A RADARGRAMMETRIC APPROACH FOR SPACEBORNE TRANSMITTER-STATIONARY RECEIVER BISTATIC SAR

Madalina Ciuca[⋆] *Andrei Anghel*[⋆] *Remus Cacoveanu*[§⋆] *Bjorn Rommen*[*] *Mihai Datcu*[⋆‡]

[⋆] University POLITEHNICA of Bucharest, CEOSpaceTech, Bucharest, Romania

[§] EOS Electronic Systems, Bucharest, Romania

[*] European Space Agency (ESA-ESTEC), Noordwijk, The Netherlands

[‡] German Aerospace Center (DLR), Oberpfaffenhofen, Germany

ABSTRACT

This paper addresses the feasibility of exploiting a radargrammetric procedure for the retrieval of height estimates using stereo images acquired in a space-surface (spaceborne transmitter-stationary receiver) bistatic geometry. Currently, the research interest concerning this particular direction is still in its infancy, as there are very few papers partially covering the subject. The method proposed in this study is applied to a set of SAR images (displaying an urban area of the Bucharest city) in order to assess the elevation of a group of selected targets within the remotely sensed zone.

***Index Terms*—** Bistatic SAR, radargrammetry, area-based matching, same-side stereoscopic pair, Sentinel-1A/B

1. INTRODUCTION

Radargrammetry is one of the first techniques for extracting height information and generating digital elevation models from SAR (Synthetic Aperture Radar) images [1, 2]. The parameter of interest for this method is the amplitude (or intensity) of a set of two or more images, acquired from (more or slightly) different incidence angles. Nowadays, due to the existence of high-resolution SAR products, radargrammetry is experiencing a rising interest from the scientific community.

Outperformed for many years in terms of practical implementations, bistatic systems are gaining more and more interest. Among them, the spaceborne transmitter-stationary receiver geometry provides a number of advantages. Firstly, it offers a greater flexibility, as such systems can use a variety of satellites, flying on various orbits, as transmitters of opportunity. Furthermore, complementary information, with respect to the monostatic case, can be collected (e.g., a target that is not visible in a monostatic image, may be visible in a bistatic one) [3].

Nowadays, the exclusive manner for obtaining radargrammetric products is done by processing repeat-pass images. They are usually obtained by spaceborne or airborne monostatic systems, with the stereo baselines in the order of hundreds of kilometers [4]. Also, by using space-surface bistatic configurations, the same technique can be employed. With respect to spaceborne bistatic, a small number of studies have described the theoretical possibility of single-pass stereo capable configurations [2], but the practical implementation remains an open chapter in the remote sensing field.

To the best of our knowledge, the only existing study concerning a radargrammetric processing for satellite transmitter-ground based receiver bistatic images is the one carried by R. Wang *et al.* [5, 6]. While the authors present a digital surface model (DSM) derived by applying a stereoscopic procedure, based on least-squares solving a system of range-Doppler equations, the overall processing chain is succinctly presented. Also, a comparison of the estimated DSM with real topographical data for the area of interest was not addressed in the study.

In the present paper we perform a quantitative analysis of the feasibility to radiometrically extract the height information from bistatic radar images in the aforementioned geometry. For this, we use two images captured by a C-band ground-based receiver, over an area of Bucharest city [7]. A same-side stereo configuration is exploited, with the Sentinel-1A/B satellites as transmitters of opportunity. Each image is acquired from a different orbit. The orbits are quasi-parallel and the spatial baseline between them is around 180 km. The timespan between the two acquisitions is of only one day, which results in a negligible movement of the scattering centers of the reflective targets, therefore improving the probability of more accurate matches. An area-based method is applied for points matching. Further, a bistatic simulator is used in the estimation process.

The remainder of the paper is structured as follows. Section II deals with the theoretical aspects regarding the radargrammetric method, Section III describes the practical implementation, and Section IV states the conclusions of the paper.

2. THEORETICAL CONSIDERATIONS

In both monostatic and bistatic geometries, radargrammetry can be applied to images forming a same-side stereoscopic configuration (but with different incidence angles), or an opposite-side one. While the former offers the probability of

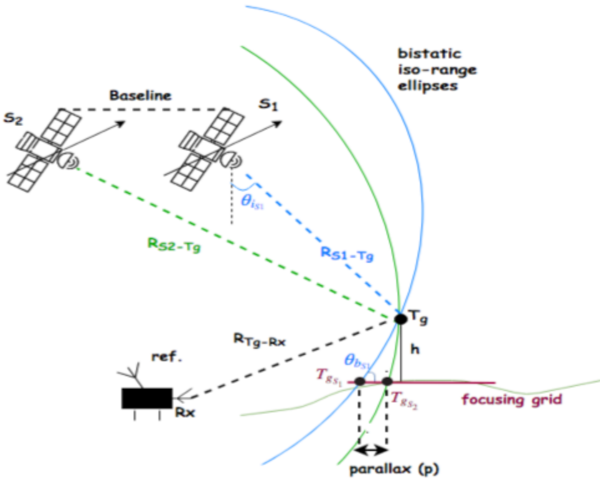


Fig. 1. Bistatic geometry (spaceborne transmitter - stationary receiver) in same-side stereoscopic configuration.

more similar images, in the later configuration the intersection angle between the two image pairs is much larger, which increases the accuracy of radargrammetric products. Depending on the application, one configuration could be preferred over the other [8].

A possible same-side geometry, with a ground-based bistatic receiver is represented in Fig. 1. The two satellites S_1 and S_2 are located on parallel orbits with the pointing arrow revealing the direction of motion. As known, in the bistatic case, the position of a scatterer is still described in terms of range-Doppler geometry, but relatively to the monostatic one, the iso-range circles (whose arcs can be approximated by straight lines in the spaceborne case) are replaced by iso-range ellipses, with the transmitter and the receiver in the two foci. An example is depicted in Fig. 2. Because of the proximity to the receiver in such configuration, for ground ranges below 1 km, it can be observed that the elliptical shape cannot be neglected. In consequence, for a target Tg, the corresponding position into a SAR image depends primarily on the elevation h of the target (relative to the height of the focusing grid) and its position on the elliptical arc.

$\theta_{i_{S_1/S_2}}$ represents the incidence angle for satellite S_1/S_2. For sufficiently large distances from the ground-based receiver (usually, a few kilometers away, where the elliptical arc can also be approximated by a straight line) we define the equivalent bistatic incidence angle (the angle between the ground range direction and the iso-range line).

The main stage of a radargrammetric technique implies matching the similar points from the two images and computing the disparity or parallax. This parameter of greatest importance, can be expressed as the euclidian distance between two homologous points of interest from the set of stereo images.

In Fig. 1, we denote the corresponding points of reflector Tg in the two images, as $T_{g_{S_1}}$, and $T_{g_{S_2}}$. The distance between them is the wanted parallax, *p*.

If $Tg_{\perp}$ is the orthogonal projection of point Tg on the

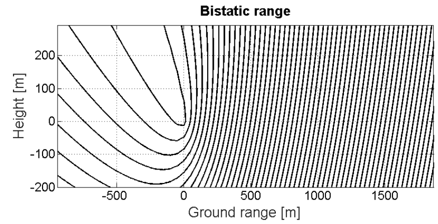


Fig. 2. Bistatic iso-range ellipses.

focusing grid (for clearness of the drawing, this point was not figured), we can then write:

$$T_{g_{S_1/S_2}}Tg_{\perp} = \frac{h}{\tan(\theta_{b_{S_1/S_2}})} \tag{1}$$

By substracting the two formulas, the obtained disparity is:

$$p = \frac{h}{\tan(\theta_{b_{S_1}})} - \frac{h}{\tan(\theta_{b_{S_2}})} \tag{2}$$

Keeping the notation from [9], the height to relative shift factor is defined as:

$$k_{h2\Delta} = \frac{1}{\tan(\theta_{b_{S1}})} - \frac{1}{\tan(\theta_{b_{S2}})} \tag{3}$$

Also, we introduce $k_{\Delta 2h} = \frac{1}{k_{h2\Delta}}$, the shift to height factor. Therefore, a target of zero elevation (measured relative to the focusing grid), should have zero parallax between two co-registered images, while with a rising value of *h*, a larger disparity should be noticed.

Regarding the automatic registration between images, the algorithms used in SAR radargrammetry can belong to one of the two categories: area-based or feature-based. The main idea of area-based techniques is the use of an estimate function to measure the similarity between two windows (often, rectangular shaped ones): a reference window from the master image, and a candidate window from the slave image. The main disadvantage of this type of algorithms is that the considered images should be quite similar in order to make a correct match. This is why they are usually used with figures in epipolar geometry, or when the variation of the incidence angles is small [8, 10].

The feature-based techniques involve the existence of an extra step, for extracting salient structures in the image (lines, well-recognizable regions, particular points). With a more intricate implementation, these algorithms are used with very smooth or highly textured images (SAR images of landscapes, hilly terrain or mountainous areas), as well when there is a great difference between incidence angles, or the acquisition orbits are in opposite directions.

Further preprocessing and/or postprocessing intermediary stages are often taken into consideration for correctly matching. Among them, orthorectification is a common preprocessing procedure, borrowed from the much older brother of radargrammetry, photogrammetry. In optical images, by means of affine transformations the homologous points can be brought to the same horizontal line, namely the epipolar line.

Following the same idea, the concept of quasi-epipolarity was introduced for monostatic SAR images where, due to the inherent model of the system, the matching points could only lie on equivalent circle arcs [10, 11]. For the bistatic case however, depending on the proximity between the imaged objects and the trasmitter/receiver, such a model is no longer accurate.

In our study, we have implemented a classical window matching technique, as described by [8], based on maximizing the zero normalized cross-correlation coefficient (ZNCC). The use of this algorithm is legitimate since the difference between the incidence angles of the two orbits is quite small (roundabout 9 degrees). Also, using a zero normalized cross-correlation rather than a simple correlation coefficient, the sensitivity due to changes in the intensity of the images (which mostly corresponds to a variation of the angle of illumination) is eliminated. In this way, the disparity between two reflectors can be estimated.

However, the main particularity of our approach (specifically designed to mitigate the more challenging conversion from parallax to height in a bistatic geometry, especially if the imaged scene is quite close to one of the elements of the system) is the use of a bistatic simulator. By means of such program, and providing real information about the geometry (regarding the location of the target, transition of satellites on orbits, etc.) coupled with the calculated disparity, the height of the reflector of interest can be assessed.

3. EXPERIMENTAL RESULTS

This section presents a first validation of the proposed radargrammetric approach for bistatic SAR images obtained in the aforementioned geometry. The raw data was collected between 6 and 7 April 2017 using a ground-based receiver mounted on the roof of the Politehnica University of Bucharest Rectorate building. A comprehensive description of the receiving system can be found in [7]. We take advantage of a same side stereo configuration, similar to the one exemplified in Fig. 1, for two distinct passes of the Sentinel-1A/B satellites. The scene is illuminated from two ascending, roughly parallel orbits (the angle between the two azimuth versors is of 1.4°). The bistatic focusing is performed on a two-dimensional cartesian grid, aligned with the local latitude and longitude. The grid pixels have dimensions of 0.5 m along each axis.

The height estimation for a selection of highly reflective targets, visible from both focused SAR images is performed in the followings. Among the selected scatterers, we also employ the use of an artificial reflector, a transponder [12]. Because the mounting height of the device is well known, its role is essential for the validation of the results. From its position, it will generate an individual, clearly observable reflection. By comparison, when dealing with multiple reflections from different heights in the same resolution cell (e.g., a building target with architectural particularities) the estimation is not

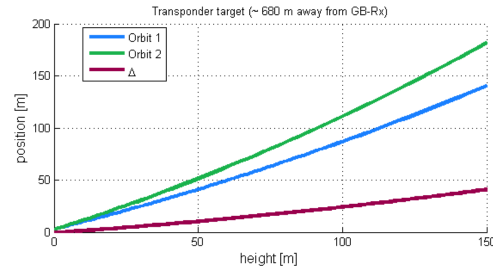


Fig. 3. Transponder target - Displacement vs. height.

very rigorous, as those reflections can overlap the main lobe, or result in secondary lobes. For example, we expect that the main lobe of the University Hospital target to contain signals from scatterers spread in a 10 m height range.

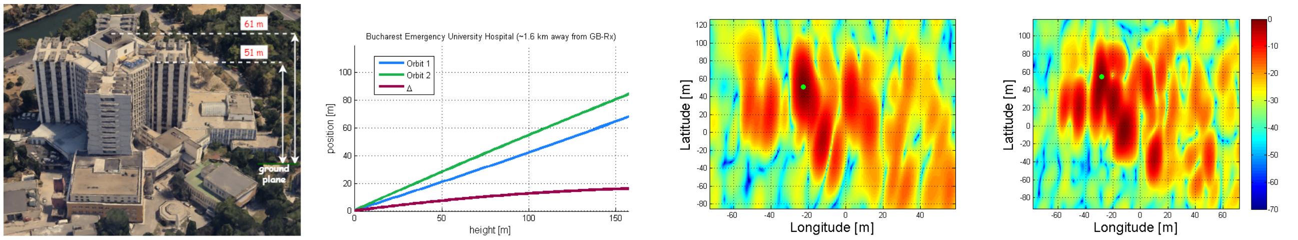
The main results are shown in Table 1 (the abbreviations from the second and third column denote the ”Estimated parallax” and ”Estimated height”). The targets are organised in Table 1 considering an increase in their distance from the ground-based receiver. The last two are the farthest located ones, at about 3 km away. For them, by analyzing the simulated results we can also extract a value for the shift to height factor, $k_{\Delta 2h}$, defined earlier.

The first phase involves applying the implemented matching algorithm in order to evaluate the disparity. The green points that can be identified in Subfigures c) and d) of Fig 4, indicate the point of maximum amplitude from the SAR image taken as reference (Subfigure c)), and the estimated position of this point in the second image, for the University Hospital building. As the pixels around this main peak have quite similar values, an estimation error exists between the true homologous point from the master image and the one given by the area-based algorithm. Such an error is noticed to exist also in the case of the other targets, including the transponder.

Secondly, by taking advantage of the real ancillary info acquired with the synchronization pulses, we use a bistatic simulator to study the displacements of a fictional scatterer (located at the exact geographical position for each point of interest) at different elevations. In this way, starting from real data, the software can simulate focused SAR images in the bistatic geometry of interest.

Fig. 3 illustrates the computed shifts introduced for height values varying from 0 to 150 m, for a target nearer to the ground receiver (the transponder). Due to the geographical placement of the scatterer, the allure of the iso-range ellipse arcs is distinguishable when concatenating the positions of the reflector in the simulated images and at each elevation (green and blue curves). Also, the same parameter is represented in Subfigure b) of Fig. 4 for the hospital scatterer.

As regarding the accuracy of the radargrammetric estimation process, we can state that the matching stage is the most susceptible to errors. The $k_{\Delta 2h}$ factor can also be considered as a range sensitivity factor, where every 1 meter shift error in the parallax computing introduces a $k_{\Delta 2h}$ meters ambiguity in the height estimation. For example, in the case of the Cathedral Plaza building, the computed shift to height value



(a) (b) (c) (d)

Fig. 4. University Hospital: (a) Google Earth image; (b) Displacement vs height; (c) Reference bistatic SAR Image; (d) Bistatic SAR Image 2.

Table 1. Results of the radargrammetric approach for the four considered targets.

	Parameters			
Targets of Interest	Real height [m]	Est. parallax [m]	Est. height [m]	Matching error [pixels]
Transponder	40	7.8	42	2
University Hospital	51 - 61	7.2	48.5	3
Palace of Parliament (lateral wing)	45	4.6	41	3
Cathedral Plaza	75	8.85	85	1

is about 9.7 (m) while the matching accuracy is of 1 pixel (0.5 m resolution). Thus, in this case, the uncertainty associated with the height presented in Table 1 is nearly ± 5 m, along with an elevation estimation error of approximately 10 m.

4. CONCLUSIONS

The approach outlined in this paper testifies the opportunity of exploiting a bistatic acquisition geometry, in order to retrieve the height of a series of targets, by radargrammetric means. It must be pointed that using such method, the estimated elevation values are relative to the height of the projection surface used for image focusing.

A quantitative analysis performed on a group of four targets, extracted from the stereo SAR images, was conducted. The prospect of extending the method to a more global scale requires the precomputing of disparity factors for different distances from the ground receiver. Also, we take into consideration the need to modify the matching strategy for a better accuracy.

5. ACKNOWLEDGMENT

This work has been funded by the European Space Agency (ESA) through the TomoSAR-1B project, contract number 4000124573/18/NL/CBi.

6. REFERENCES

[1] S. Meric *et al.*, “Radargrammetric SAR Image Processing,” in *Geoscience and Remote Sensing*, Pei-Gee Peter Ho, Ed., chapter 20. IntechOpen, Rijeka, 2009.

[2] A. Renga and A. Moccia, “Performance of Stereoradargrammetric Methods Applied to Spaceborne Monostatic-Bistatic SAR,” *IEEE Trans. Geosci. Remote Sens.*, vol. 47, no. 2, pp. 544–560, February 2009.

[3] A. Anghel, R. Cacoveanu, and M. Datcu, “Repeat-Pass Spaceborne Transmitter-Stationary Receiver Bistatic SAR Interferometry - First Results,” in *2018 IEEE IGARSS*, July 2018, pp. 3651–3654.

[4] H. Cheng *et al.*, “Two-side Long Baseline Radargrammetry from Ascending-Descending Orbits with Application to Mapping Post-Seismic Topography in the West Sichuan Foreland Basin,” *Journal of Mountain Science*, vol. 11, no. 5, pp. 1298–1307, September 2014.

[5] R. Wang *et al.*, “Double-Channel Bistatic SAR System With Spaceborne Illuminator for 2-D and 3-D Remote Sensing,” *IEEE Trans. Geosci. Remote Sens.*, vol. 51, no. 8, pp. 4496–4507, August 2013.

[6] Y. Shao *et al.*, “Error Analysis of Bistatic SAR Imaging and Stereoscopy Bistatic SAR,” *IEEE Trans. Geosci. Remote Sens.*, vol. 51, no. 8, pp. 4518–4543, August 2013.

[7] A. Anghel *et al.*, “Bistatic SAR Imaging with Sentinel-1 Operating in TOPSAR Mode,” in *2017 IEEE RadarConf*, May 2017, pp. 601–605.

[8] S. Meric *et al.*, “A Multiwindow Approach for Radargrammetric Improvements,” *IEEE Trans. Geosci. Remote Sens.*, vol. 49, no. 10, pp. 3803–3810, 2011.

[9] K. Goel *et al.*, “Three-Dimensional Positioning of Point Scatterers Based on Radargrammetry,” *IEEE Trans. Geosci. Remote Sens.*, vol. 50, no. 6, pp. 2355–2363, June 2012.

[10] H. Ding *et al.*, “An Improved Multi-Image Matching Method in Stereo-Radargrammetry,” *IEEE Geosci. Remote Sens. Lett.*, vol. 14, no. 16, pp. 806–810, June 2017.

[11] K. Gutjahr *et al.*, “The Epipolarity Constraint in Stereo-Radargrammetric DEM Generation,” *IEEE Trans. Geosci. Remote Sens.*, vol. 52, no. 8, pp. 5014–5022, August 2014.

[12] M. Tudose *et al.*, “Electronic Target for Bistatic/Monostatic SAR Systems,” in *12th EUSAR Conf.*, June 2018, pp. 1–5.