EXTRACTION OF VERY-HIGH RESOLUTION TOPOGRAPHY FROM TRI-STEREO KOMPSAT-3 IMAGERY THROUGH REFINED GEOMETRIC MODELING

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Abstract

This study presents a methodology on how to extract topographical features from tri-stereo satellite imagery using a Refined Rational Function Model (RFM) and build a Digital Elevation Model (DEM). KOMPSAT-3 tri-stereo images captured on Carabao Island in the Philippines were used on this study.

The RFM refinement from tri-stereo imagery is based on the GeoEye-1 reference image and SRTM 30m DSM where Ground Control Points (GCP) and Tie-Points (TP) are calculated. Prior to refinement, the raw Level 1O KOMPSAT-3 images show overlapping offset of around 26 to 30 meters. After the refinement, the resulting orthorectified panchromatic KOMPSAT-3 tri-stereo images show improved georeferencing accuracy of 3 to 5 meters based on a single point of reference.

The resulting Digital Surface Model (DSM) was able to achieve a ground resolution of 1.4 meters. The quality of tri-stereo DSM is assessed with respect to ALOS 30m DSM by calculating the correlation coefficients and elevation differences for all pixels in the study area. Histogram analysis revealed a mean of -0.63 meters and standard deviation of 4.05 meters. The linear regression and Pearson correlation coefficients were both 0.99. In general, the ALOS 30m DSM has slightly higher measurements than the tri-stereo DSM but are highly correlated with each other.

This study demonstrated that optical satellite imagery can be used to extract topographic features and monitor geomorphic processes such as landslides, generate flood routing models and other derivative applications.

Keywords: Tri-stereo Image, Digital Elevation Model, Digital Surface Model, Rational Function Model, Photogrammetry, Geometric Modeling, Topography Extraction

1. INTRODUCTION

Earth observation satellites help with data-driven assessment and decision-making by providing timely and relevant information extracted from a specific area of interest. With the establishment of the Philippine Earth Data Resource and Observation (PEDRO) Center by the Department of Science and Technology–Advanced Science and Technology Institute (DOST-ASTI), the country was able to gain access to terabytes of data generated by different earth observation satellites. As the operations of the PEDRO Center transitions to the Philippine Space Agency (PhilSA), sources of quality spaceborne data will be sustained and expanded as the latter continuously strengthens the foundation started by DOST-ASTI. With access to volumes of earth observation data, new opportunities for earth surface monitoring are opened not just by looking into images but also extracting relevant features from it.

With different changes on the environment further amplified by human activity, the need for monitoring the surface of the earth is continuously increasing. Consequently, the number of earth observation satellites have increased, driving the cost of data lower. The capability to acquire multi-temporal datasets have improved, as well as the ability to monitor geomorphic processes and the effects of natural disasters on the Earth's surface (Aati and Avouac, 2020). These types of analyses require a good understanding of image geometry to allow the extraction of accurate Digital Elevation Models (DEM). DEMs show a 3-dimensional view of a particular area of interest that can be displayed on a computer. DEMs provide valuable insights to researchers while saving time and resources in analyzing large areas virtually impossible to be covered on foot.

DEMs are spatial data that contains location and elevation values of the terrain over a specific area usually represented as a structured grid. Two types of DEM are the Digital Terrain Model (DTM) and the Digital Surface Model (DSM).

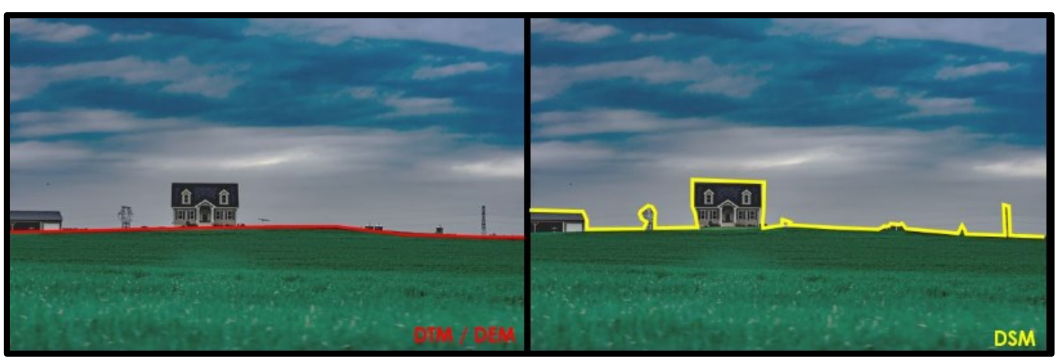


Figure 1: Comparison between a digital terrain model (DTM) and the digital surface model (DSM).

This study proposes the use of Rational Function Model to extract the DSM from a tri-stereo image captured by KOMPSAT-3. The tri-stereo image was captured simultaneously with varying pitch angles, creating a parallax between each image. The area of image capture is located at Carabao Island, Philippines.

Figure 2: Area of study: Carabao Island, Philippines. Base map: ESRI.

The resulting DSM will be assessed by comparing its terrain profile to other elevation models, being the ALOS PALSAR world DSM version 3.1 as the only available data, with a spatial resolution of 30 meters.

2. METHODOLOGY

2.1. Stereo imagery satellite capture.

The extraction of topographic features of the area of study will be done on a stereo satellite image captured by KOMPSAT-3 satellite. Stereo satellite imaging called stereoscopy or 3D imaging is a photogrammetric technique developed to create the terrain of an area from sets of images. Satellites can be tasked to collect either stereo imagery or tri-stereo imagery to produce high-quality DEMs.

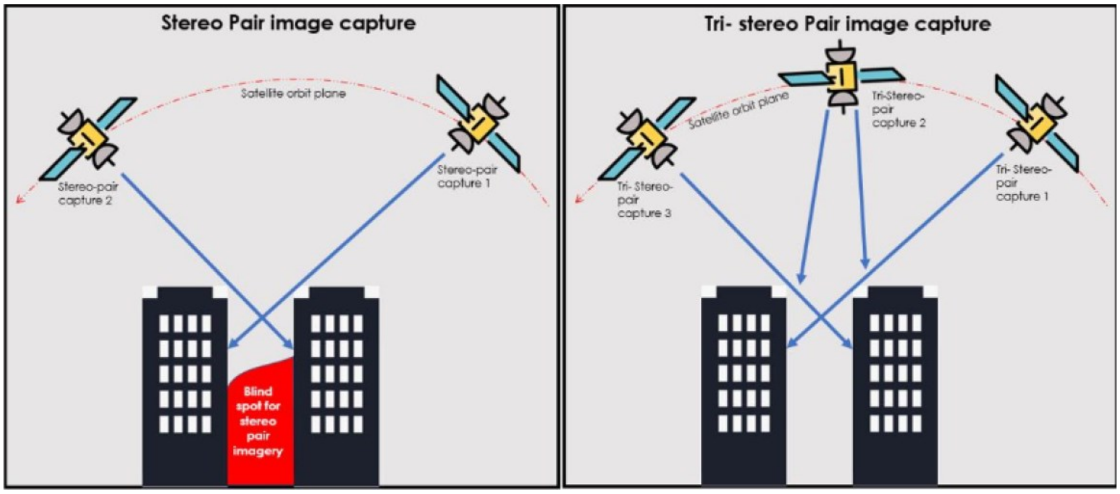


Figure 3: Comparison of standard stereo pair and tri-stereo pair image capture modes.

The standard stereo pair image capture method captures an area from just two angles, which may not capture relevant information between tall structures. The improved tri-stereo mode captures images from three angles so that it can provide information that may be hidden on steep terrains, clustered buildings, and densely built-up areas.

2.2. KOMPSAT-3 satellite imagery

The KOMPSAT-3 satellite uses an AEISS (Advanced Earth Imaging Sensor System) (Figure 4.a) push broom imager capable of capturing multispectral images with resolution of 2.8 meters and panchromatic images with resolution of 0.7 meters. The tri-stereo imagery was captured on February 03, 2021 on Carabao Island, Philippines, producing three overlapping nadir images with pitch, tilt, and yaw angles of 27.94 degrees, -0.072 degrees and -27.89 degrees, respectively.

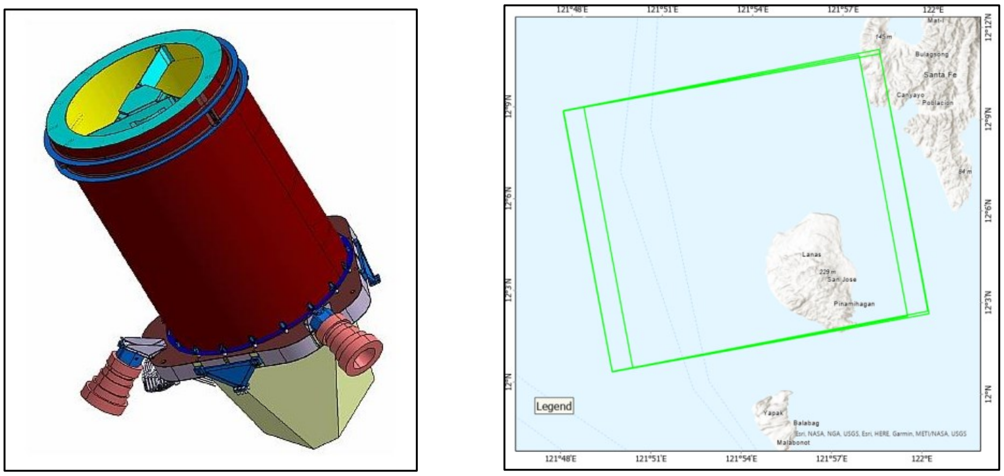


Figure 4: (left) Illustration of the Advanced Earth Imaging Sensor System of KOMSPAT-3 (right) Number of overlapping Kompsat-3 images captured using tri-stereo configuration in various tilting angles.

Level 1O tri-stereo KOMPSAT-3 images was acquired, but only the panchromatic band from each image were used for the extraction of the DSM. Level 1O are preprocessed ortho-ready images, where geometric distortions are corrected and projected to UTM51P.

2.3. Rational Function Model

The tri-stereo KOMPSAT-3 images are processed using the Rational Function Model (RFM), which is a simple math model that builds a correlation between pixels and their ground location (Cheng, 2014). This model is best used when satellite sensor model is proprietary, the imagery has been processed geometrically and math model has been precomputed by the satellite image provider. The RFM can be refined to improve the geometric correction of the imagery by adding Ground Control Points (GCP) distributed across the whole imagery (Yong, n.d.). The workflow on using the RFM for DSM extraction is summarized in Figure 5. A terrain-independent approach was used and the given RPC file from KOMPSAT-3 was used for the RFM solution.

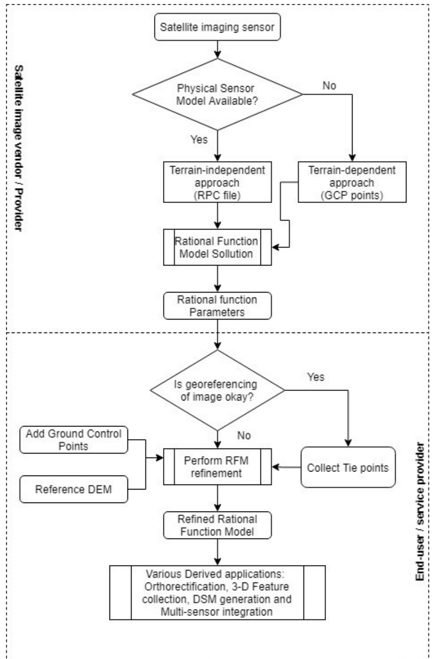


Figure 5: General process of using the Rational Function Model for DSM extraction.

2.3.1 Rational Function Model Refinement

Prior to RFM refinement, the raw Level 1O KOMPSAT-3 images show georeferencing offsets between each image of around 40 to 90 meters. As shown in Figure 6, the reference point shown on the leftmost image landed on different areas between the images which indicates poor georeferencing on the Raw Level 1O KOMPSAT-3 image. A Rational Function Model refinement can be run, wherein a validated orthorectified image, reference Digital Elevation Model and GCPs will be used to improve the georeferencing between the three overlaps of the imagery with their real-world locations (Cheng, 2014). Using PCI Geomatics software, the RFM refinement on three overlapping tri-stereo KOMSPAT-3 images was performed.

Figure 6: Raw Level 1O tri-stereo KOMPSAT-3 images shown with a reference point to assess georeferencing quality.

A GeoEye-1 image from ESRI's world imagery orthorectified base map captured on August 15, 2019, with a resolution of 0.5 meter and georeferencing accuracy of 5 meters was used as the reference imagery to improve the georeferencing of the tri-stereo images.

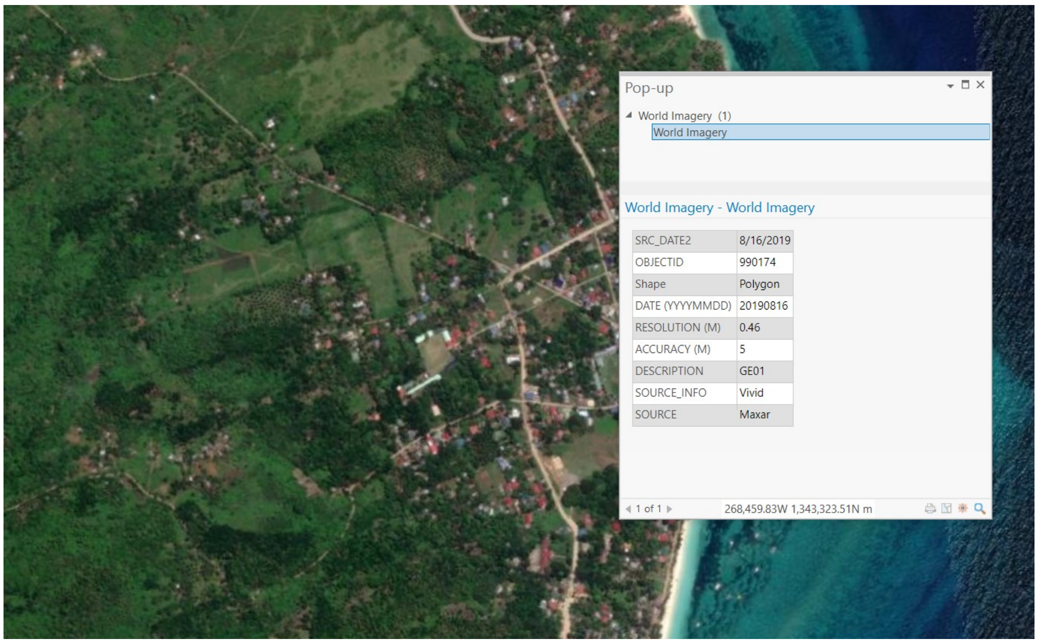


Figure 7: GeoEye-1 reference image from ESRI World imagery base map.

Aside from the reference imagery, the Shuttle Radar Topography Mission (SRTM) 1 arc-second global 30m DEM was used to orthorectify the tri-stereo KOMPSAT-3 image. The reference elevation model will be used together with the reference orthoimage to gather enough GCPs across the tri-stereo images to improve the georeferencing between each overlap.

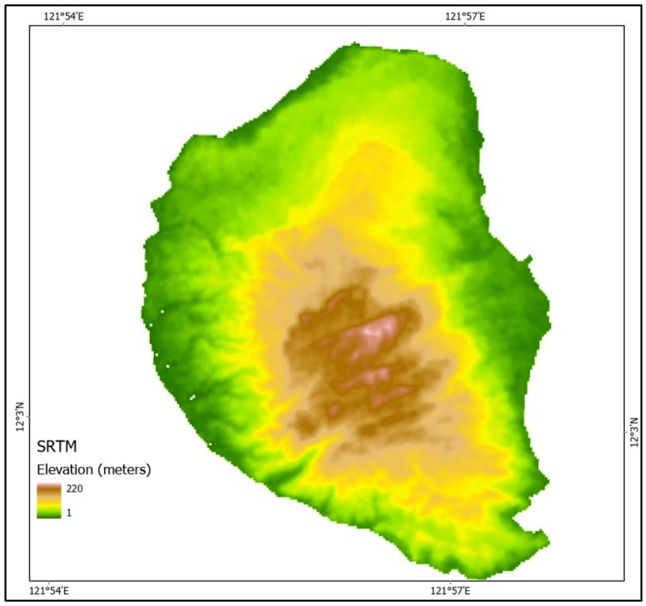


Figure 8: SRTM with 30-meter ground resolution used for RFM refinement.

As part of the RFM refinement, an automatic Tie-Point (TP) collection was added to the process. The Tie-Point collection is a set of locations that are recognizable visually between two or more overlapping images. Image correlation techniques such as Susan Method and fast-Fourier transfer phase (FTTP) algorithm were used to automatically collect TPs between all the images.

2.4. Digital Elevation Model Extraction

3D reconstruction from a set of images can be performed in the image space or object space. The image space is mostly used with stereoscopy pairs or tri-stereo pair and therefore used in this study. The object space is commonly used with multiple overlapping images, such as images acquired through drone and close-range photogrammetry. After the refinement of RFM, the following steps were needed (Figure 10) to extract the DSM from the tri-stereo image:

Generation of epipolar pairs:

Epipolar geometry is focused on resampling stereo pairs based on the refined RFM so that two images have a common orientation and matching features as it appears along a common axis (Pan, 2011). Epipolar images increase the speed of the correlation process and reduces incorrect matches during 3D reconstruction. Epipolar pair selection (Figure 9) can be done by choosing the maximum overlapping pairs or extracting them from all overlapping pairs within the set of images. Since the three tri-stereo images overlap within each other, all overlapping pairs were chosen for this study.

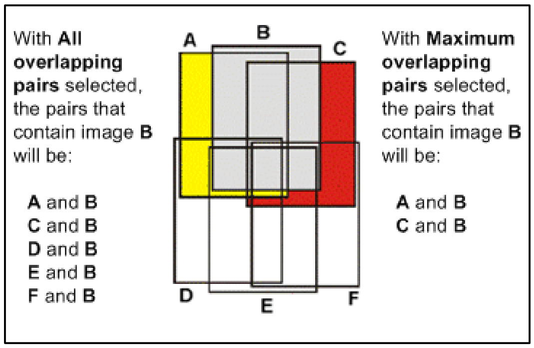


Figure 9: Comparing all overlapping pairs and maximum overlapping pairs for epipolar pair selection.

Stereo–Matching for Extraction of Digital Elevation Model:

Stereo-matching computes the correspondence between the pixels of epipolar pairs. These are computed using correlation techniques such as Normalized Cross-Correlation (NCC) and Semi Global Matching (SGM). NCC produces lower quality results with more error but will take less processing time. SGM is used in this study, which produces higher quality results with fewer errors but requires more processing time.

Digital Elevation Model Geocoding and Fusion:

The resulting DSM from each stereo pair are fused to create the final geocoded DSM. The DSMs are fused using different approaches such as Merge and Blend.

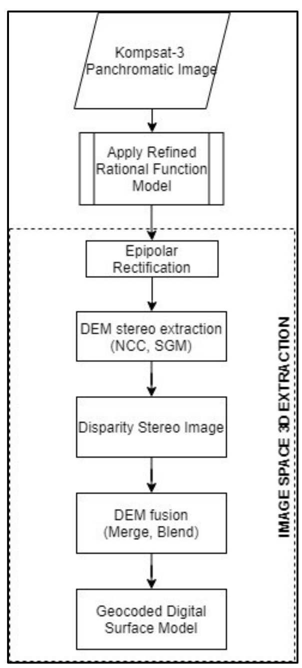


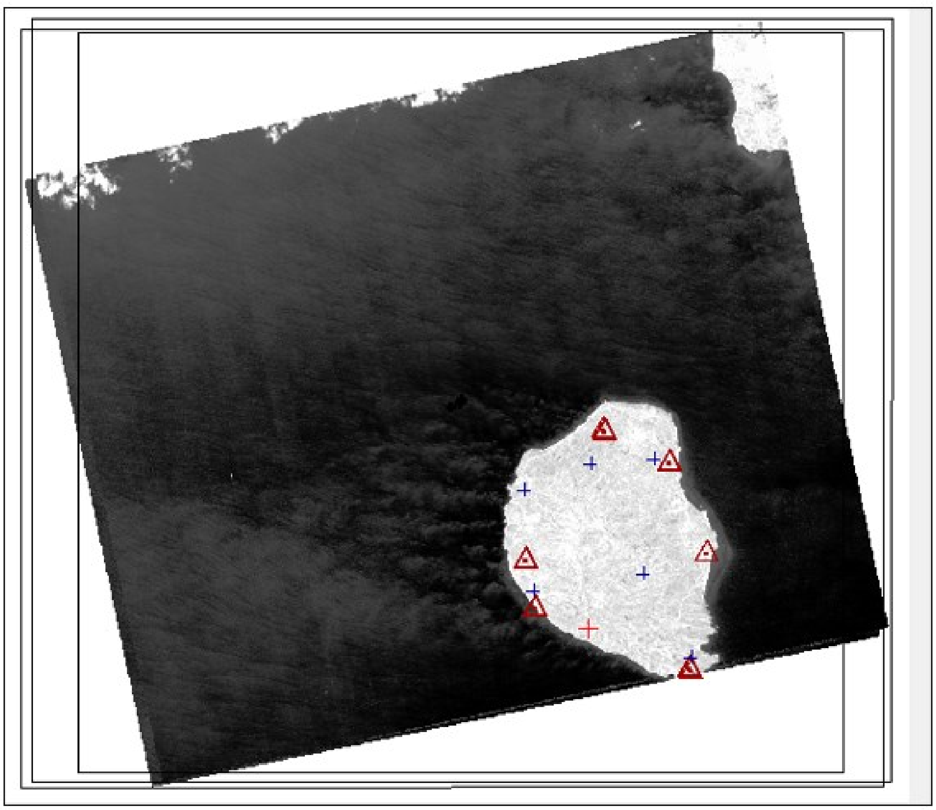
Figure 10: Workflow for KOMPSAT-3 tri-stereo image DSM extraction.

3. Results and Discussion

The proposed method of DSM extraction is demonstrated on KOMPSAT-3 tri-stereo imagery taken over Carabao Island.

3.1 Refined Rational Function Model Results

Prior to RFM refinement, the overlapping raw Level 1O tri-stereo KOMPSAT-3 images does not properly overlap as observed on a single reference point, having georeferencing offsets of around 26-30 meters. The refinement of RFM was based on GeoEye-1 orthorectified image and SRTM 30m DSM. A total of 6 GCPs were chosen across the tri-stereo imagery and 6 TPs were automatically generated using Sparse Fast Fourier Transform (SFFT) phase matching method.



Point ID	Residual	Res X	Res Y	Type	Image X	Image Y	Ground X	Ground Y	Ground Z
G0001	5.43	3.97	3.70	GCP	24950.50	19597.50	386719.61	1333601.29	14.12
G0002	5.14	-1.97	4.74	GCP	24354.25	23921.90	386290.19	1330600.22	61.16
G0005	4.38	-3.18	-3.01	GCP	18282.75	19890.17	382045.78	1333409.26	26.27
G0007	4.24	-1.98	-3.74	GCP	21154.00	15120.44	384055.21	1336761.35	48.36
G0004	2.40	1.70	-1.69	GCP	18611.13	21630.91	382281.48	1332174.05	0.00
G0008	1.39	1.38	0.12	GCP	23571.50	16293.68	385752.10	1335924.20	26.65

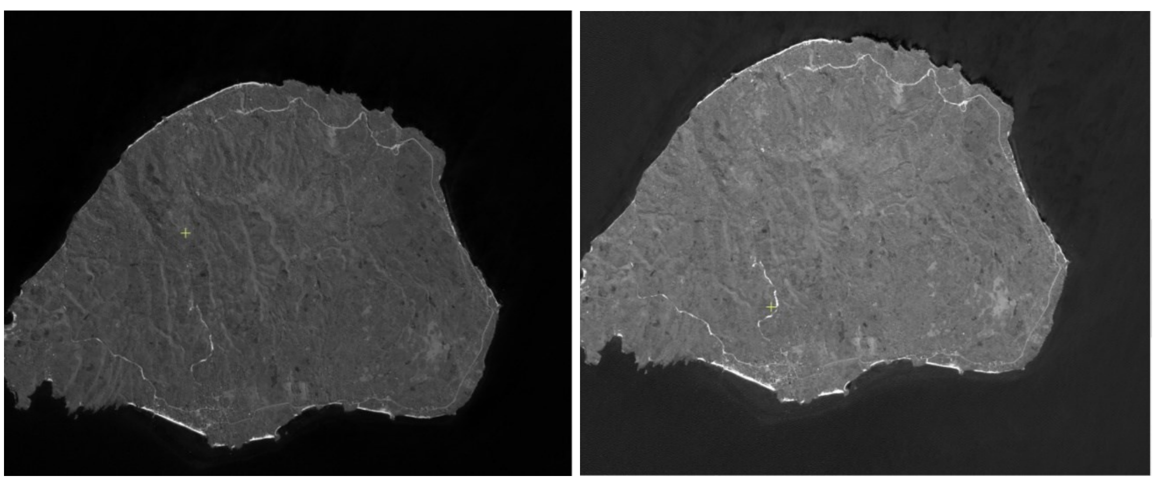
Figure 11: GCPs and TPs collected for the RFM refinement of the tri-stereo KOMPSAT-3 imagery.

The GCPs show a root mean square (RMS) residual of 2.54 pixels for the X-axis and 2.48 pixels for the Y-axis. The RMS error for the TPs show an RMS of 0.71 pixels for the X-axis and 0.38 pixels for the Y-axis. The resulting orthorectified panchromatic KOMPSAT-3 tri-stereo image after RFM refinement shows an improved georeferencing offset of 3-5 meters between the images based on a single point of reference.

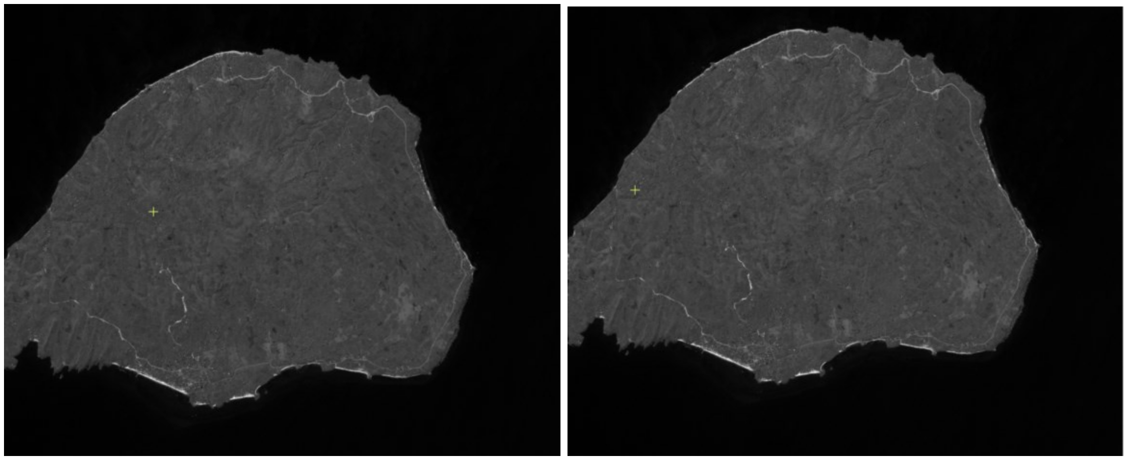
Figure 12: Post RFM refinement orthorectified L1O Kompsat-3 tri-stereo imagery.

3.2 Resulting Digital Elevation Model

After refining the RFM, DEM extraction was done in the image space from epipolar pairs between the three tri-stereo images. These epipolar pairs were generated based on a minimum percentage of 50% overlap between the tri-stereo images, thus creating 4 pairs of epipolar images.



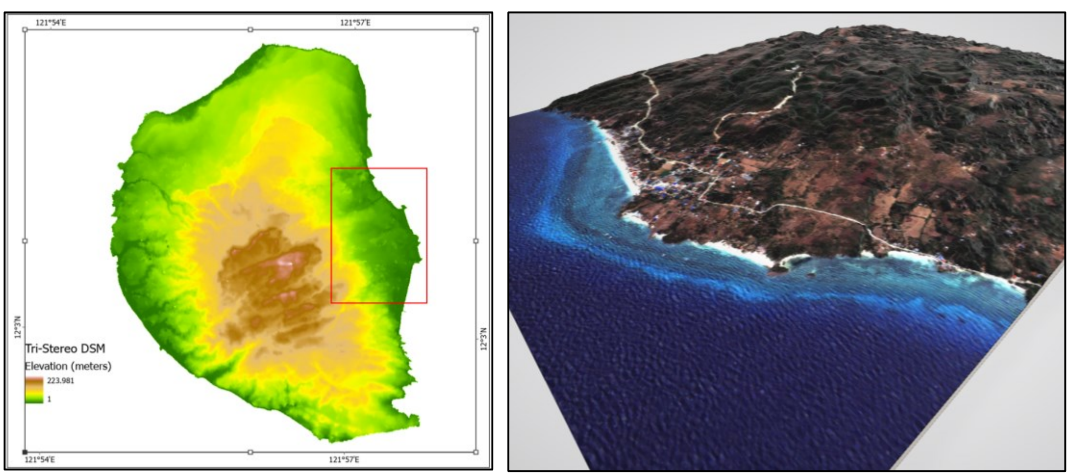
(a) (b)



(c) (d)

Figure 13: (a) Resulting left epipolar image from the forward and backward image capture of the tri-stereo image; (b) resulting left epipolar image from the nadir and backward image capture of the tri-stereo image; (c) resulting right epipolar image from the forward and backward image capture of the tri-stereo image; (d) resulting right epipolar image from the nadir and backward image capture of the tri-stereo image.

The resulting epipolar images were then processed using a Semi-Global Matching algorithm to produce a DEM with vertical datum of mean sea level. Low smoothing filter was used to lessen the noise from the edges. A total of two DEMs were generated from four epipolar pairs, and these were merged through averaging to build the final geocoded DSM of 1.4 meters ground resolution.



(a) (b)

Figure 14: (a) Geocoded DSM produced from the tri-stereo satellite image capture and (b) Subset 3D visualization of DSM with pansharpened KOMPSAT-3 image.

3.3 Assessment of DSM

We compared the resulting DSM to version 3.1 AW3D ALOS 30-meter world DSM to estimate the assess the similarity of the generated elevation model with respect to the latter (Santillan, 2016). Terrain profile from two transects were extracted from both DSMs. Transect AA' (Figure 15) represents the mountainous area, while transect BB' (Figure 16) is along the residential areas on the East coast of Carabao Island. The terrain profile of the two transects has demonstrated good similarity. The terrain profiles from transect BB’ shows noticeable differences on the 1500 to 2700-meter segment due to the presence of built-up structures.

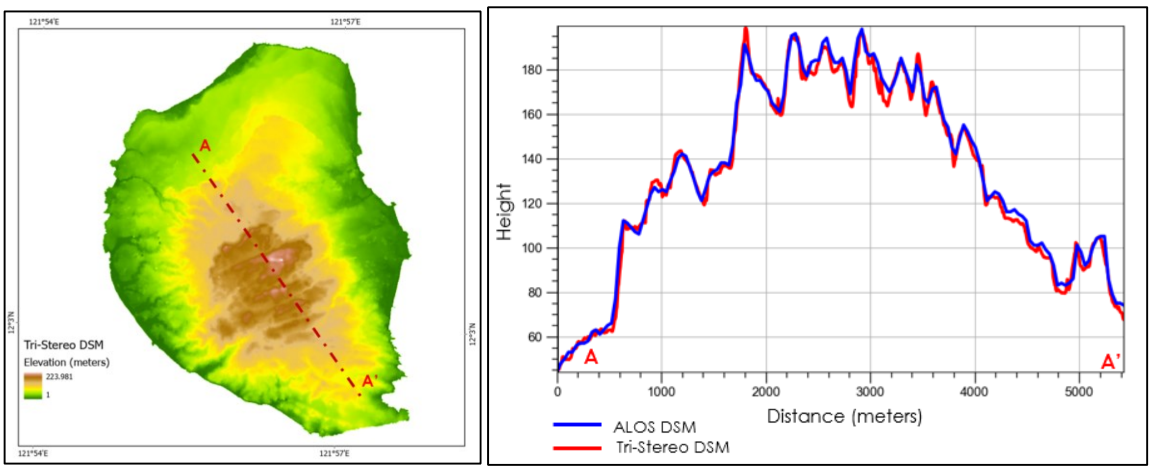


Figure 15: Terrain profile comparison of tri-stereo DSM (red line) and ALOS 30m DSM (blue line) for transect AA’.

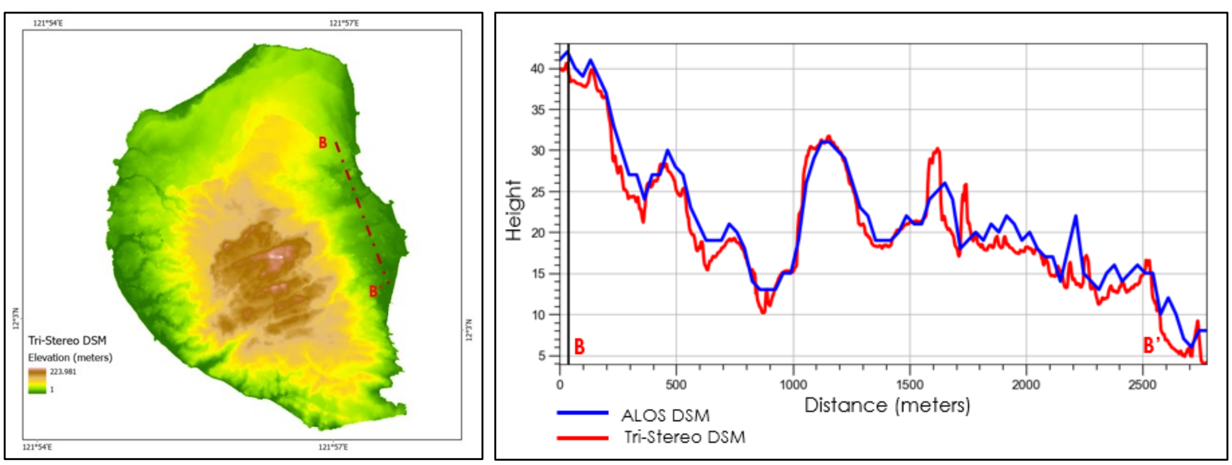


Figure 16: Terrain profile comparison of tri-stereo DSM (red line) and ALOS 30m DSM (blue line) for transect BB’.

To assess the similarity of the reference DSM and the KOMPSAT-3 tri-stereo DSM, an elevation difference (Figure 17) between the two was done on the whole area of study. The histogram of elevation differences (Figure 18) was then produced. This shows a mean of -0.63 meters with a standard deviation of 4.05 meters from a total of 30,207 data points.

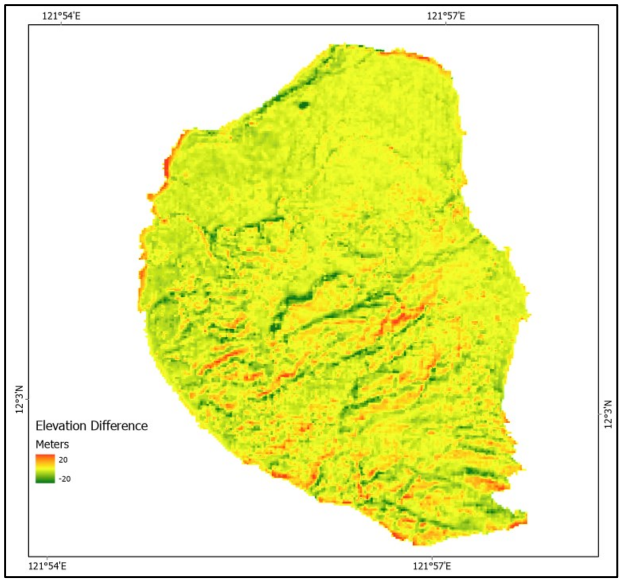


Figure 17: Elevation difference between reference ALOS 30m DSM and KOMPSAT-3 tri-stereo DSM, computed as <K3_DSM> minus <ALOS_DSM>.

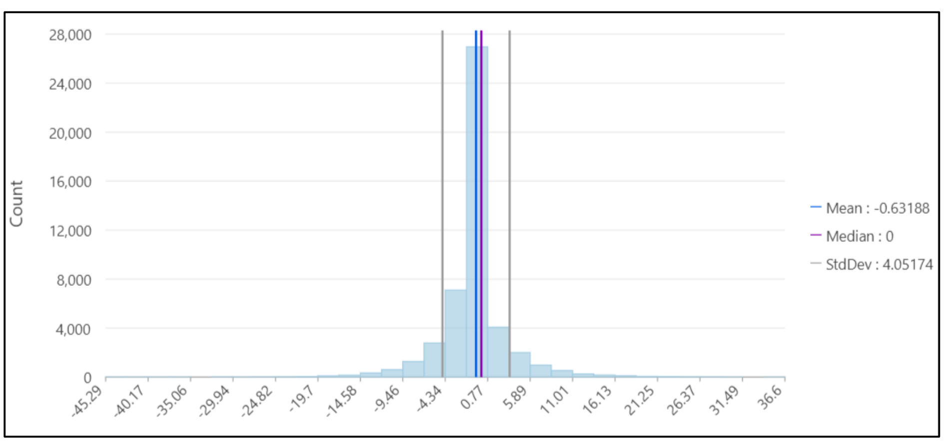


Figure 18: Histogram statistics of the elevation difference for the whole Carabao Island DSM.

Linear regression analysis (Figure 19) revealed a correlation coefficient of 0.9927 which shows very high correlation on both DSMs. Negative bias coefficient means that the ALOS DSM has slightly higher values than the tri-stereo DSM. The Pearson correlation coefficient was calculated with a value of 0.9963 and a P value of almost 0, which also emphasizes high correlation.

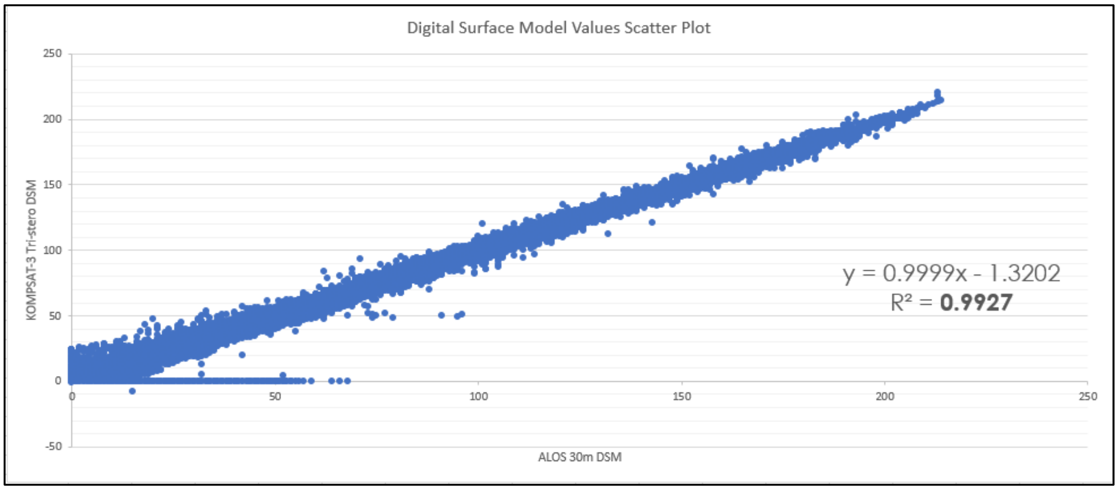


Figure 19: Linear regression on both KOMPSAT-3 tri-stereo DSM and ALOS 30m DSM.

4. Conclusion

The use of Rational Function Model refinement was presented for precise image registration, orthorectification and DEM extraction from tri-stereo satellite imagery. RFM refinement was effective on correlating the pixels between the overlapping images and improving the georeferencing offsets up to an order of magnitude. This method relies on the quality of the tri-stereo image capture and the reference data for refinement of the RFM and is necessary on generating high-quality DSMs.

After RFM refinement, the final tri-stereo DSM was generated with high quality ground resolution of 1.4 meters. This was made possible by the Semi-Global Matching algorithm. Lastly, the quality of the tri-stereo DSM was assessed by comparing it to version 3.1 ALOS 30m global DSM. Calculation of elevation differences show that the ALOS 30m DSM has slightly higher measurements than the tri-stereo DSM but are highly correlated with each other.

This study demonstrates the potential of processing tri-stereo satellite imagery to extract and monitor topographical changes brought by natural events, especially on inaccessible areas. Further improvement of the method includes the calculation of optimal distribution of GCPs across the image and as well as the use of better reference data.

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