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SIR-C/X-SAR **data calibration and ground truth campaign over the** NASA-CB1 **test-site** (*)(**)

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Summary. — During the Space Shuttle Endeavour mission in October 1994, a remote-sensing campaign was carried out with the objectives of both radiometric and polarimetric calibration and ground truth data acquisition of bare soils. This paper presents the results obtained in the experiment. Polarimetric cross-talk and channel imbalance values, as well as radiometric calibration parameters, have been found to be within the science requirements for SAR images. Regarding ground truth measurements, a wide spread in the height rms values and correlation lengths has been observed, which has motivated a critical revisiting of surface parameters descriptors.

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1. – Introduction

Earth monitoring using microwave remote-sensing techniques has received much interest in the last years. To a large extent, the success of this approach depends on the ability to relate sensor measurements to environment parameters. In this context, well-controlled experiments were conducted in October 1994 when the Space Shuttle Endeavour flew over some areas of the Earth surface with two synthetic aperture radars (SAR) on board. Purpose of this mission was the acquisition of geo-physical parameters related to the environment. The first of these sensors operated in *L*- and *C*-band (1.2

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GHz, 5.3 GHz) at four linear polarizations HH, VV, HV, VH, and the second in X-band (9.6 GHz) at VV polarization.

During the mission, in a collaboration among the Politecnico of Bari, the ITIS-CNR of Matera and the CO.RI.STA of Naples, a remote-sensing campaign was carried out with the following objectives:

1) radiometric calibration of radar images using active (Active Radar Calibrators, ARCs) and passive (Trihedral Corner Reflector, TCRs) calibrators;

2) polarimetric calibration based on the analysis of the observed scattering matrix coefficients;

3) ground truth data acquisition for bare soils over six selected fields.

The study area covers 19.5×18.5 km^2 (range × azimuth) and it is located in a south-eastern region of Italy (NASA-CB1 Test-site, Matera). Due to the different conditions required by the analysis, two sites were considered: Murgia del Ceraso, used as a calibration site, and Poggiorsini, where ground truth data were collected.

2. – Calibration

The calibration of SAR imagery can be separated into four major parts: the radiometric calibration, the antenna pattern measurement and removal, the geometric correction of images using point-like calibrators and the polarimetric calibration.

The radiometric calibration allows to quantify the radar performances during the flight and its real in-flight operation. Moreover, the distortions that affect the radar signal during its propagation from the antenna to the target and back to the antenna can be evaluated. Adequate radiometric correction of SAR data also requires knowledge of the sensor-target geometry and the antenna elevation pattern.

For the geometric calibration, active and passive calibrators are deployed on the calibration site; their point-like response contributes to create a network of ground control points (GCP), accurately measured with GPS technique, later to be located on processed images.

Furthermore, a correct use of polarimetric data requires as a fundamental step their polarimetric calibration. This calibration is necessary in all quantitative applications of polarimetric SAR data; the complex way in which the antennae, the radar electronics and the signal propagation affect the acquired data makes their correction a computationally intensive operation. In this paper we focus on radiometric and polarimetric calibration.

2˙1. *Radiometric calibration.* – In this SIR-C/X-SAR experiment, the radiometric calibration has been performed by using both active radar calibrators (ARCs) and passive trihedral corner reflectors (TCRs).

2˙1.1. *Description and use of ARCs and TCRs.* In the framework of this campaign, seven ARCs were deployed, covering the three operational bands of the active microwave sensor. Table I indicates their geographical position, determined using GPS. In particular, two ARCs in L-band, two in X-band and three in C-band were used. The C-band ARCs were designed for a previous campaign with the ERS-1 satellite, while the L- and X-band active devices, built after the experience gained from laboratory and *in situ* validation, were designed following the same layout of the C-band calibrators. ARCs

Table I. – *Geographical position of reference targets.*

Reference points	Calibrators	Latitude (degrees)	Longitude (degrees)	Height (m)
A	ARC-L2	40°57′48.6″	16°30′33.7″	530.43
A	ARC-C2	40°57′48.6″	16°30′33.7″	530.43
A	ARC-X2	40°57′48.6″	16°30′33.7″	530.43
B	CR1	40°57′11.0″	16°29′55.9″	527.35
C	ARC-L21	40°59′28.0″	16°28′28.0″	497.0
C	ARC-C1	40°59′28.0″	16°28′28.0″	497.0
C	ARC-X1	40°59′28.0″	16°28′28.0″	497.0
C	CR2	40°59′28.0″	16°28′28.0″	497.0
D	CR3	40°58′13.6″	16°26′55.7″	539.08
E	ARC-C3	40°57′27.5″	16°28′51.4″	490.00

mainly consist of two similar antennae, one receiving and the other transmitting, coupled to a Radio Frequency amplifier section (fig. 1). By means of a directional coupler, a signal detection circuitry, connected to the ground by a 1 kΩ resistor, sends a small portion of the received signal (-10 dB with respect to the power amplifier output) to an external circuit, in order to verify the triggering of the device by the SAR signal and the correctness of its positioning during the overpass of the satellite sensor. The RF section is designed with a modular approach, using two stages. The pre-amplifier section is cascaded to a band-pass filter centred on the working frequency, so as to attenuate out-of-band spurious signals. The power amplifier follows a fixed attenuator which determines the dynamic range, ensuring linearity and stability, and avoiding, on the other hand, saturation at the radar impulse peak. All the devices are powered by a $+12$ V DC source. A more detailed description of the principal components of the ARC is given in [1]. Electronics and antennae are weatherproof and the structure is able to withstand normal winds without readjustment. The deployment and orientation are easily accomplished, and the adjusting/locking mechanisms are manual.

Fig. 1. – Block diagram of ARCs circuitry.

The devices' weights are, respectively, 22 kg (L-band), 20 kg (C-band) and 16 kg (X-band). Pre-flight measurements, described in [2, 1], were performed in order to evaluate the system transfer function, gain over the frequency bandwidth and thermal effects on the Radar Cross-Section (RCS). Their RCS is given by

$$\sigma_{\mathrm{ARC}} = \frac{\lambda^2}{4\pi} G_{\mathrm{ARC}} G^2_{\mathrm{Ant}}, \tag{1}$$

where λ is the wavelength at central frequency, G_{ARC} is the measured RF-section gain, inclusive of mismatch and insertion losses, and G^2_{Ant} the combined antenna gain. A typical SAR image containing an ARC signal is shown in fig. 2. The ARC response is evidenced by the white rectangle. This is the second X-band ARC used in the experiment (ARC-X2, in the third row of table I). Just above the ARC "cross", another point-like response is visible, corresponding to a 180-cm leg-length TCR. The TCRs RCS can be assessed according to the formula

$$\sigma_{\mathrm{CR}} = \frac{4\pi}{\lambda^2} \frac{L^4}{12}, \tag{2}$$

where L is the "leg" length, *i.e.* the trihedron side length.

Being passive calibrators, CRs can be regarded as reference points on the processed images allowing the absolute determination of RCS for the active devices.

2˙1.2. *SAR images calibration results.* The radiometric calibration strategy follows, with little modification, the integral approach, described in [3]; by choosing a reference RCS value σ_{ref} and evaluating the energy terms associated with the ARC response (E_{gp}), the background clutter (E_{gu}) and the thermal noise on a small rectangle (*e.g.*, 16×16 pixels) centred around the brightest pixel, which is representative of the position of the calibrators, the estimate of the average backscattering coefficient σ^0 was carried out by applying on a pixel-by-pixel basis the following relation:

$$\langle \sigma^0 \rangle = K(R_u, R_p)\sigma_{\mathrm{ref}} \frac{E_{gu}}{A_u E_{gp}} \left(\frac{R_u}{R_p}\right)^3 \left[\frac{G(\theta_p)}{G(\theta_u)}\right]^2 \sin\theta_u, \tag{3}$$

where A_u is the area associated with the uniform background, viewed at slant range R_u and incidence angle of θ_u, G represents the sensor two-way antenna gain patterns, and the factor K takes into account the atmospheric attenuation. The accuracy on the estimate of E_{gp} is mainly due to the clutter+noise contribution and to the speckle autocorrelation function: on the data sets analyzed, the mean accuracy of the calibration results was found to be ±0.9 dB. This figure was derived by considering all the sources contributing to the error budget, namely the thermal noise, the clutter bias, and the error in estimating the CR return.

The shape of the sensor normalized antenna pattern in elevation was assumed as the one estimated from the pre-flight panel measurements. The numerical results derived from the analysis of the SIR-C/X-SAR data sets 125-20 and 66-42 are listed in table II, where the one-dimensional resolutions, integrated sidelobe ratio (ISLR) and peak to sidelobe ratio (PSLR), in both range and azimuth directions, together with the reconstructed RCS value from the calibrated images, are reported. Both the JPL and I-PAF processors show good performance, with mean broadening factors of 13% in ground range and 10% in azimuth, and ISLR and PSLR are below the science requirements for SAR images.

Fig. 2. – Sample image of ARC responses. (a) Amplitude SAR X-band image of the Matera test-site, acquisition of 02/10/94; (b) 3-D plot of the ARC response, corresponding to the area evidenced by the rectangle in (a).

TABLE II. – *Results derived from data analysis.*

ARC	Resolution (m) (broadening) Ground Ran.	Azim.	ISLR (dB) Ran.	Azim.	PSLR (dB) Ran.	Azim.	RCS (dBm^2)
X1	24.7 (+10%)	6.71 (+7%)	−12.6	−11.4	−15.2	−14.3	58.2±0.8
X2	26.8 (+13%)	6.59 (+7%)	−7.06	−11.4	−15.4	−14.2	53.6±0.8
L1	19.7 (+15%)	11.5 (+45%)	−7.78	−11.5	−10.0	−18.0	57.5±1.0
L2	18.8 (+14%)	11.4 (+45%)	−7.6	−11.0	−9.19	−15.9	55.0±1.0
C1	19.2 (+15%)	8.52 (+10%)	−15.7	−18.4	−21.6	−36.5	50.9±0.9
C2	19.2 (+15%)	8.40 (+10%)	−16.3	−17.2	−20.9	−26.7	50.3±0.9
C3	19.6 (+16%)	8.65 (+11%)	−16.0	−18.2	−21.3	−25.7	51.0±0.9

The azimuth resolution evaluated on the L-band ARCs presents a severe degradation (45% broadening with respect to the theoretical value), probably due to wrong estimates in the azimuth processing parameters.

The RCS extracted after the calibration strategy are in good agreement with the laboratory estimates: the deviation from the expected values may arise from the different temperature on the site, or uncertainties in the calibration method. Satisfactory performances of the ARCs can be stated from the described analysis. The polarimetric capability at L- and C-band of the sensor, and the different mode of the radar operation allows a thorough characterization of the ARC performances.

2·2. *Polarimetric calibration.* – A polarimetric radar records, for each image pixel, an array of quantities, known as scattering matrix. Basically, the radar transmitted wave is decomposed into a horizontally (H) and a vertically (V) polarized component, according to

$$\mathbf{E}^t = E^t_{\mathrm{H}}\hat{\mathbf{h}} + E^t_{\mathrm{V}}\hat{\mathbf{v}}. \tag{4}$$

The backscattered field can in turn be decomposed into the horizontal and vertical components, E^r_{H}, and E^t_{V}, which are related to the transmitted components through the following expression:

$$\begin{pmatrix} E^r_{\mathrm{H}} \\ E^r_{\mathrm{V}} \end{pmatrix} = \frac{e^{ik_0 r}}{r} \begin{pmatrix} S_{\mathrm{HH}} & S_{\mathrm{HV}} \\ S_{\mathrm{VH}} & S_{\mathrm{VV}} \end{pmatrix} \begin{pmatrix} E^t_{\mathrm{H}} \\ E^t_{\mathrm{V}} \end{pmatrix}, \tag{5}$$

where the right-term multiplicative factor takes into account the propagation to and from the antenna, and the 2×2 matrix is the polarimetric scattering matrix. The polarimetric radar independently measures each element of the scattering matrix, by typically using two orthogonally polarized antennae.

2·2.1. *Polarized signal model.* The radar signal is affected by noise and distortions which are different for each polarization channel. Hence, such distortions are usually modeled through a matrix notation. The *observed* scattering matrix for a given pixel is related to the "real" one by

$$\begin{pmatrix} O_{\mathrm{HH}} & O_{\mathrm{HV}} \\ O_{\mathrm{VH}} & O_{\mathrm{VV}} \end{pmatrix} = \begin{pmatrix} T_{\mathrm{HH}} & T_{\mathrm{HV}} \\ T_{\mathrm{VH}} & T_{\mathrm{VV}} \end{pmatrix} \begin{pmatrix} S_{\mathrm{HH}} & S_{\mathrm{HV}} \\ S_{\mathrm{VH}} & S_{\mathrm{VV}} \end{pmatrix} \begin{pmatrix} R_{\mathrm{HH}} & R_{\mathrm{VH}} \\ R_{\mathrm{HV}} & R_{\mathrm{VV}} \end{pmatrix} + \begin{pmatrix} N_{\mathrm{HH}} & N_{\mathrm{HV}} \\ N_{\mathrm{VH}} & N_{\mathrm{VV}} \end{pmatrix}, \tag{6}$$

or, in compact form,

$$\mathcal{O} = \mathcal{T}\,\mathcal{S}\,\mathcal{R}^T + \mathcal{N}. \tag{7}$$

The quantities R_{ij} and T_{ij} represent receive and transmit distortions, respectively, where the first index denotes the polarization state of the transmitted radiation, and the second one that of the received radiation. The non-diagonal elements of matrices $\mathcal{R}$ and $\mathcal{T}$ represent cross-talk effects between the two antennae, while the diagonal elements include both imbalance effects between the two polarized channels and an overall absolute factor. In the expression, the matrix $\mathcal{N}$ represents system thermal noise and all other unmodelled additive noise sources. It is generally assumed that the elements of $\mathcal{N}$ are negligible with respect to the others.

A calibration procedure allows to estimate the elements of the distortion matrices defined in (6), up to a constant factor, not measurable from the data.

2˙2.2. *Overview of calibration algorithms.* Current research in the field of polarimetric calibration at the time of this experiment basically involved development of estimation algorithms exploiting distributed targets, rather than relying on the presence of point targets with known scattering characteristics.

Distributed-target algorithms typically make use of some symmetry properties satisfied by a large class of soil types. These characteristics affect the form of the covariance matrices calculated over the polarimetric channels on the image [4]. The most widely used kind of symmetry is the azimuthal one, known as the property that the surface backscattering characteristics do not change under rotation and/or reflections of the reference frame defining the wave polarization. This kind of symmetry is exhibited by bare or lightly vegetated soils.

From these premises, it is possible to derive a series of conditions on the covariance matrix coefficients, which is generally defined as the product

(8)

$$\begin{aligned}\mathcal{C}_S = \langle \mathbf{S}^\dagger \mathbf{S} \rangle &= \left\langle \begin{pmatrix} S^*_{\mathrm{HH}} \\ S^*_{\mathrm{HV}} \\ S^*_{\mathrm{VH}} \\ S^*_{\mathrm{VV}} \end{pmatrix} \begin{pmatrix} S_{\mathrm{HH}} & S_{\mathrm{HV}} & S_{\mathrm{VH}} & S_{\mathrm{VV}} \end{pmatrix} \right\rangle \\ &= \begin{pmatrix} \sigma_{\mathrm{HHHH}} & \sigma_{\mathrm{HHHV}} & \sigma_{\mathrm{HHVH}} & \sigma_{\mathrm{HHVV}} \\ \sigma_{\mathrm{HVHH}} & \sigma_{\mathrm{HVHV}} & \sigma_{\mathrm{HVVH}} & \sigma_{\mathrm{HVVV}} \\ \sigma_{\mathrm{VHHH}} & \sigma_{\mathrm{VHHV}} & \sigma_{\mathrm{VHVH}} & \sigma_{\mathrm{VHVV}} \\ \sigma_{\mathrm{VVHH}} & \sigma_{\mathrm{VVHV}} & \sigma_{\mathrm{VVVH}} & \sigma_{\mathrm{VVVV}} \end{pmatrix} = \begin{pmatrix} \sigma_{\mathrm{HHHH}} & \sigma_{\mathrm{HHHV}} & \sigma_{\mathrm{HHVH}} & \sigma_{\mathrm{HHVV}} \\ \sigma^*_{\mathrm{HHHV}} & \sigma_{\mathrm{HVHV}} & \sigma_{\mathrm{HVVH}} & \sigma_{\mathrm{HVVV}} \\ \sigma^*_{\mathrm{HHVH}} & \sigma^*_{\mathrm{HVVH}} & \sigma_{\mathrm{VHVH}} & \sigma_{\mathrm{VHVV}} \\ \sigma^*_{\mathrm{HHVV}} & \sigma^*_{\mathrm{HVVV}} & \sigma^*_{\mathrm{VVVH}} & \sigma_{\mathrm{VVVV}} \end{pmatrix},\end{aligned}$$

where the ensemble average $\langle \cdot \rangle$ is meant to be computed over a homogeneous image area.

Taking into account the preceding considerations, as well as the reciprocity condition, common to the backscattering from all natural targets, implying that the cross-polarized components of the scattering matrix are equal, eq. (8) reduces to

$$\mathcal{C}_S = \begin{pmatrix} \sigma_{\mathrm{HHHH}} & 0 & \sigma_{\mathrm{HHVV}} \\ 0 & \sigma_{\mathrm{HVHV}} & 0 \\ \sigma^*_{\mathrm{HHVV}} & 0 & \sigma_{\mathrm{VVVV}} \end{pmatrix} = \begin{pmatrix} \sigma_{11} & 0 & \rho \\ 0 & \sigma_{21} & 0 \\ \rho^* & 0 & \sigma_{21} \end{pmatrix}. \tag{9}$$

By exploiting (9) and (6) it is possible to set up various algebraic methodologies to estimate the distortion parameters. One of these [5] is based on several relationships between the first eigenvector (corresponding to the minimum eigenvalue) of the covariance matrix and the (normalized) elements of $\mathcal{R}$ and $\mathcal{T}$, and relies on iterative techniques.

Another algorithm makes the same assumptions about the covariance matrix, but estimates the values in a direct, noniterative way, relying on the least-squares solution of an overdetermined system of equations. The algorithm is described in detail in [6].

2˙2.3. *Polarimetric calibration results*. In this section, the calibration of polarimetric L- and C-band data acquired by the SIR-C/X-SAR system is assessed. Cross-talk values have been estimated using responses from a large area including uniform bare fields for which azimuthal symmetry is assumed. Following the approach by Quegan [6], cross-talk values less than -33 dB were found for L-band, and of the order of -30 dB for C-band, thus revealing a negligible channel polarization impurity. Copolarized channel imbalance and radiometric gains were measured from the signatures of the trihedral corner reflector deployed in the test-site (figs. 3 and 4). To get reliable values, the integral method [3] was chosen for both amplitude and phase measurements. The residual values of antenna cross-talk, copolarized amplitude/phase imbalance, and absolute radiometric gains have been compared to the uncertainties provided by JPL for this mission [7]. For both frequencies, the values are equivalent or well within the values estimated over the mission duration.

3. – Ground truth measurements

In order to assess the validity of electromagnetic scattering models, related to the soil geo-physical parameters extraction from SAR data, ground truth measurements were carried out on selected fields within the CB1 area.

3˙1. *Field measurement description*. – The Poggiorsini site is an agricultural area located near Matera in the south of Italy. In October 1994, the fields in the area were completely bare and not yet sown. For the ground measurements, six large (*i.e.* larger than two hectares) and homogeneous fields were selected. They included different roughness states ranging from smooth to very rough soil conditions. On October 2nd and 4th 1994 during the two over-flights performed by the SIR-C/X-SAR system over the CB1 site, ten soil samples at 0–5 and 0–10 cm depths were collected on each field. These samples were used to estimate the soil moisture content exploiting the gravimetric method. Figure 5 displays the averaged moisture values estimated over each field and each depth. The measured soil moisture contents ranged between 0.05 and 0.20 g/cm^3. These values have been subsequently transformed into soil dielectric values using the empirical model developed in [8]. In order to characterise the surface roughness status of each field, a 3 m long needle-like profiler (with a horizontal and vertical resolution of 1.5 and 0.5 cm, respectively) was used. More precisely, 9 surface profiles, along three different directions, were recorded by using a photo camera. Subsequently, the pictures have been digitised and, finally, the traditional surface parameters, namely the profile rms height (s), the height correlation length (l) and the profile autocorrelation function (ACF), have been estimated for each measured profile.

3˙2. *Field measurement results*. – A large variability in the estimated ACF shapes has been found. However, the majority of ACFs show an exponential rather than a Gaussian trend. The analysis of the s and l parameters is summarised in fig. 6 where

Fig. 3. – L-band polarimetric cross-talk (u, v, z, and w, top graphs) and imbalance (α, bottom graphs) parameters estimated on the Matera-test site images.

their variability is displayed. As can be seen, the s parameter shows a larger spreading for very rough soils. On the contrary, the l parameter shows a strong scatter (in the order of the mean value) independently of the status of vertical roughness. For all the analysed fields, the s and l estimates did not show any systematic dependence on the measuring direction. The effect of such a strong variability in the roughness parameters on the backscattering coefficients predicted by theoretical direct models has been widely investigated in [7]. Direct models describe the surface scattering properties as a function of the parameters characterizing the surface status, namely the soil dielectric constant, the profile ACF, the s and l parameters. In this respect, the spreading in s

Fig. 4. – C-band polarimetric cross-talk (u, v, z, and w, top graphs) and imbalance (α, bottom graphs) parameters estimated on the Matera-test site images.

and, particularly, in l shown in fig. 6 may induce a spread in the predicted σ_0 up to 10 dB. Moreover, when considering the predicted mean σ_0, in some cases a satisfactory agreement between theoretical (derived from the IEM model [9]) and experimental values is found within 2 standard deviations (see fig. 7). Unfortunately, in some cases an important disagreement is present without any clear explanation. Such a discouraging result has recently motivated a critical revisiting of traditional surface parameters. In fact, the surface roughness characterization in terms of profile ACF, s and l corresponds to the assumption that roughness can be represented as single-scale stationary processes. However, recent works [10] have introduced the hypothesis that surface roughness could be better described by multi-scale rather than stationary single-scale processes.

Fig. 5. – Averaged volumetric soil moisture content measured over the samples collected on the test sites.

Fig. 6. – Profile root-mean-square height variability (a), and profile correlation length variability (b) for the various field measurements.

Fig. 7. – *C*-band backscattering coefficients: comparison between experimental and theoretical values for HH (a) and VV (b) components. Fields 2 and 6 are outside the range of validity of the IEM model.

4. – Conclusions

We have presented a description of some of the main results obtained in the SIR-C/X-SAR calibration and ground truth campaign of October 1994, performed over two test sites in Southern Italy.

Both radiometric and polarimetric calibration were performed with the aid of a number of trihedral corner reflectors and active radar calibrators, deployed on the site. The overall accuracy of the radiometric calibration was assessed at ±0.9 dB, while polarimetric calibration proved to be practically unnecessary, due to the good quality of the data.

A brief description of the ground truth data collection has also been given, as well as the main results obtained by their analysis and comparison with the remotely sensed images. In particular, rms height and autocorrelation characteristics of the collected bare surface profiles have shown consistent spreads in the predicted σ_0, triggering critical revisiting of the traditional description parameters for bare surfaces involved in SAR backscatter calculations.

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