

Stereoscopic SAR Techniques for Generating Elevation Data over Caribbean Territories Using ENVISAT Imagery: A Case of Jamaica

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Abstract: Tropical zones are affected by continual cloud cover making it challenging to apply many of the optical or laser-based techniques existing today for the generation of elevation data. The Caribbean is no exception. Elevation data is a fundamental layer for any Geospatial Information System (GIS) and critical for many spatial modelling activities; the geo-referencing of earth observation; and the visualisation of landscapes. The ENVISAT satellite with its microwave imaging characteristics, along with its cloud penetrating and day/night imaging capabilities makes it a compelling complementary tool for generating elevation data over these cloud affected territories. In this paper, we describe a stereoscopic Synthetic Aperture Radar (SAR) technique developed at the Institute of Engineering Surveying and Space Geodesy (IESSG), The University of Nottingham, for extracting elevation data from pairs of ENVISAT imagery over cloud affected Caribbean territories. Results are shown for a test site over the island of Jamaica and comparisons with 'ground truth' data are used to quantify the elevation data quality.

Keywords: Elevation data, stereoscopic SAR technique, ENVISAT imagery, Caribbean

1. Introduction

Elevation datasets in the form of Digital Surface Models (DSMs) and other topographic data models are required for several applications which have been stimulated by the increased use of Geospatial Information Systems (GIS). Ground-Based (surveying and global positioning system (GPS)) and traditional airborne approaches are proving to be time consuming and costly for applications in developing countries. Where these countries are located in the tropical zone, they are affected by the additional problem of cloud cover which could cause imaging delays for almost 75% of the year (Kost, 2002). The Caribbean happens to be one such affected territory that is in need of national digital topographic information for its GIS database developments and for use in the digital ortho-rectification of satellite imagery.

The use of Synthetic Aperture Radar (SAR), with its cloud penetrating and day/night imaging capabilities, is emerging as a possible remote sensing tool for use in cloud affected territories. There has been success with airborne single-pass dual antennae systems (e.g.

STAR3i) and the Shuttle Radar Topographic Mapping (SRTM) mission, however, the use of these systems in the Caribbean is restrictive and datasets will not be generally available. The launching of imaging radar satellites (such as ERS-1, ERS-2, RADARSAT-1) and more recently ENVISAT have provided additional opportunities for augmenting the technologies available for generating topographic information in developing countries by using techniques of Radargrammetry (StereoSAR) and Interferometric SAR (InSAR). Unfortunately, little research has been conducted into the suitability of these sensors for extracting topographic information over developing regions such as the Caribbean. Previous research have shown that the automatic image matching process, which is a precursor to elevation extraction, is the greatest obstacle to the successful implementation of the StereoSAR technique because of the large quantity of speckle noise in the imagery; yet there has been little progress in providing improved algorithms for solving this problem.

This paper describes The Nottingham StereoSAR

system and evaluates its potential for producing low-cost, medium accuracy DSMs over cloud affected developing countries using stereoscopic imagery from the new ENVISAT SAR sensor. The work here was drawn from the PhD studies of the corresponding author (Edwards, 2005).

2. The Nottingham StereoSAR System

The Nottingham StereoSAR system is designed to generate DSMs based on stereoscopic data from both the Radarsat and Envisat sensors. In this paper however, our focus will be limited to the new ENVISAT sensor. The processing chain used as the basis of the StereoSAR system is shown in Figure 1.

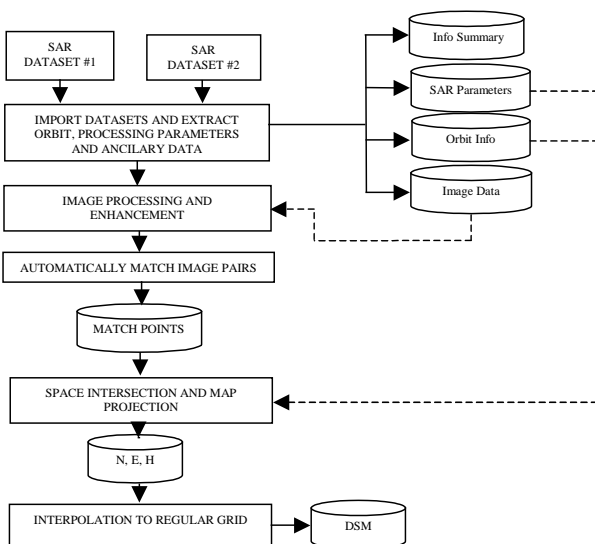


Figure 1. Flow diagram for the Nottingham StereoSAR System

The process starts by first identifying a suitable stereoscopic pair of SAR data in CEOS format (see RSI, 2000); these are imported into our system and the images along with ancillary information (e.g. orbital data and processing parameters) extracted from the SAR datasets. One image is the reference image and the other acts as the search image. Pre-processing of the images is conducted to reduce speckle noise thus enhancing the matching capability and restricting the search space by co-registration of the image pair. The image pairs are automatically matched and the result of the matching is converted to a local map projection system as a cloud of points using space intersection techniques. The point cloud is then resampled into a regular grid to form a DSM. The critical aspects for the successful implementation of this processing chain lie with the automatic matching and the space intersection techniques. In the next two sub-sections we outline the algorithms implemented in our StereoSAR system for these two critical steps in the chain.

2.1 An Adaptive Matching Algorithm for SAR Imagery

The automatic stereo-matching of image pairs is the most difficult step in the processing chain, especially for SAR imagery. Yet, it is the most important because it dictates the quality of the topographic data being extracted. The objective of stereo-matching is that for each pixel in the reference image the automatic matcher tries to locate its conjugate in the search image. Previous researchers (e.g. Sowter, 1998; Ka and Kim, 2001) used a coarse-to-fine (pyramidal) area-based matching approach in which the correlation window sizes and correlation threshold values were kept fixed throughout the matching process. The use of fixed values can be problematic especially in low textured or homogeneous areas. Texture refers to the spatial variation of tonal elements as a function of scale (Haralick et al., 1973) and can be very useful in interpreting radar images and discriminating among different landscape types (Ulaby et al., 1986). In order to describe texture, it is necessary to select some measure that encapsulates the information. Tso and Mather (2001) and Ulaby et al. (1986) described several approaches, with varying complexity, for the quantisation of texture in SAR images.

In our StereoSAR system, we implemented an algorithm that utilises an area-based, multi-scale pyramidal automatic matching approach which adapts the correlation threshold based on the texture in the image and also adapts the correlation window size between pyramid levels. To make this possible, a texture mask is generated from the reference image using a simple first order statistical texture measure proposed by Ulaby et al. (1986). This mask segments the reference image into areas of low texture and high texture/structure. In developing this algorithm, we experimented with various values and found that a correlation threshold of 0.65 in areas of high texture/structure and 0.40 in areas of low texture produced suitable results. We also found that by starting with a correlation window size of 5x5 pixels on the first pyramid and increasing this by two pixels between pyramids to a maximum of 13x13 pixels on the last pyramid was sufficient for providing area patches suitable for use in the computation of the correlation values. A more detailed description of the algorithm can be found in Edwards (2005).

2.2 The Space Intersection Algorithm

Consider two radar satellites in space, imaging the same ground location in such a way that a pair of overlapping images is acquired. The solution for the ground position of any conjugate point - determined from the image matching process - will be the intersection of the range and Doppler equations formed for each satellite. This is based on the stereo principle whereby the complete 3D position of a terrain point can be determined by imaging the same point from two different positions in space.

Figure 2 illustrates the basic principle involved in the space intersection strategy for a same side repeat-pass orbit pair.

Here, the ground point P is being imaged from satellite positions S_1 and S_2 ; \dot{S}_1 and \dot{S}_2 are the velocity vectors, while S_1 and S_2 represent the position vectors of the respective satellites. P is the location of the terrain point and its position vector is given by \mathbf{P} . R_1 and R_2 are the observed ranges to the terrain point. In Figure 2, all position vectors are given with respect to a geocentric Earth Centred Earth Fixed (ECEF) Cartesian system with its centre at O .

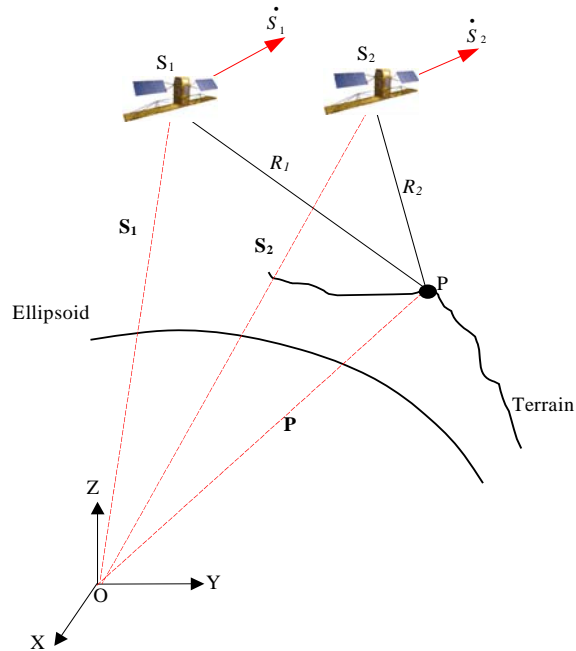


Figure 2. Space intersection principle

The range and Doppler equations, which were first proposed by Curlander (1982) for the geo-coding of single SAR imagery, can be formed for each satellite orbit and used as observation equations in the space intersection process. The basic range and Doppler equations for a single satellite are given as Equation 1 and Equation 2 respectively, where f_D is the Doppler centroid frequency and λ , the wavelength of the SAR signal. These are:

$$R = |\mathbf{S} - \mathbf{P}| \quad (1)$$

$$f_D = \frac{2(\mathbf{S} - \mathbf{P}) \cdot (\dot{\mathbf{S}} - \dot{\mathbf{P}})}{\lambda |\mathbf{S} - \mathbf{P}|} \quad (2)$$

At the IESSG we developed, from scratch, an algorithm for performing the space intersection process in an ECEF coordinate system. This algorithm was

implemented using the C# programming language. The flow diagram for the algorithm used in our space intersection strategy for this study is shown in Figure 3. The values of the parameters required for input into the program can be extracted, or computed, from the auxiliary information contained in the SAR image header. A full description of this algorithm and a sensitivity analysis along with experimental results has already been presented in Edwards et al. (2004).

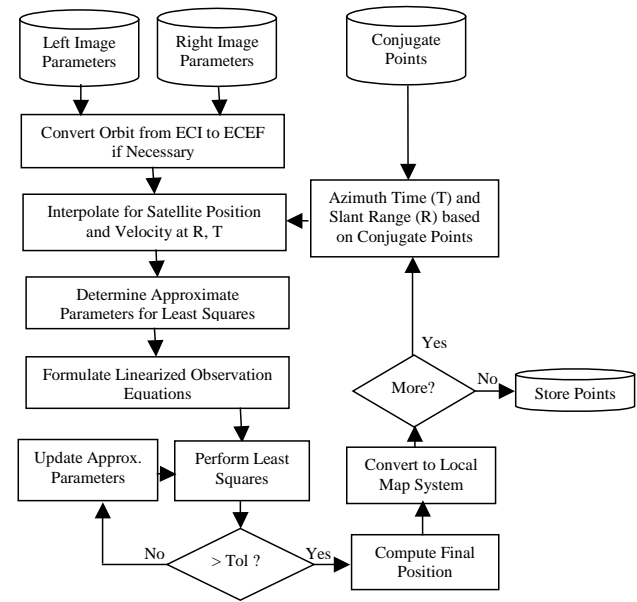


Figure 3. Flow diagram for IESSG space intersection algorithm

3. Study Area and Data

The requirement is to generate a stereo-derived DSM over a part of the Caribbean Island of Jamaica (see Figure 4) using the algorithms developed as part of the Nottingham StereoSAR Software which were outlined in Section 2. This site is a mountainous island of 10,991 km² with its tallest peak, the Blue Mountains in the east, rising to 2,256m. The island is situated at 77°W and 18°N and is the third largest of some twenty-five islands in the Caribbean Sea forming the West Indies. Jamaica has been chosen because it best represents the surface characteristics that dominate the Caribbean landscape with its varying land use types and topographical features. It is the only Island with a dataset capable of validating the results of this study. Recent attempts (Edwards, 2002) to generate a DSM over the island using ERS tandem interferometry failed due to the low coherence over the hilly and vegetated areas; which accounts for nearly 80% of the island. This site, therefore, provides an excellent opportunity to test the capabilities of the StereoSAR algorithms as a complementary approach for the extraction of

topographic data from spaceborne SAR imagery over cloud affected territories.



Figure 4. Location of Jamaica (circled red)

Figure 6 (a) shows the reference DSM with different elevations represented by different colours. The elevation range over this test site is between 16 and 1,295m. The reference DSM was derived using the airborne InSAR method (Hensley et al., 2001) with a

spatial resolution of 5m and vertical accuracy of $\pm 3m$ which is expected to degrade with the increasing slope of the terrain.

This dataset is held as proprietary information by Spatial Innovision Ltd, a local GIS company. In this study, we utilised a pair of ENVISAT detected images which were acquired during a descending orbit. Table 1 summarises the characteristics of these images and Figure 5 shows an anaglyph generated using the imagery and subsets of the images over the test site.

Table 1. Characteristics of ENVISAT ASAR images

	Image 1	Image 2
Scene Date	25-Oct-04	26-Mar-04
Scene Time (GMT)	15:02:14	14:56:30
Image Swath	IS 4	IS 6
Scene Size (pixels)	8696 x 7004	8570 x 5737
Pixel Spacing (m)	12.5	12.5
Incidence Angle (deg)	34	41
Number of Looks	4	4

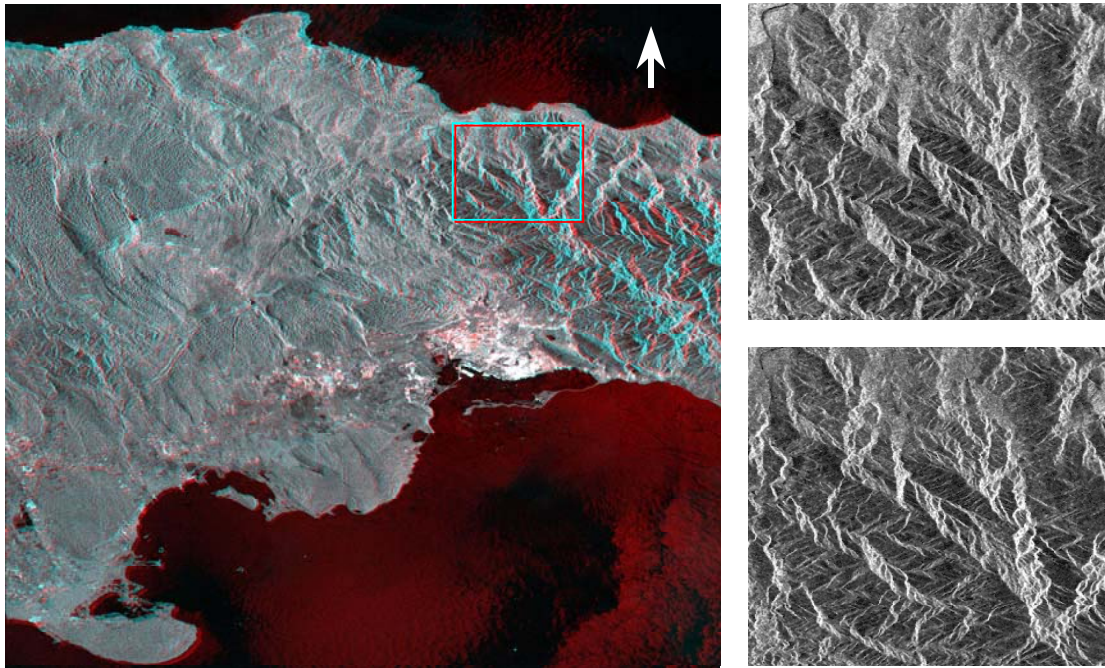


Figure 5. Left - ENVISAT Anaglyph showing study area (requires red/blue glasses). Right - Subset of ENVISAT images

4. Experimental Results

The images in Table 1 were chosen so that the layover and foreshortening in the steep terrain will be reduced; this however, led to a rather small stereo intersection angle of $\sim 7^\circ$, but it ensured that the images were similar, a requirement for automatic stereo-matching. A stereo pair was formed from these images using image 2 as the

reference image and image 1 as the search image. Following the workflow outlined in Figure 1, for the Nottingham StereoSAR System, the first step was to perform pre-processing of the images. This involved linear stretching from 16 bits to 8 bits to reduce the dynamic range of values; speckle filtering using a Gamma Map 5x5 filter to suppress the effects of speckle

noise; and texture mask generation to segment the reference image into area of high and low texture to be used with the adaptive matching algorithm. The second step was to co-register the images which would allow restriction of the search space to within ± 1 pixel of the predicted position in the search image. The third step was to conduct the automatic stereo-matching using the adaptive algorithm outlined in Section 2.1. We used four pyramid levels with correlation window sizes ranging from 5x5 to 13x13 pixels and correlation threshold of 0.65 in high textured areas and 0.40 in low textured areas. The points passing the requirements were used on the next pyramid level as approximate locations in the

search area and the search process continued until the last pyramid level was reached. The result was a list of row and column values for the matching conjugate points on the last pyramid level. In the fourth step, the list of conjugate points was used in the space intersection algorithm outlined in section 2.2 and based on Figure 3. The 3D positions of points (Eastings, Northings and Heights) were computed in the local Jamaican Grid system for ~880,000 points. In the final step, this point cloud was resampled into a regular grid with 50m spacing to form the DSM. A 3D perspective view of the Nottingham StereoSAR derived DSM can be seen in Figure 6(b).

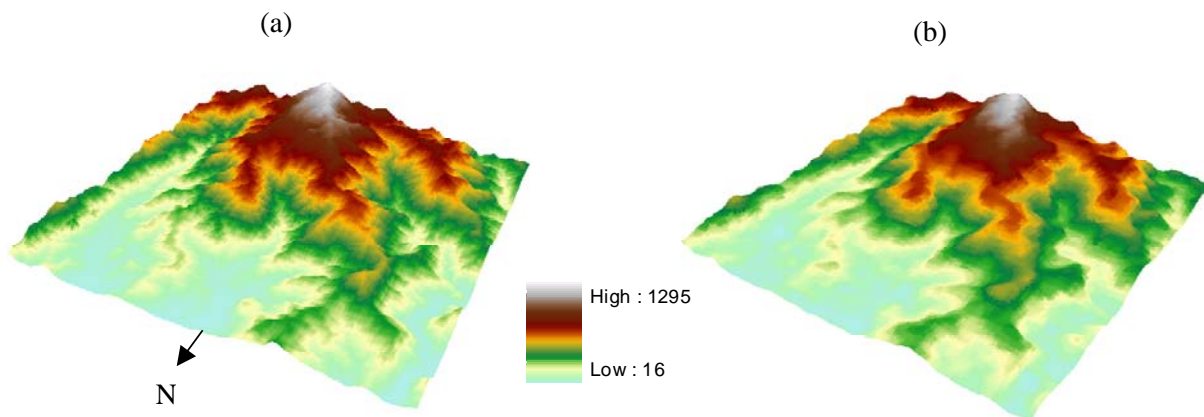


Figure 6: (a) Reference InSAR DSM; (b) Nottingham StereoSAR Derived DSM

The vertical accuracy of the Nottingham StereoSAR DSM was assessed by comparing it with the airborne InSAR reference DSM at 295 randomly located points, well distributed across a 10km x 10km subset of the DSM as shown in Figure 7.

ArcGIS 9.0 and their elevation values determined, using an ESRI ‘spot height’ script (obtained from www.esri.com), for both the reference DSM and the StereoSAR DSM. The statistical summary of the comparison is shown in Table 2. The analysis shows that the comparison with the check points yielded a RMSE of $\pm 30.3\text{m}$ and that 70% of the differences are less than this value.

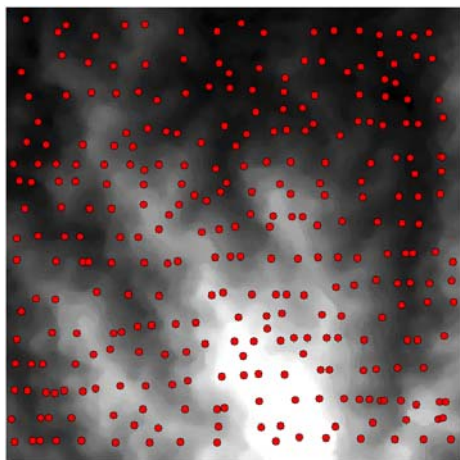


Figure 7. Distribution of 295 check points in 10km x 10km StereoSAR DSM

These random points were created using ESRI

Table 2. Summary of Statistics for DSM Comparisons (Ref. DSM-StereoSAR DSM)

No. of Points Compared	Mean (m)	Std. Dev.(σ) (m)	RMSE (m)	< 1 σ (%)	< 2 σ (%)	< 3 σ (%)
295	+ 4.6	30.0	30.3	70	94	100

Additional assessment of the StereoSAR DSM was accomplished by performing quantitative and qualitative analyses of DSM quality through the construction of profiles across the DSMs. This was done using ERDAS Imagine software to create a layer stack of the images and then utilising the spatial profile tool to generate three profiles as shown in Figure 8. The spatial profiles created showed that the StereoSAR DSM was able to characterise the main terrain features, which is more

than adequate for a low-cost medium accuracy product; however, finer surface information is missing or smoothed out. Also the algorithms tend to fill in valleys

making them too high or smooth out hill tops making them too low. These issues will have to be addressed in the future.

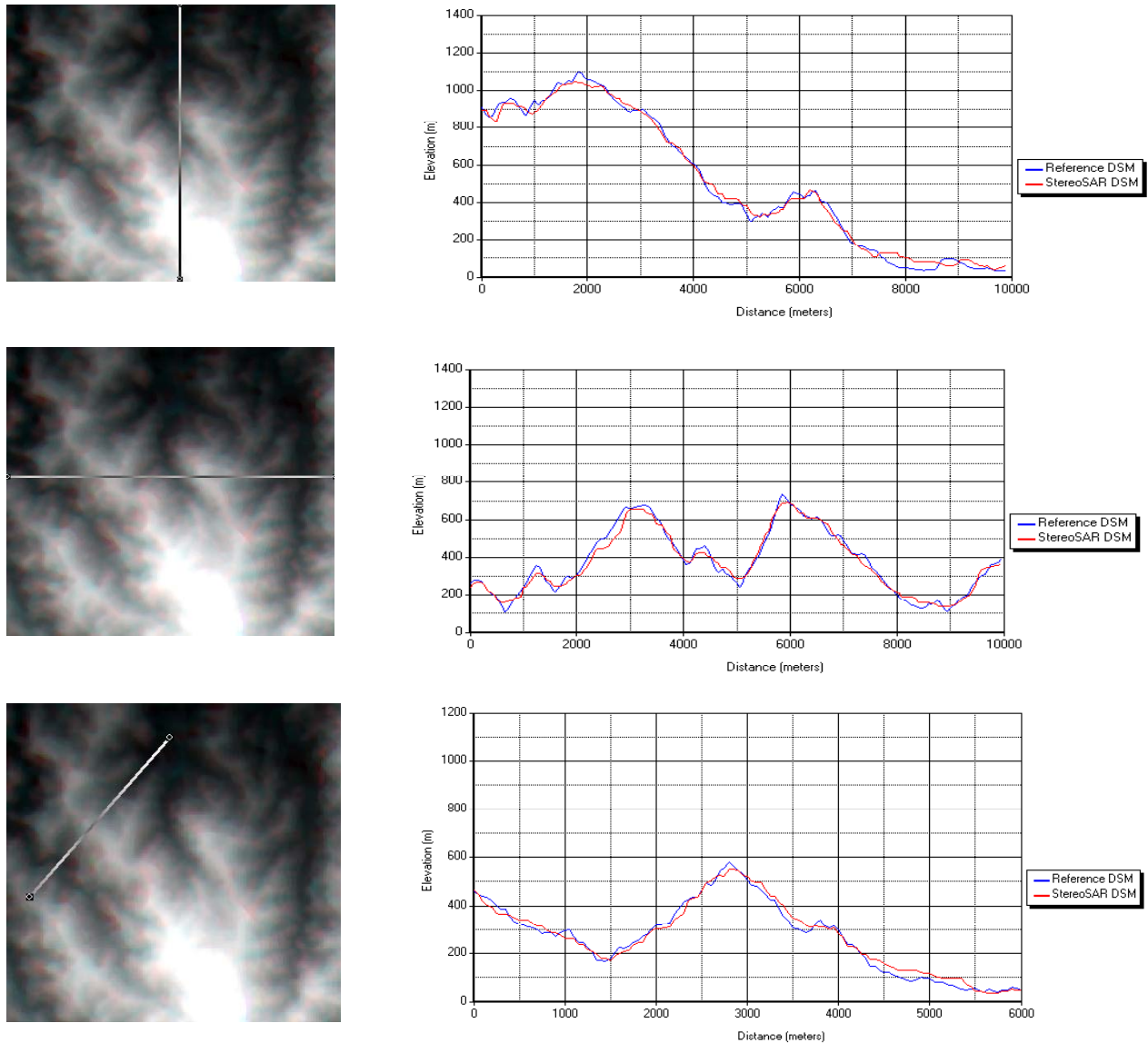


Figure 8. Profile comparison between InSAR reference DSM and Nottingham StereoSAR DSM at three locations

5. Conclusion

In our experiment with stereoscopic ENVISAT images over the Jamaica study area, we found that the Nottingham StereoSAR system is capable of producing a result in an area where spaceborne interferometry failed, which shows the complementary nature of our method. The comparisons with the airborne InSAR DSM show that our system is able to characterise the terrain at a level suitable for a low-cost medium accuracy product with RMSE of $\sim \pm 30\text{m}$, which is about the size of the resolution cell, without any need for ground control points. The largest discrepancies are in areas where the

interpolating routine and filters, adopted in the system, either fill in too much in the case of valleys or smooth too much in the case of hill tops. This needs to be looked at further in the future. The new Radarsat-2 satellite will have further improvements to orbital data and spatial resolutions up to 3m for SAR imagery. The Nottingham StereoSAR system is designed to process this dataset, once it is in a CEOS format, and results and performance will be compared to Envisat in future studies.

The results so far from the Nottingham StereoSAR system are quite encouraging and future work should focus on improving the robustness of detecting false

matches and further enhancements to the interpolation and filtering routines adopted here.

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Earl P. Edwards is a certified Project Management Professional with both the IMPA and the ASAPM and also a member of the Institute of Surveyors of Trinidad and Tobago. He obtained his BSc with first Class honours in land surveying from The University of the West Indies, St. Augustine; an MPhil in GIS and Remote Sensing from the University of Cambridge, UK; and a PhD in Geospatial Information Sciences from The University of Nottingham, UK. Dr. Edwards is currently a lecturer in Geospatial Information Sciences at UWI and an Enterprise GIS consultant in the Caribbean region.

Andrew Sowter holds a PhD in satellite orbital dynamics from Aston University and has spent 13 years in industry where he became a recognised expert in the processing and interpretation of satellite radar imagery of the Earth. In 2001, he joined the Institute of Engineering Surveying and Space Geodesy (IESSG) in the School of Civil Engineering at The University of Nottingham where he remains to this day, lecturing in many topics at undergraduate and postgraduate level and supporting research. His main research topic at the moment is in the mapping of land deformation using a technique called interferometric synthetic aperture radar. Dr Sowter is currently on secondment to The University of Nottingham, Ningbo China campus.

Martin J. Smith BSc, MSc, PhD, FRICS, MCIInstCES, is an Associate Professor in the Institute of Engineering Surveying and Space Geodesy (IESSG), which is part of the Department of Civil Engineering and the Infrastructure and Geomatics Research Division, in the Faculty of Engineering. Dr. Smith has had many PhD students and publications and been involved in a wide range of research projects from fundamental algorithm development to application projects in the fields of surveying and photogrammetry (geomatics). Research areas have included ground, airborne and mobile laser scanning, integrated systems (GPS/IMU/sensors), metric and non-metric camera calibration, the analysis and application of digital photogrammetric procedures, digital surface modelling, close-range photogrammetry, and industrial measurement.

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