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A novel Radargrammetric Model and a RPCs Generation Strategy: Application with COSMO-SkyMed and Terra SAR-X Imagery

Paola Capaldo, Mattia Crespi, Francesca Fratarcangeli, Andrea Nascetti and Francesca Pieralice
University of Rome "La Sapienza" DICEA – Dipartimento di Ingegneria Civile, Edile, Ambientale, Italy; {paola.capaldo,mattia.crespi,francesca.fratarcangeli,andrea.nascetti,francesca.pieralice} @uniroma1.it

Abstract. The topic of this paper is the definition of a geometric model for stereo pair orientation of SpotLight Synthetic Aperture Radar (SAR) imagery collected by the new high amplitude resolution radar sensors COSMO-SkyMed (Italian) and TerraSAR-X (German). The suite for radargrammetric approach has been implemented in SISAR (Software per Immagini Satellitari ad Alta Risoluzione), a scientific software developed at the Geodesy and Geomatic Institute of the University of Rome "La Sapienza". The rigorous model performs a 3D orientation based on two range and two zero-Doppler equations, allowing for the least squares estimation of some calibration parameters, related to satellite position and velocity and to the range measure. Starting from this model, according to a terrain independent scenario, an additional tool for the Rational Polynomial Coefficients (RPCs) generation has been implemented. In this last respect, it has to be noticed that only the imagery collected by the high amplitude resolution radar sensor RADARSAT-2 (Canadian) are presently supplied with RPCs. In order to validate the orientation model and the RPCs generation strategy, they were applied to imagery collected over three test sites. The first test site is a zone of Merano (Northern Italy), the second test site is the San Pietro Island (Sardinia, Italy), where SpotLight images were acquired by COSMO-SkyMed; the third test site is Hannover (Northern Germany), where imagery were acquired by TerraSAR-X. The results obtained and here discussed clearly show that the geometric potentialities of COSMO-SkyMed and TerraSAR-X stereo pairs as regards 3D surface reconstruction is at the level of 2-3 meter both with rigorous model and with generated RPCs.

Keywords. High resolution SAR imagery, radargrammetry, COSMO-SkyMed, TerraSAR-X, radargrammetic model, RPCs generation.

Introduction

Synthetic Aperture Radar (SAR) imagery are suitable for the Digital Surface Model generation using radargrammetric or interferometric methods; to this aim, special mission have been set up, as the Shuttle Radar Topography Mission (SRTM), specially designed to yield elevation data on world scale, or ERS-1/2 tandem mission, or TanDEM-X mission in the last years.

In the last decades the interferometric methods have been commonly used since the spaceborne radar sensors available until now supplied only low resolution amplitude (at the level of tens of meters), therefore the phase information offered much more accurate measurements.

Thanks to the second generation satellites (as COSMO-SkyMed, RADARSAT-2 and TerraSAR-X), it is now possible to acquire imagery with high resolution (up to 1 m) in amplitude, so that the radargrammetric approach can come back suitable again to generate DSM with reasonable accuracy.

The radargrammetric approach was first used in the 1950s; then, as mentioned, it was less and less used, due to the quite low resolution of radar imagery in amplitude, if compared to their high resolution in phase. Only in the last decade some researchers have investigated the DSMs generation from very high resolution SAR data, for instance Raggam et al. [1] studied the potentialities of TerraSAR-X, and Toutin and Chenier [2] studied the RADARSAT-2 ones.

In analogy with photogrammetry, radargrammetry is based on a stereo model coming from two or more imagery and exploits the radiometry of the SAR images. The gray tones of the image depend on several characteristics of the imaged surface, since the radar scene reflects a certain amount of radiation according to its geometrical and physical characteristics.

The research group of the Geodesy and Geomatic Institute of the University of Rome “La Sapienza” have implemented in a scientific software SISAR (Software per Immagini Satellitari ad Alta Risoluzione) an orientation model for SAR SpotLight imagery; the model is based on the classical Range-Doppler equations proposed in the book of Leberl [3]; moreover a refinement of the orbital model have to be taken into account to comply with and to exploit the potentialities of the novel high resolution (both in azimuth and in range). Using a set of Ground Control Points (GCPs), the corrections for some calibration parameters, whose approximate values are supplied within the image metadata, are estimated, so that the final orientation of the stereo model is obtained.

Moreover, a tool for the SAR Rational Polynomial Coefficients (RPCs) generation has been implemented in SISAR software, similarly to the one already developed for the optical sensors [4]. The Rational Polynomial Functions (RPFs) model with the employment of RPCs is a well known method to orientate optical satellite imagery. In fact, some satellite imagery vendors have considered the use of RPFs models as a standard to supply a re-parametrized form of the rigorous sensor model in terms of the RPCs, that implicitly provide the interior and external sensor orientation. This generalized method is very simple, since its implementation is standard and unique for all the sensors; in addition, the performances of the RPFs model using the RPCs can reach the level of the rigorous models, so that RPCs can be an useful tool in place of the rigorous model in processes as the image orthorectification/geocoding or as the DSMs generation. Therefore, the possibility to generate RPCs starting from a rigorous model sounds of particular interest since, at present, the most part of SAR imagery is not supplied with RPCs, although the RPFs model is available in several commercial software.

The two models (rigorous and RPCs models) are tested on three stereo pairs, two acquired by COSMO-SkyMed and one acquired by TerraSAR-X.

Moreover, since the points identification and image coordinate measurements over SAR imagery appear much more difficult and uncertain due to speckle, a Monte Carlo simulation has been performed to evaluate the effect of this uncertainty on the final orientation results.

The radargrammetric orientation model

Radargrammetry technique performs a 3D reconstruction based on the determination of the sensor-object stereo model, in which the object position is computed by the intersection of two radar rays with two different look angles. The model is based on the two fundamental equations (1). The first equation of (1) represents the general case of zero-Doppler projection: in zero-Doppler geometry the target is acquired on a heading that is perpendicular to the flying direction of satellite; the second equation of (1) is the slant range constrain.

$$\begin{cases} V_{XS}\cdot(X_S-X_P)+V_{YS}\cdot(Y_S-Y_P)+V_{ZS}\cdot(Z_S-Z_P)=0 \\ \sqrt{(X_S-X_P)^2+(Y_S-Y_P)^2+(Z_S-Z_P)^2}-(D_S+CS\cdot I)=0 \end{cases} \tag{1}$$

where: V_{XS}, V_{YS}, V_{ZS} are the cartesian components of the satellite velocity in the local coordinate system (time dependent); X_S, Y_S, Z_S are the coordinates of the satellite in the local coordinate system (time dependent); X_P, Y_P, Z_P are the coordinates of the generic Ground Point (GP) in the local coordinate system (time independent); D_S is the so-called near range, a calibration parameter related to the range measurements considered unknown (a quite approximate value is available in the metadata); CS is the column spacing; I is the column position of point P on the image.

The satellite orbit could be conveniently modelled with a circular arc since the orbital arc, related to the image acquisition in SpotLight mode, is quite short (about 10 Km) and its parameters are estimated in a least squares adjustment using few orbital state vectors available in the image metadata.

The satellite position is related to the acquisition time of each line of the image, that can be computed using the so called *acquisition start-time* and the *PRF*, that is the sampling frequency in azimuth direction. Approximate values for this parameters are available in the metadata, but they have to be corrected, using a set of Ground Control Points (GCPs), to obtain the best accuracy. A third parameter that has to be corrected is the so called *near range*. Overall, the least squares solution of the orientation problem is devoted to the estimation of corrections of these three parameters (the *acquisition start-time*, the *PRF* and the *near range*). In particular, the linear relationship between the acquisition time of each GP and its line number J (2) reads as follow:

$$t = start - time + \frac{1}{PRF} \cdot J \qquad (2)$$

RPCs model and coefficients generation

The Rational Polynomial Functions (RPFs) model is a well known method to orientate optical satellite imagery. This model relates the object point coordinates (latitude φ, longitude λ¸ and height h) to the pixel coordinates (I, J) in the form of ratios of polynomial expressions whose coefficients (Rational Polynomial Coefficients - RPCs) are often supplied together with imagery. In fact, some satellite imagery vendors, as Digital Globe for QuickBird and WorldView sensors and GeoEye for GeoEye-1 and Ikonos sensors, have considered the use of RPFs models as a standard to supply a re-parametrized form of the rigorous sensor model in term of Rational Polynomial Coefficients (RPCs), secretly generated from their own physical sensor models.

Moreover, since residual biases may affect RPCs supplied by vendors, the orientation can be refined on the basis of some GCPs even if RPFs models are used; usually a 2D shift (2 parameters) or a 2D affine (6 parameters) transformations are estimated, so quite few GCPs are necessary to obtained a refined RPFs orientation, which can reach the accuracy level of a rigorous model based one [5], [6], [7].

Overall, the use of the RPFs of model is common in several commercial software, at least for three important reasons: the implementation of the RPFs model is standard, unique for all the sensors and much more simple that the one of a rigorous model, which have to be customized for each sensor; the performances of the RPFs model via RPCs can be at the level of the ones from rigorous models, provided refinement transformations are used; the usage requires zero or, at maximum, quite few GCPs if an additional refinement transformations are used, so that the cost for ancillary information is remarkably reduced with respect to rigorous models, especially for optical imagery, which may require up to 10-12 GCPs to supply a stable orientation. For these reasons, the use of RPCs could be conveniently extended also to SAR imagery, which presently are not supplied with RPCs except for RADARSAT-2.

Therefore, the RPCs generation tool already implemented in SISAR for optical imagery and based on the so called terrain independent scenario has been extended to comply with SAR imagery [5], [6], [7]. A 2D image grid covering the full extent of the image is established and its corresponding 3D object grid with several layers slicing the entire elevation range is generated. The horizontal coordinates (X; Y) of a point of the 3D object grid are calculated from a point (I; J) of the image grid using the already established and mentioned rigorous orientation model with an a priori selected elevation Z. Then the RPCs are estimated in a least squares solution using as input of 3D object grid points and the image grid points [4].

In order to avoid instability due to high RPCs correlations, in our approach the Singular Value Decomposition (SVD) and QR decomposition are employed to evaluate the actual rank of the design matrix and to select the actual estimable coefficients. Moreover, the statistical significance of each estimable coefficient is checked by a Student T-test, so to avoid overparametrization; in case of not statistically significant coefficients, they are removed and the estimation process is repeated until all the estimated coefficients are significant (“parsimony principle”) [4].

In the end, it has to be underlined that, usually, the RPCs generated on the basis of the terrain independent scenario are calibrated on accurate GCPs and are not affected by biases, so that a refinement transformation is not needed.

Data set

The available data for the experimentation are COSMO-SkyMed and TerraSAR-X SpotLight imagery collected over three test sites.

As regards COSMO-SkyMed, we have four images forming two stereo pairs, the first stereo pair is over the area of Merano (Northern Italy) and the second is over the San Pietro Island (Sardinia, Italy). All images belong to the Level 1A (SCS) category products, that is focused data in complex format, in slant range and zero-Doppler projection.

The two scenes of Merano were acquired with incidence angles of 25.9 and 42.3 degrees respectively along a descending orbit, forming a same-side configuration stereo pair, with a base-to-height ratio equal to 0.3. As regards the two images of San Pietro Island they were acquired with incidence angles of 48.2 degrees along a descending orbit and 54.6 degrees along an ascending orbit respectively, forming an opposite-side configuration stereo pair, with a base-to-height ratio equal to 2.5. The areas covered by the two stereo pairs are approximately 10 Km x 10 Km wide.

The stereo pair orientation of Merano is based on 20 GPs, used both as GCPs and CPs too; horizontal coordinates are derived from cartography (scale 1:5000) whereas the heights come from a LiDAR Digital Terrain Model (mean elevation accuracy of 0.25 m); both these data are free available on the website of the “Provincia Autonoma di Bolzano” (http://www.provincia.bz.it\-/urbanistica/cartografia/cartografia\-.asp). Concerning San Pietro Island images the GPs used for the orientation are 16, their ground coordinates derived from DSM obtained by LiDAR survey with horizontal and vertical accuracy equal to 0.25 m, DSM is free available on the website http://www.sardegnageoportale.it.

As for TerraSAR-X, we have three images acquired over the town of Hannover (Northern Germany); all images are HighResolution SpotLight (HS) products with extension of 10 Km x 5 Km. Two images were acquired along an ascending orbit with incidence angles of 33.8 degrees and 44.9 degrees respectively, one of these along a descending orbit with incidence angles of 31.8 degrees. Therefore, it is possible to choose various image combinations in order to form different stereo pairs; we selected a same-side stereo pair (composed by the first and the second images) with a base-to-height ratio equal to 0.15 and an opposite-side stereo pair (composed by the first and the third images) with a base-to-height ratio equal to 1. On the Hannover images 20 GPs was been selected, whose coordinates have been derived from a LiDAR DSM.

It has to be pointed out that the identification and the image coordinate measurements of GPs on the SAR image is usually much more difficult and uncertain than in the case of optical imagery, so that an average error of 2-3 pixels (if not larger) have to be considered; below the effect of this uncertainty has been assessed. As example, in the Fig. 1 the difference between a SAR image and an aerial optical image is shown. Further, additional problems came out for the GPs identification on the opposite-side stereo pair. In fact, only 13 GPs are visible on both images, since the areas illuminated on the first image are in the shadow on the second one. The GPs used in this case are in open area, non-occluded, visible and well illuminated by the satellite on both looking side.

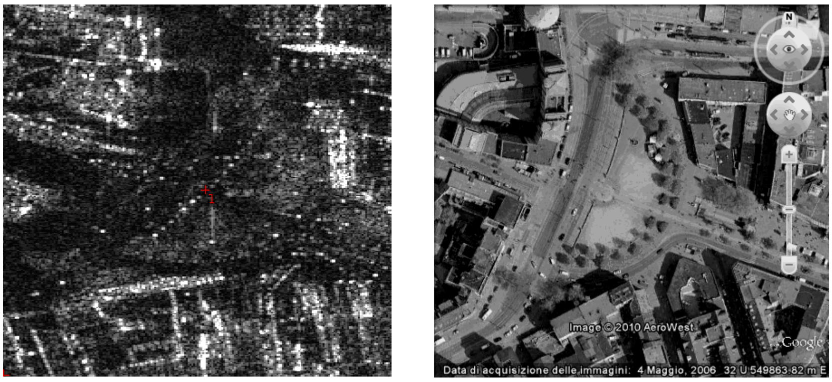

Figure 1: Example of a GP in the center of a place on TerraSAR-X (left) and on an optical aerial image (right)

Accuracy results

Rigorous radargrammetric model

To test the effectiveness of the new rigorous model implemented in SISAR, the stereo pairs have been orientated and the model accuracy is analyzed, evaluating the average, the standard deviation and the RMSE computed over Check Points - CPs residuals (RMSE CPs), following the standard Hold-Out Validation procedure for accuracy assessment [8]. From previously investigations [9] it is noted that the increase of GCPs number to orientate the SAR image does not improve significantly the level accuracy therefore the three stereo pairs were been oriented using 3 GCPs that can be the appropriate number to estimate the orientation parameters of SAR model to have a good compromise between a good accuracy and a low number of GCPs requirement.

In addition, it has to be noted that some tests were performed just using the ground coordinates (on the WGS84 at zero ellipsoidal height) provided for the scene corners directly into the metadata file; these tests highlight that for the COSMO-SkyMed imagery a good accuracy may be achieved just using the information related to scene corners, so that actual GCPs do not appear necessary, saving the time for their (GPS) surveys on the ground and their identification and coordinate measurements on the images. The accuracy results, both with three GCPs and with four scene corners, are summarized in the Table 1. The accuracy level for the two images is around 2.5 – 3 m in height component.

In the Table 2 the accuracy results of TerraSAR-X are presented; the accuracy again is around 2.5 – 3 m in elevation component. In this case only the results obtained using 3 GCPs are shown because preliminary tests with the metadata scene corner coordinates displayed a lower accuracy.

Table 1. Accuracy results for San Pietro Island and Merano area – radargrammetic model, COSMO-SkyMed

	Average CPs [m]			Standard Deviation CPs [m]			RMSE CPs [m]		
	East	North	Up	East	North	Up	East	North	Up
	San Pietro island								
3 GCPs	-1.11	-2.48	0.26	1.89	2.16	2.86	2.19	3.29	2.87
4 corners	0.65	0.37	0.12	1.84	2.38	2.80	1.96	2.40	2.81
	Merano								
3 GCPs	2.20	1.90	-0.93	3.13	2.54	2.24	3.83	3.17	2.42
4 corners	2.18	-1.16	0.94	3.29	2.36	2.14	3.95	2.62	2.34

Table 2. Accuracy results for Hannover area – radargrammetic model, TerraSAR-X

	Average CPs [m]			Standard Deviation CPs [m]			RMSE CPs [m]		
	East	North	Up	East	North	Up	East	North	Up
	Hannover – same-side								
3 GCPs	-1.60	-0.10	0.09	1.97	2.03	2.75	2.54	2.04	2.75
	Hannover – opposite-side								
3GCPs	0.85	-0.06	-0.73	2.02	1.77	1.94	2.19	1.77	2.08

RPCs model

The results of RPCs generation and their application for COSMO-SkyMed and TerraSAR-X images are presented. As regard RPCs generation, instead of 78 coefficients generally employed in a third order rational polynomial function, a much lower number of coefficients (about 20) were estimated, avoiding the overparametrization and selecting only the estimable and significant parameters as mentioned before. Overall, the RPCs related to both the denominators of the RPFs are estimated up to the first order at maximum or they are not estimated at all, whereas those related to both the numerators are estimated up to the first or the second order. The generated RPCs were used to orientate the stereo pairs; in particular in Table 3 and Table 4 the results of RPCs applications are presented; in details, the RPCs were generated starting from rigorous radargrammetric model both with 3 GCPs and 4 scene corners following the mentioned terrain independent scenario.

The accuracy level is close to rigorous radargrammetric model, what proves the effectiveness of the RPCs generation tool implemented in SISAR. Moreover, the RPCs refinement is not necessary, since the SISAR RPCs are calibrated on GCPs and are not affected by biases.

Monte Carlo simulation

As mentioned before, we feel that an uncertainty up to 2-3 pixel for point identification and image coordinate measurement is common at the resolution of SpotLight imagery. Monte Carlo simulations have been performed in order to assess the impact of this uncertainty over the final orientation results,. Starting from an error-free configuration, a Gaussian error on the image coordinates of the GCPs with a standard deviation ranging from 1 to 6 pixels have applied; then, the effect of these errors with respect to the CPs, which were considered error-free, has been evaluated, which represent the error induced into the orientation due to the identification and image coordinate measurements of the GCPs. It is recovered that the average effect in the height ranges between 0.8 and 1.2 meters with 2 and 3 pixels standard deviation respectively using just 3 GCPs; if the GCPs number increase, the effect becomes obviously smaller and smaller, decreasing down to 0.5 and 0.75 meters respectively with 9 GCPs (Table 5), proportionally to the square root of the GCPs number ratio (for example, with 9 GCPs the effect is $1/\sqrt{3}$).

Table 3. Accuracy results for San Pietro island and Merano area – RPCs model, COSMO-SkyMed

	Average CPs [m]			Standard Deviation CPs [m]			RMSE CPs [m]		
	East	North	Up	East	North	Up	East	North	Up
	San Pietro island								
3 GCPs	-0.89	-2.71	0.19	1.93	2.06	2.87	2.13	3.40	2.88
4 corners	0.54	0.46	0.15	1.85	2.29	2.83	1.93	2.34	2.84
	Merano								
3 GCPs	2.59	1.79	-1.29	3.15	2.58	2.26	4.07	3.14	2.61
4 corners	2.35	-1.12	0.83	3.26	2.37	2.16	4.02	2.62	2.31

Table 4. Accuracy results for Hannover area – RPCs model, TerraSAR-X

	Average CPs [m]			Standard Deviation CPs [m]			RMSE CPs [m]		
	East	North	Up	East	North	Up	East	North	Up
	Hannover – same-side								
3 GCPs	-1.10	0.04	0.51	2.27	2.02	2.74	2.53	2.02	2.79
	Hannover – opposite-side								
3GCPs	1.35	-0.10	-0.75	2.05	1.78	1.95	2.45	1.78	2.09

Table 5. Results of Monte Carlo simulation

Collimation error	RMSE CPs due to collimation errors [m]								
	3 GCPs			6 GCPs			9 GCPs		
St.Dev[pix]	East	North	Up	East	North	Up	East	North	Up
Error free	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00
1	0.64	0.35	0.43	0.46	0.26	0.31	0.38	0.20	0.26
2	1.25	0.68	0.84	0.89	0.53	0.59	0.75	0.40	0.50
3	1.93	1.04	1.30	1.40	0.82	0.92	1.12	0.59	0.75
4	2.63	1.36	1.74	1.94	1.08	1.29	1.91	0.78	1.26
5	3.25	1.69	2.16	2.33	1.39	1.54	1.88	1.06	1.26
6	3.78	2.09	2.57	2.72	1.64	1.78	2.32	1.25	1.54

Conclusions

A new model for the orientation of SAR stereo pairs collected by high resolution amplitude radar sensor in SpotLight mode was defined and implemented in the scientific software SISAR. An experiment was carried out with imagery collected over the test sites of Merano (Northern Italy) and San Pietro Island (Sardinia-Italy) by COSMO-SkyMed and over Hannover (Northern Germany) by TerraSAR-X.

The accuracy evaluation shows that the vertical accuracy is at level of 2.5 – 3.0 m for all stereo pairs considered. A few GCPs number is enough to achieve a good accuracy level; in addition, the usage of corner coordinates is suitable to the image orientation for COSMO-SkyMed imagery, whereas for TerraSAR-X further investigations are surely needed since the preliminary results are doubtful.

Moreover a tool for the RPCs generation suited to SAR imagery has been included in SISAR software. The application of RPCs model to SAR stereo pairs gave good results, at the same accuracy level of those derived using the radargrammetric rigorous model.

Finally, a Monte Carlo simulation assessed that the uncertainty in point identification and image coordinate measurements due to speckle has a relevant impact on the orientation results, ranging between 0.8-1.2 meters with 2-3 pixels standard deviation respectively, if just 3 GCPs are used. In this last respect, it raises to a much higher relevancy the possibility to orientate the imagery just on the basis of scene corners metadata information, since no image coordinate measurements are needed in this case due to the fact that scene corners image coordinates are directly known from the metadata itself.

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