Cosmo SkyMed: antenna elevation pattern data evaluation

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Abstract
In modern SAR instruments the radiometric accuracy represents a fundamental requirement to improve the exploitation of targets reflectivity measurement that depends on the antenna pattern in elevation plane. The large phased array antenna pattern may deviate from the on-ground characterization due to the local different gravitational stresses and temperature gradients on the antenna plane that might deform its structure. A method to evaluate the antenna elevation pattern is represented by the measurement of the distributed targets scattering estimated on focused image. In this paper, the above mentioned procedure for the phased array antenna elevation pattern estimation will be described and some results from the COSMO-SkyMed instrument presented.

Keywords: COSMO-SkyMed, SAR, Calibration.

COSMO-SkyMed: stima del fascio d’antenna nel piano di elevazione

Riassunto
Nei moderni sensori SAR l’accuratezza radiometrica rappresenta uno degli elementi fondamentali richiesti per l’utilizzo della misura di riflettività. L’accuratezza radiometrica dipende principalmente dalle caratteristiche del fascio d’antenna nel piano di elevazione che, nel caso di antenne “phased array” di grandi dimensioni, può variare rispetto alle misure di caratterizzazione eseguite a terra a causa di diversi fenomeni che possono modificare le caratteristiche meccaniche dell’antenna. Uno dei metodi disponibili per stimare il fascio d’antenna nel piano di elevazione è basato sulla misura della riflettività di un bersaglio esteso con caratteristiche omogenee. In questo articolo, viene descritta una procedura per la stima del fascio d’antenna nel piano di elevazione, che prende spunto dal suddetto approccio, e verranno forniti alcuni risultati relativi al sistema COSMO-SkyMed.


Introduction
COSMO-SkyMed (Constellation of Small Satellites for Mediterranean basin Observation) is a 4-spacecraft constellation funded by ASI (Agenzia Spaziale Italiana) and Italian Ministry of Defence [Caltagirone et al., 2003], and [Caltagirone et al., 2001]. The overall objective of this program is global Earth observation and the relevant data exploitation
for the needs of the military community as well as for the civil (institutional, commercial) community. The first satellite was launched on June, 7th 2007. Each of the four satellites is equipped with a SAR operating at X-band with multimode (spotlight, stripmap, and scansar) and multipolarisation capability. Operational flexibility (multimode, access area, left and right looking) is one of the major system requirements leading to a quite large number of different modes configurations and antenna beams (>100). Moreover, the requirements on radiometric accuracy (1 dB) and radiometric stability (0.5 dB), together with the requirement to have a commissioning phase less than three months and the need to keep the cost affordable required the development of an advanced calibration concept. The calibration concept [Torre et al., 2006] is based on three elements: i) radiometric stability; ii) relative radiometric accuracy; iii) absolute radiometric accuracy.

**Instrument gain evaluation**

The required radiometric stability is achieved through the compensation of instrument fluctuation; this is done by in-flight verification of the instrument against the pre-flight characterisation data.

The critical part of the instrument is the active antenna (SAA), which is composed by 40 tiles each including 32 T/R modules (TRM) each one feeding a patch linear array (H and V polarisation). The instrument gain and phase stability is based on two mechanisms i) the compensation of the TRM variations versus temperature; ii) the internal calibration. The compensation of the TRM variation vs. temperature is implemented by the Tile Control Units (SBC) as background operation during the instrument functioning. The TRM compensation is based on the complete characterisation of each module during the on-ground test: characterisation is performed over the full operational temperature interval and for each pair of amplitude and phase settings. Characterisation data are stored in the SBC look-up table and used to select the TRM setting values according to the commanded ones and the actual temperature value of the specific TRM. The refresh rate of the TRM setting is equal to PRF, at the base of this choice is the need to change the beam at PRF rate and to have the compensation of TRM setting distributed in time (autonomously triggered by the specific TRM temperature variation) in order to avoid any change of beam phase due to a simultaneous variation of the settings of all the TRMs.

The internal calibration sub-system of the COSMO SAR monitors all the critical part of the radar (i.e. only the passive linear arrays are outside the loops), and is used on devoted calibration modes (TRCAL) and for initial and final calibration operations during the imaging modes. The internal calibration is performed by sending dedicated pulses along signal path, according to the specific system timeline. Such pulses are looped on the signal main and calibration chains.

**Relative radiometric calibration**

Relative radiometric accuracy mainly depends upon the compensation of the antenna pattern. The in-flight determination of the actual patterns, being the COSMO SAR a complex instrument implementing a multitude of modes and different beams, would lead to an increase of the commissioning period were a reliable antenna model not available. For this purpose an antenna model has been developed to provide the required support to
the relative calibration of the SAR data. The development flux is based on pre-launch on-ground activity, in-flight validation activity and in-flight routine monitoring. The on-ground activity includes: the synthesis and optimisation of the antenna patterns for all the modes; alignment of the antenna and measurements of reference patterns in near field; fitting and validation of the antenna model on the actual measurements results. Measurements data (at tile, panel and antenna level) have been used to evaluate the calibration values to be fed to the theoretical antenna model to reproduce the measured pattern.

In-flight validation activity includes: measurement of reference patterns over uniform (e.g. Amazon forest) target; verification of predicted pattern (from antenna model) with measured ones; use of TRCAL mode for actual setting verification; update of the model if major differences between predicted and measured patterns are detected.

Routine calibration activity now includes: check of the TRM status through the TRCAL mode and optimisation of the illumination functions whether TRM failures be detected.

**Absolute radiometric calibration**

Absolute accuracy mainly depends on the estimation and compensation of the system gain bias. This activity is done with the acquisition of images of standard targets on known RCS. The COSMO SkyMed CALVAL system is based on the following major items: i) the SAR Engineering Calibration Facility (SECF) where all the operations related to the system calibration are managed and where the S/W tools for the analysis and calibration of the SAR are integrated; ii) the external site with the passive calibrators and the active transponders.

**Antenna model and beam pattern estimation**

Relative radiometric accuracy accounts for the stability of radiometric errors between identical targets in multiple images in order to achieve uniformity in sensor response across the field of view of the sensor. The main contribution to radiometric errors is given by inaccuracies in the determination of beam pattern which lead to erroneous estimation of antenna gain profile. An antenna model is then necessary to predict at any time, during sensor operative life, the actual behaviour of the antenna according to functional status, failures and ageing. The use of an antenna model to predict the antenna beam patterns and to ease the calibration activity is an approach shared by other systems like ASAR [Torres, 2002] and TerraSar-X [Bachmann et al., 2007], in those cases the basic steps in antenna modelling are quite the same of the ones described in this paper and the main differences depend on the solutions used in the implementation of the antennas (e.g. technology of the radiating elements: patches or slotted waveguides).

Cosmo-SkyMed embarks a phased array antenna which provides capability both to electronically steer the beam (by opportune controlling element phase settings) and to modify beam conformation according to operative mode and incidence angle. Cosmo-SkyMed antenna is modelled by mean of a phased array simulator developed by Thales Alenia Space Italia in the frame of SAR calibration activities. In a linear phased array the radiated beam can be steered by introducing a progressive phase shift between adjacent elements. Say $\theta_o$, the scan angle with respect to normal direction, the phase delay can be calculated as:
\[ \Delta \Psi = \frac{2\pi d_s}{\lambda} \sin(\Theta_o) \quad [1] \]

where \( d_s \) is the inter-element spacing, \( \lambda \) is the wavelength and \( \Theta_o \) is the desired steering angle.

The linear array factor (AF), i.e. the total field achieved as combination of single modules radiations, is given by:

\[ AF = \sum_n |a_n| e^{j \frac{2\pi}{\lambda} n_{dx}(u - m)} \quad [2] \]

where \( u = \sin(\Theta_o) \) and \( a_n \) are the amplitude weights assigned to each module.

For a two-dimensional array, assuming T/R modules’ phase centers at locations

\[ r_m, n = m d \hat{x} + n d \hat{y} \quad [3] \]

and for a beam peak required at \((\Theta_o, \phi_o)\), the array factor is given by:

\[ AF = \sum_n \sum_m |a_{mn}| e^{j \frac{2\pi}{\lambda} [m d(u - u_o) + n d(v - v_o)]} \quad [4] \]

The developed simulator, PHARSIM (PHased ARray SIMulator), is based on array factor computation by mean of Fast Fourier Transform applied on the amplitude-phase excitation matrix. Main limitation of models based only on far field extraction by FFT applied to the nominal excitation matrix (as the one derived by an optimization tool) is that the achieved pattern doesn’t generally fit the real one, because second-order effects, mutual couplings, mismatches and in general deviations from ideal case are not kept into consideration. Even if PHARSIM is not an electromagnetic model, it performs excitations correction by importing data coming both from near-field pre-flight measures and in-flight calibration data, i.e. the predicted beam is achieved by matching both information on antenna configuration (operative frequency, bandwidth, element spacing, number of T/R modules, TDLs settings, failures), near field measures (pre-optimisation and post-optimisation holograms) and in-flight calibration data in terms of T/R module response to dedicated calibration pulses. Such a procedure allows applying a correction to the ideal pattern in order to meet the real characteristics of the beam, as generated by the real antenna.

Concerning pre-flight measures, PHARSIM may load the holograms generated in the frame of near-field scanning activities and may then self estimate the correction parameters for antenna compensation by opportunely sampling such holograms according to the antenna geometry and the patch/slot location.

Figure 1 and Figure 2 show an example of the phase antenna response in the frame of near-field measures, as loaded by PHARSIM.

The correction matrix is computed both for transmission and reception mode, as well as for each polarization, but applies linearly to the whole set of beams generated by the antenna.
It shall be kept into account that near field test probe scans the antenna by a distance of several wavelengths. According to the antenna theory, the far-field pattern is already forming at such distance and this effect leads to an error in the estimation of the right amplitude and phase setting, as sampled along the probe plane. The far-field pattern is then corrected to compensate for this effect, according to:

\[ AF_\delta(u, \nu) = AF_\delta(u, \nu) e^{j2\pi w(u, \nu)z} \]  

where:
\( AF_\delta(u, \nu) \) is the spectrum which would be achieved without any correction;
\( AF_\delta(u, \nu) \) is the spectrum obtained by mapping the excitation on the aperture;
\( w(u, \nu) = \sqrt{1 - u^2 - \nu^2} \);
z is the separation between the measurement plane and the aperture plane.

Figure 1- Phase Hologram (from near-field measurement).

Figure 2 – Amplitude (left) and phase (right) Hologram.
Validation

PHARSIM has been initially validated versus an electromagnetic model (MOM) where mutual coupling, mismatching and non linear effects are accounted for. Further validation is performed over actual measurement results achieved by near field test results as shown in Figure 3.

![Figure 3 - PHARSIM vs. near field measures: elevation cut: Tx H & V polarization (top), Rx H & V polarization (bottom).]

General results from an extended measurement campaign show the capability to achieve a standard deviation of pattern estimates < 0.4 dB as compared to pattern estimations from rainforest data; synthesis capability from TRCAL data with an error < 0.5 dB; elevation patterns prediction with an error smaller than 0.5 dB; azimuth patterns prediction with an error smaller than 0.02 dB. A result of beam pattern compensation in the elevation plane is shown in Figure 4.

TRCAL

Cosmo-SkyMed antenna implements a dedicated calibration network [Torre et al., 2008] which allows system status monitoring and TRM characterization along the whole operative life of the sensor. TRCAL is an operative mode expressly devoted to characterization of TRM response. During TRCAL mode, the whole antenna is switched off with the exception of the module under test (MUT) and, in such a way, a periodic check of the antenna subsystem is performed. Data coming from MUT are processed and loaded into the antenna model in the form of actual excitation matrix to achieve a further verification of the real antenna performance. Figure 5 and Figure 6 shows the high correlation between the pattern generated by PHARSIM (once
correction of the excitation matrix is performed on the base of near field measures) and that generated by PHARSIM through exploitation of TRCAL data.

![Figure 4 - Range Pattern Compensation in STRIPMAP images (beam H4-0A-20°-21° incidence angle) before and after beam elevation pattern and residual elevation pointing compensation.](image)

![Figure 5 - Beam reconstruction by TRCAL data (black: PHARSIM, grey: TRCAL DATA).](image)
Conclusions
Simulations show the effectiveness in reconstructing antenna beam profile with high level of accuracy both by exploiting near field data and TRCAL data. PHARSIM supports engineering activities related to SAR system design, providing a valuable multifunctional tool for synthesis, analysis and performance assessment during in-flight commissioning and calibration operations.

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References


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