieve an accuracy to the level of 0.1 dB, depending on the range gain calibration it would be expected of ± 0.2 or ± 0.3 dB

b) Antenna Model. Module stepping results, T/R calibration data and central electronics delivered RF power can be combined in the Antenna Model to derive the expected radiated power. This will be correlated with the measured gain in the range. The overall accuracy will be assessed
c) Transponder tests. During the commissioning period gain measurements will be performed by using calibrated transponders. This is expected to achieve a high accuracy and to be correlated to the pre-launch estimations
d) Gain estimation with rainforest data to be done during the satellite lifetime

Instrument Short-term Stability

The variations of the instrument characteristics within every data take will be tracked with the *Calibration Pulses*. These calibration pulses will be routed through the signal and calibration paths for transmit and receive and the two polarisations. The calibration pulses will switch along the antenna sub-arrays at row level and will follow a *Pulse Coded Calibration* (PCC) scheme [2] that allows a continuous operation of all antenna sub-arrays simultaneously and a nominal load of the power supply units.

ANTENNA MODEL

The antenna model is the essential tool where the calibration concept is based. It will be capable of modelling the antenna radiating characteristics to a high order of accuracy, typically 0.1 dB of absolute gain and 0.02 dB of relative gain within the imaging swath. This high accuracy is given by a precise characterisation of each sub-array and a close monitoring of the transmit and receive characteristics of the T/R modules connected to them.

Measurements of the antenna passive front end (Return loss, S_{11}, and Insertion loss, S_{21}) may be necessary to complete the Antenna Model. These measurements will be performed at tile-embedded radiator level:

The validation of the Antenna Model will be done by correlating the results with Near-Field antenna tests of a uniform-illumination test beam (all T/R modules at maximum gain and equal phase) and a limited selection of the operational beams (see below).

A post-launch verification of the model will be performed during the commissioning period by using repeat passes over the rainforest. This verification can only be done for the part of the main beam that corresponds to the swath and can also be used to verify elevation pointing.

Antenna Characterisation

The main contribution to the Antenna Model and its accuracy are the *Embedded Sub-array Test*. It consists of the measurement of the radiation characteristics of each individual sub-array embedded in its location within the antenna final configuration. The interactions caused by the rest of the sub-arrays are present in the measurement in this set-up. Particular care must, therefore, be taken in order to terminate properly the inactive sub-arrays. Likewise, the radiation tests must be defined with the consideration of the whole antenna as the object to measure and not only the active sub-array.

$\overline{E}^h_{mn}(\theta,\phi)$ Embedded Sub-array Pattern of sub-array (m,n) in horizontal polarisation

$\overline{E}^v_{mn}(\theta,\phi)$ Embedded Sub-array Pattern of sub-array (m,n) in vertical polarisation

In order not to repeat the NF range radiating test for the 160 sub-arrays and considering that the sub-arrays have a highly imbalanced radiation pattern (narrow-azimuth and broad-elevation beam) an alternative approach can be taken: The measurement can be performed at column level (i.e. all sub-arrays of the same column are activated and the rest are off) for azimuth, and row level (i.e. all sub-arrays of the same row are activated and the rest are off) for elevation, and the results combined for each sub-array.

For sub-array (m,n):

$$\overline{E}^h_{mn}(\theta,\phi) = K^h_{mn} \cdot \overline{E}^h_{column\_m}(\theta,\phi)\Big|_{azimuth} \cdot \overline{E}^h_{row\_n}(\theta,\phi)\Big|_{elevation} \quad \text{for horizontal polarisation}$$

$$\overline{E}^v_{mn}(\theta,\phi) = K^v_{mn} \cdot \overline{E}^v_{column\_m}(\theta,\phi)\Big|_{azimuth} \cdot \overline{E}^v_{row\_n}(\theta,\phi)\Big|_{elevation} \quad \text{for vertical polarisation}$$

where:

K_{mn}^{h}	Gain constant for sub-array (m,n), horizontal polarisation
$\left.\overline{E}_{column\_m}^{h}(\theta,\phi)\right\vert_{azimuth}$	for column m, horizontal polarisation
$\left.\overline{E}_{row\_n}^{h}(\theta,\phi)\right\vert_{elevation}$	for row n, horizontal polarisation

and similarly for vertical polarisation.

K_{mn}^{h} and K_{mn}^{v} are the gain correction factors that will apportion the column- or row-measured power gain, individually to each sub-array. They can be obtained from the product of the two fractioned power gains (column and row) fine-tuned from further analysis of the aperture back-transform data The individual power gain will be correlated with the previous characterisation of the passive sub-array radiator and the Module Stepping performed at the same instance, and will be referred to that Module Stepping value.

The embedded sub-array tests will be referred to the antenna system of coordinates stored in a mirror cube, typically.

The Module Stepping test consist of a measurement through the internal calibration network of the transmit and receive settings and characteristics of the individual sub-array T/R modules. The Module Stepping will be performed for transmit and receive and the two orthogonal polarisations. The *Pulse Coded Calibration* (PCC) scheme will be used as it makes the system and, in particular, the power supply load closer to real operating conditions [2].

The PCC scheme to be used can be performed for all TRMs only for maximum gain and zero-phase state, based on:

- The phase shifters can be assumed to be stable with respect to the pre-flight characterisation
- The deviations of the maximum gain are main contributors to the overall error, deviations at lower gain levels are weighted by the gain setting

Finally, the Calibration Pulses will track the short-term variations of the transmit and receive conditions of the antenna during each data take. Although the T/R modules will be compensated for the temperature sensitivity, uncompensated variations together with any other variation of the rest of the signal routing will be corrected by the ground processor.

The calibration pulses are defined at row level as the antenna beam forming is always defined on a row-by-row basis, i.e. all sub-arrays within the same row are set to the same radiating parameters (gain and phase). They will be routed with the radar signal at the beginning and the end of the data take. Additionally, subsequent sets will be possible to be interleaved with the radar signal on a adjustable basis. The frequency for insertion of calibration pulses will be defined considering the expected variation rate. The possibility of using a single-shot calibration pulses is also being considered to track only variations in the transmitter and receiver of the Central Electronics unit.

The calibration pulses will be defined as they were defined for ENVISAT ASAR:

- Transmit calibration pulse (ASAR p1) to track changes of the transmitting signal
- Receive calibration pulse (ASAR p2) to track changes of the receive characteristics
- Central electronics internal calibration pulse (ASAR p3) to track changes of the transmit/receive characteristics of the auxiliary transmitter and receiver

The *Pulse Coded Calibration* scheme at row level will also be applied, so to maintain the same power supply conditions and avoid the need of using a correction calibration pulse, as it was p1a for the ENVISAT ASAR system.

The calibration pulses are generated with the TRM setting as defined by the mode beam coefficients.

Antenna Model Validation

The *Antenna Model* must be validated by an accurate and detailed comparative analysis of the results of the modelling of several antenna beams against the results of the actual antenna measured beams.

This comparative analysis must be supported by detailed error and sensitivity analyses that will provide:

- The validation criterion
- The accuracy of the *validated* Antenna Model

- The assessment of the accuracy with what the Characterisation Data (sub-array patterns, passive antenna scattering-matrix parameters, etc.) are required to be measured

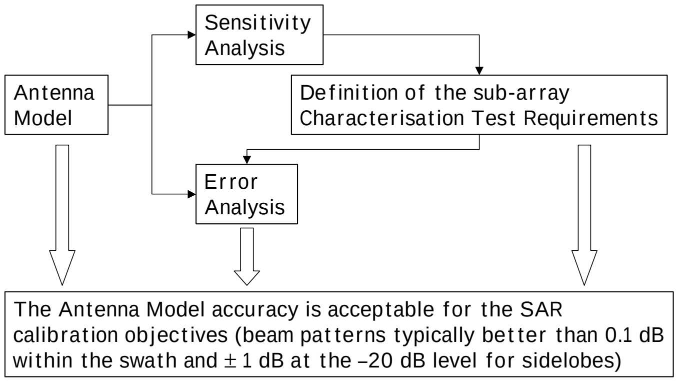

Figure 3: Derivation of the Characterisation Data Test Requirements for the Antenna Model

Figure 3 summarises the process for the definition of the Characterisation Data test requirements based on the sensitivity analysis and the error analysis. These Characterisation Data constitute the basis of the *Antenna Model*. The sensitivity analysis will derive the characterisation data tests requirements from the *Antenna Model* accuracy requirement. Once these tests requirements are confirmed to be feasible, the error analysis gives the frame for the validation success criterion.

Figure 4 shows that for each test beam, the modellised antenna pattern is compared with the measured pattern. The results of the comparison must be consistent with the results of the error analysis. This comparison must be performed for a minimum of different beams in transmission and reception and both polarisations. And it requires:

- To perform the antenna patters tests with sufficient accuracy that allows the comparative analysis with the modellised pattern
- To include the pattern measurement test error budget in the comparative analysis
- To maintain the antenna operating conditions throughout the complete planar scanning (it is recommended to perform the tests with the antenna in thermally stable conditions and disable the update of the thermal compensation coefficients throughout the planar scanning measurement process)

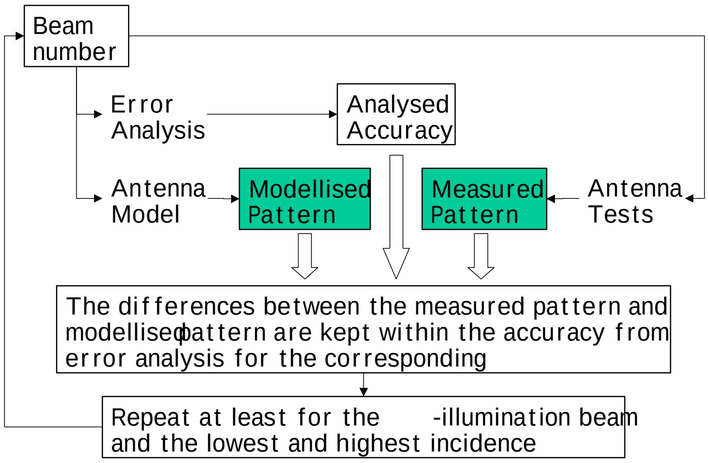

Figure 4: Antenna Model Validation Concept

GROUND PROCESSOR CALIBRATION

Calibration Pulse Processing

Calibration pulses shall be extracted in the pre-processing (screening) step for complete data take segments. Cal pulse processing to instrument gain values shall be implemented in a dedicated/separate module. Cal pulse extraction and processing shall always be performed and the results shall always be provided as part of the screening output to the ICS. A dedicated switch in the processor shall allow to enable/disable the application of the resulting gain correction to the data.

Processor Normalisation
Precise normalisation of the processor gain for varying instrument and processing parameters is a crucial step in the overall calibration activity. Instrument characteristics (e.g. azimuth patterns) have to be taken into account properly. Ideally processor normalisation shall achieve consistent radiometric levels across all modes and beams for each product type (SLC, MGD, EEC) and hence enable common calibration factors (one number for SLC, one for MGD, etc.).

Noise Processing – Noise Gain
The instrument will acquire noise samples at the start of each data take (burst) during the first n pulses (n corresponds to two-way round trip time of the transmit pulses/echo signals). Averaging of these noise samples provides an estimate of the system noise floor at that certain time. Noise estimates shall be either converted to radar brightness by applying the corresponding range dependent noise gain or the necessary parameters (including range dependent modulation) shall be provided to convert the noise estimates to NESZ.

CONCLUSIONS

Based on an accurate development of an Antenna Model that will be validated on ground and verified in orbit, the TerraSAR-L calibration concept will allow the TerraSAR-L mission to reduce dramatically the commissioning period to three months and to cope with antenna graceful degradation, i.e. expected drift and eventual mortality of T/R modules, whilst giving the same calibration performance and product quality.

Moreover, the concept of using a high accuracy Antenna Model and a close monitoring of T/R Modules may introduce the possibility of handling the antenna patterns no longer as structural characterisation data but highly accurate calibration data to be provided together with each data take.

REFERENCES

[1] M. Zink, R. Torres, “The TerraSAR System and Mission Objectives”. *CEOS 2004.* Ulm, Germany, May 2004.

[2] D. Bast. “A Pulse Coded Calibration for SAR Antennas”. *EUSAR 2004*,volume 2, pp 921-924. Ulm, Germany May 2004.