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EVALUATION OF HEIGHT ACCURACY FOR DIGITAL ELEVATION MODELS (DEMS) FROM HIGH RESOLUTION STEREO SATELLITE IMAGERY: (WV-3)

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ABSTRACT

Topographic variation description through Digital Elevation Models (DEMs) is quite commonly used for several applications especially in the field of Geographic Information Analysis (GIA). Many procedures are now used to prepare data for DEMs construction. These include classical ground surveying methods: levelling plus triangulation or traversing, total station and stereo images from air photos captured by aerial cameras. All these techniques would give very high accurate DEM, but they are very much time consuming and labor intensive. Recent techniques of space imagery techniques for capturing stereo images is the satellite borne WV-3. Although such remote sensing methods save a lot of time and expenditure the limitation is the accuracy. This paper addresses the elevation accuracy of DEM derived from WV-3 compared to that derived by total station observations. The test was carried for an area within King Saud University campus where imagery was available. Result show that DEM composed from WV-3 imagery is quite close in accuracy to that obtained from total station observations, and can thus be used for several applications including production of 1:5000 scale topographic maps, saving both money and time.

INTRODUCTION

Digital Elevation Model (DEM) is defined as the digital representation of the land surface elevation with respect to any reference datum. It can be considered as the simplest form of topographic representation. DEMs are used to determine terrain attributes such as elevation at any point, slope and aspect. It is vastly used for earthwork calculations in route construction, hydrologic and geologic analysis as well as in channel networks and drainage basins (Balasubramanian, 2017). It can as well be considered as one of the most important tools and applications in Geographic Information Systems (GIS). Since it provides a three dimensional view of the earth's terrain, thus it forms tremendous application potential in many scientific fields.

DEMs can be linked to the earth’s physical processes, like water infiltration, overland flow, floods and vegetation distributions. This is because the models that drive these processes are each impacted by 3D space – elevation. Water runs downhill quicker on steeper land etc. These days floods are a huge issue, thus DTM are in high demand for insurance reasons, as example (Thursonand Ball, 2007).

Methods for obtaining elevation data used to create DEMs include digitization from topographic maps, land topographic collection techniques: total station, real time kinematic global positioning system (RTK-GPS), stereo photogrammetry from aerial photographs, stereo photogrammetry from drones, light detection and ranging (LIDAR), interferometry from radar data and stereo photogrammetry from high resolution satellite imageries.

DEMs can be extracted from topographic contour maps where contour lines can be converted into raster or vector form and algorithms are used to interpolate elevations at every grid corner, but in this case the accuracy of obtained DEM is only as good as the original maps. DEMs can also be generated through direct field measurement of point coordinates x, y, z values. The most common direct collection, of course, is through field surveying using theodolites, EDM and levels or total stations, but most commonly with GPS receivers. These direct measurement techniques can be very accurate but also extremely time consuming and expensive.

Today, DEMs are usually generated from remotely sensed data sets collected either from an aircraft (airplane, helicopter or unmanned aircraft / drone) or spacecraft (satellite or Space Shuttle). One of three types of digital sensors typically collecting data that can be used to derive elevation measurements are optical imaging sensor (frame camera / push broom scanner), synthetic aperture radar (SAR) sensor, or laser scanner (also called LIDAR) sensors. These technologies are dramatically different from one another.

DEMs from air photography can be formed manually or automatically, from film photographs or digital photographs. For decades, aerial imagery had been the only approach available for generating digital elevation models (DEMs) over large areas. Although airborne photogrammetric flights with new digital aerial cameras make it possible to capture highly detailed imagery, the drawback is that they require “ad hoc” photogrammetric flights at detailed scale and the handling of a high number of frames. The drawback of stereo-photogrammetric DEM production is the added expense of acquiring ground control point survey, in addition to the fact that the process can be time consuming (A. Balasubramanian, 2017).

The second remote sensing DEM creation technology is LiDAR or laser scanning. As the name implies, this active system uses a laser to emit tens of thousands of light pulses from the bottom of the aircraft towards the surface of the Earth below. These light beams strike ground and surface features before bouncing back to the device where calculations determine the precise time, and therefore range or distance, between surface points and the aircraft. Precise positional data of the airborne sensor platform from onboard GPS and inertial measurement units, which measure the attitude (pitch, roll, and yaw) of the aircraft, are critical for the calculation of precise x, y, z point measurements.

LIDAR mapping is efficient at quickly mapping relatively large areas, such as cities or counties, and the devices can be operated any time day or night. The single most important advantage of laser scanning is that every elevation point is measured directly. Modern LIDAR units are powerful enough to hit the ground with laser pulses separated by just a few centimeters, resulting in a very accurate representation of the terrain. The only significant downside of LIDAR is that the resulting dense point cloud of x, y, z measurements is difficult to interpret and identify specific ground features and extract measurements from them, compared to optical photogrammetric image mapping, which can identify specific features on the terrain.

IFSAR (Interferometric Synthetic Aperture Radar) mapping is another active sensing data collection technology in which radar pulses, typically X-band, are emitted from the spacecraft or aircraft down toward the Earth’s surface. These radar signals reflect off the surface and return valuable information content to a receiving antenna. The phase difference measured in the return signal yields accurate x, y and z measurements of surfaces and features. Elevation mapping with SAR technology is often called INSAR or IFSAR mapping.

SAR sensors can be operated in any weather or lighting conditions, which means it is extremely useful in capturing elevation data in tropical regions where cloud cover is persistent and at latitudes where darkness is pervasive for long periods of the year. While SAR typically delivers medium- to coarse-resolution data sets, it can acquire data quickly and cost-effectively over large regions, including entire countries or regional size areas.

Satellite images are one of the most powerful and important tools used by the geomatics engineers to collect data for forming DEMs (Elkhrachy, I. 2018).

In 2011, Deilami and Hashim, 2011 published a review article on accuracy of using very high resolution satellite imageries for DEM formation. The reviewed imageries include: IKONOS and GeoEye, SPOT5, QuickBird, WorldView 1 & 2, EROS-A1 and B1, CartoSat 1, ALOS, KOMPOSAT-2, available at that time. The study states that VHR optical satellites stereo images allow DEM extraction and ortho-rectification since they offer the highest resolution ever available which is varied between 0.5m and 2.5m in panchromatic mode and 2m and 10m in multispectral mode besides significant swath width and optional repeat cycle. Conversely, there are also some drawbacks which reduce the application of satellite images in DEM extraction such as dependency on the ground control points which increase the expenses.

One of the most recent very high resolution stereo satellite imageries that can be used for creation of DEM is the WV03 which will be the aim of study in this paper.

WV-3 IMAGERY

WorldView-3 is a commercial Earth observation satellite owned by Digital Globe. It was launched on 13 August 2014 to become Digital Globe's sixth satellite in orbit, joining Ikonos which was launched in 1999, Quick Bird in 2001, WorldView-1 in 2007, GeoEye-1 in 2008, and WorldView-2 in 2009. WorldView-3 provides commercially available panchromatic imagery of 0.31 m (12 in) resolution, eight-band multispectral imagery with 1.24 m (4 ft 1 in) resolution, shortwave infrared imagery at 3.7 m (12 ft 2 in) resolution, and CAVIS (Clouds, Aerosols, Vapors, Ice, and Snow) data at 30 m (98 ft) resolution.[4] It is capable of collecting about 1 billion km^2 of Earth imagery per year (Marchisio, 2014).

WorldView-3 is the first multi-payload, super-spectral, high-resolution commercial satellite sensor operating at an altitude of 617 km. WorldView-3 satellite provides 31 cm panchromatic resolution, 1.24 m multispectral resolution, 3.7 m short wave infrared resolution (SWIR) and 30 m CAVIS resolution. The satellite was launched on August 13, 2014. The satellite has an average revisit time of <1 day and is capable of collecting up to 680,000 km^2 per day from an altitude of 617 km. Its expected life time is 7.25 years while its estimated service life is 10 to 12 years. Its swath width is 13.1 km at nadir. It has dynamic range of 11-bits per pixel Pan and MS; 14-bits per pixel SWIR. SWIR bands penetrate haze, fog, smog, dust and smoke and the spectral diversity enables new imagery applications.

WorldView-3 satellite bears a strong resemblance to WorldView-2 launched on October 8, 2009 in terms of its performance characteristics. The WorldView-3 satellite sensor benefits from significant improvements including cost savings, risk reduction, and faster delivery for its customers.

Maximum contiguous area collected in a single pass (30^o off nadir angle is 66.5 km x 112 km mono viewing (5 strips) and 26.6 km x 112 km stereo (2 strips).

LITERATURE REVIEW

WV-3 super-high resolution imagery has been used in different applications, other than DEM formation WV-3 which is the objective of this. Some of these various applications including DEM formation that appeared in the literature are summarized below:

Johnson and Koperski (2017**)** have demonstrated through predictive statistical analysis carried out on the eight visible to near infrared (VNIR) bands (0.42 to 1.04 μm) and eight shortwave infrared (SWIR) bands (1.2 to 2.33 μm) of WV-3 imagery using Land Cover/ Land Use classification for all 16 WV-3 bands provides a quick and accurate solution for mineral/geologic mapping.

Fretwell, et al, 2017 carried out the first study utilizing 30-cm resolution imagery from the WorldView-3 (WV-3) satellite to count wildlife directly. They have tested the accuracy of the satellite method for directly counting individuals at a well-studied colony of Wandering Albatross Diomedea exulans at South Georgia, and then apply it to the closely related Northern Royal Albatross Diomedea sanfordi, which is near-endemic to the Chatham Islands and of unknown recent population status due to the remoteness and limited accessibility of the colonies. At South Georgia, satellite-based counts were comparable to ground-based counts of Wandering Albatross nests, with a slight over-estimation due to the presence of non-breeding birds.

Parente and Pepe (2018) concluded that the use of optical satellite sensors allows to obtain bathymetry data on large area in a short time and in a cheap way. In addition, in particular places where it is difficult to carry out the survey by classic methods, the bathymetry from satellite data can be the only mode to obtain the depth of the backdrop. They analyzed the potential of the eight bands and the very high resolution of the commercial satellite (WV-3) in order to obtain bathymetric data. Using WV-3 satellite data and the Stumpf method, the study investigated the possibility of obtaining bathymetric data in a specific area where the water is not particularly clear.

Capaldo et al, 2012 presented and discussed some results obtained with a new proprietary matching strategy for DSMs generation, which is implemented in the SISAR software developed at the Area di Geodesia e Geomatica-Universita di Roma "La Sapienza". In order to assess the accuracy of the new strategy, some tests were carried out, using a stereo pair of Augusta coastal zone (Sicily, South Italy) acquired from WorldView-1 and one of the first available GeoEye-1 stereo pairs, which was acquired over Rome. The results show that an accuracy at the level of about 2 m is achievable in open areas with both WorldWiew-1 and GeoEye-1 stereo pairs, whereas higher errors are displayed in urban areas.

Barazzetti et al, 2016 presented the orientation results for a single WV-3 image collected over Milan. The use of a bias-compensated RPC camera model based on two shifts parameters improved geolocalization accuracy up to 0.7 m for both X and Y directions. The comparison was carried out with a set of GCPs and CPs measured with RTK GNSS, as well as an independent evaluation between the terrain corrected image (orthophoto) and the geospatial database of the city (vector layer). Both tests confirmed a similar geolocalization accuracy.

In their paper, Hu, et al 2016 demonstrated that the geo-positioning accuracy of WV-3 stereo-images in a mountainous test area is desirable without or with only a few GCPs, which is superior to the nominal value. Compared with the high-accuracy airborne LiDAR point cloud, the elevation biases of DEM extracted from the WV-3 stereo-pairs were about 0.62 m (std. value). If considering the potential uncertainties in the image point measurement, image matching and also elevation editing, the accuracy of generating DEM from WV-3 stereo-images in mountainous areas should be more desirable. Therefore, WV-3 has the potential for 1:5000 or even larger scale mapping application was the derived conclusion.

The study by Rupnik, et al, 2018 attempted the generation of high quality digital surface models by fusing multiple depths maps calculated with the dense image matching method. The algorithm is adapted to very high resolution multi-view satellite images, and the main contributions of this work are in the multi-view fusion. The algorithm is insensitive to outliers, takes into account the matching quality indicators, handles non-correlated zones (e.g. occlusions), and is solved with a multi-directional dynamic programming approach. No geometric constraints (e.g. surface planarity) or auxiliary data in form of ground control points are required for its operation. Prior to the fusion procedures, the RPC geolocation parameters of all images are improved in a bundle block adjustment routine. The performance of the algorithm is evaluated on two VHR (Very High Resolution)-satellite image datasets (Pléiades, WorldView-3) revealing its good performance in reconstructing non-textured areas, repetitive patterns, and surface discontinuities.

Barbarella et al, 2017 concluded that very high-resolution satellite stereo images play an important role in cartographical and geomorphological applications, provided that all the processing steps follow strict procedures and the result of each step is carefully assessed. We outline a general process for assessing a reliable analysis of terrain morphometry starting from a GeoEye-1 stereo-pair acquired on an area with different morphological features. The key steps were critically analyzed to evaluate the uncertainty of the results. A number of maps of morphometric features were extracted from the digital elevation models in order to characterize a landslide; on the basis of the contour line and feature maps, we were able to accurately delimit the boundaries of the various landslide bodies.

Loghin, et al, 2019 analyzed and assessed the potential in geometric quality of DEMs generated from high-resolution Pléiades and WorldView-3 stereo and tri-stereo scenes. They have studied the impact of the different acquisition geometries (stereo / tri-stereo, ground sample distance, viewing and incidence angles) on the estimated surface and its properties. The study area is located in Allentsteig, Lower Austria, a hilly region covered by arable lands and coniferous forests stretching from 300 m to 690m above MSL. The entire photogrammetric workflow, comprising the satellite image triangulation, dense matching and 3D reconstruction were performed with the Match-AT and Match-T DSM modules of the Trimble Inpho software. The 3D reconstructed point clouds are interpolated into high resolution Digital Surface Models (DSMs) and their absolute vertical accuracy is evaluated against a LiDAR-derived Digital Terrain Model (DTM). The vertical quality of the reconstructed DEMs derived from the tri-stereo combination is analyzed with traditional and robust accuracy measurements, resulting in non-Gaussian distributions of errors, with a RMSE of 0.96 m (1.4 pixels) for Pléiades and of 0.37 m (1.2 pixels) for WorldView-3. When compared to a ground truth LiDAR DTM, the elevation differences show an undulation (~1.5 pixel), similar to waves that are visible in the along-track direction. In order to minimize this effect and the vertical error caused by horizontal and vertical offsets, the photogrammetrically derived DEMs are aligned to the reference DTM by applying an affine 3D transformation determined with the least squares matching (LSM) techniques. The results show improvements in the vertical accuracy to 0.61 m (0.9 pixels) and 0.24 m (0.7 pixels) for Pléiades and WorldView-3 tri-stereo scenes, respectively, and a decrease of the "wave-effect" to less than one pixel.

METHODOLY

Test Area

The selected area is the open area in side King Saud University campus, opposite faculty of engineering. Figures 1 (a) and b) show the test site area and surroundings. The topography of the area is not highly undulating varying between 640m and 652m above mean sea level.

(a) (b)

Fig. 1: Test Site Area (a) surroundings; (b) exact position.

Test Procedure

To assess WV-3 accuracy in elevation extraction and DEM formation, a test area is chosen where reliable ground truth is to be initiated using total station instrument.

The main job in this test include collection of height data. Two ground control points are used to tie the site area. A number of 180 points were well marked to be used in height accuracy and DEM formation. Figure 2 shows the distribution of the test points.

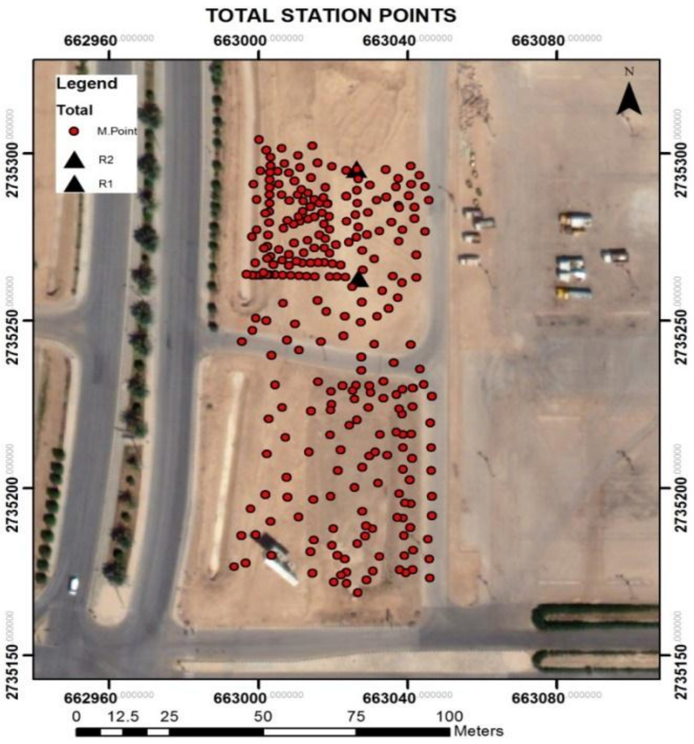


Fig. 2: Distribution of Control and Test Points.

Field work is carried out using TPS 1101 Leica total station to determine ground coordinates of all test points. A stereo pair of high resolution WV-3 satellite imagery was available to produce elevations for all test points and to form a DEM for the same area.

The instrument (Leica TPS 1101 total station) was set up at one control point, and the target set up at the other control point was observed for referencing and orientation. The final coordinates were saved as a new project file in the card memory. The coordinates of total station and object station are entered in the project. Then a reading is carried out for the object to tie the instrument with reference coordinate system of the coordinate points “UTM Zone 38 N, WGS 84, Mean Sea Level Datum”. Then the measurements of coordinates of the required points along strips inside the test area is carried out smoothly.

Generation of Dem from Wv-3 Stereo Imagery

Very High Resolution (VHR) optical satellites offers the most ever available overlapped area and Base to Height (B/H) ratio in satellite stereo images (Figure 3) which is really needed to produce high accuracy of image matching and thus in the resulting height accuracy for DEM formation.

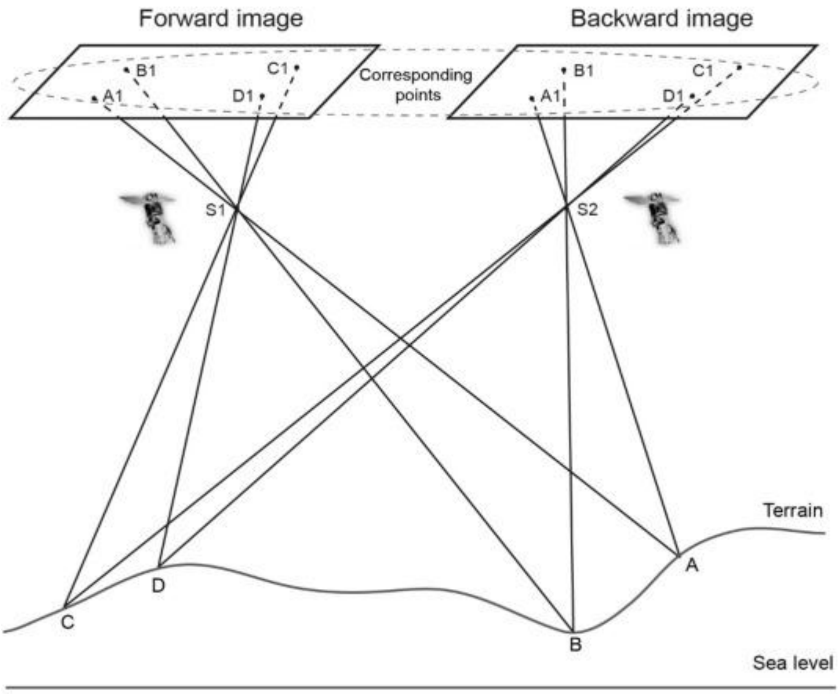


Fig. 3: DEM generation from stereo imagery (Wang, et al, 2019).

The Worldview series satellites allows short revisit period and enriches the satellite working mode to a large extent. The devices used make the stereo imaging process flexible. There are primarily two situations for the along-track stereo area collection, i.e. multiple-view stereo and stitched stereo. Both of them utilize the attitude maneuver ability of satellite, the former acquires stereo-images of the same target area from at least triple view angles, while the latter aims at achieving a wide ground coverage by acquisition of several stitched stereo-pairs, alleviating the restriction in swath width of sensor due to the enhancement of spatial resolution (Hu, et al, 2016). Taking the situation of dual stereo-pairs for instance, the stereo area covering a size of 26.6 km by 112 km at maximum is available. The test area in this research is considerably small and not undulating.

The workflow for DEM extraction from WV-3 stereo-images and accuracy evaluation is demonstrated in figure 4.

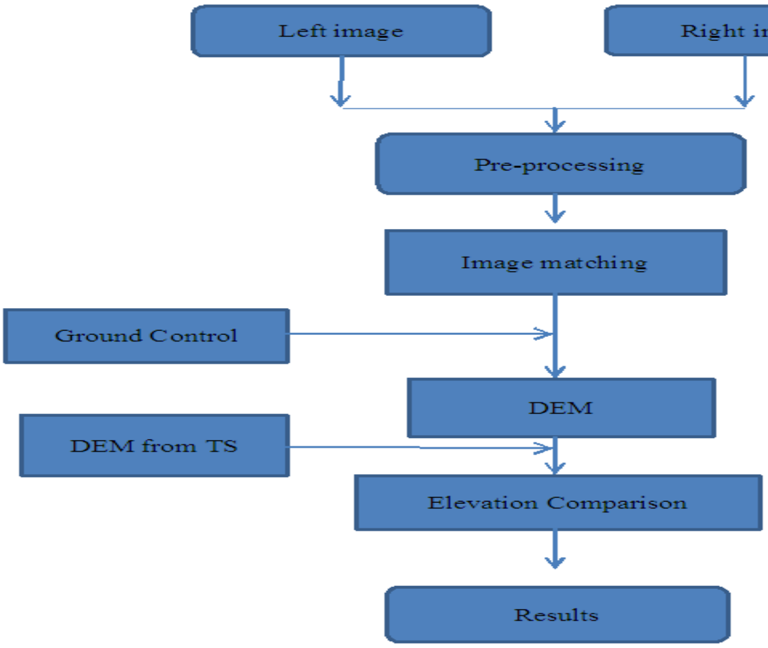


Fig. 4: Workflow for DEM generation and height accuracy testing.

The main steps of the test, shown on the workflow are explained as follows:

- Image point measurement of GCPs and tie points (TPs) for all test points. To generate high-accuracy DEM, GCPs these were measured semi automatically to high accuracy.
- Satellite images are subject to geometric distortions during acquisition. These distortions can be due to the acquisition system and the natural effects such as atmospheric refraction and earth topography (Brovelli et al, 2008). During pre-processing systematic image errors were removed using Rational Polynomial Functions (RPF) of known coefficients (Rational Polynomial Coefficients, RPC) provided by the company that manages the satellite using their proprietary rigorous models.
- Formation of stereo model can be created from quasi epi-polar images from the available stereo-pair after image error compensation, and carrying out density image matching, parallax and then elevation computing.
- Since the 3-D points automatically extracted by density image matching are all located on surface of the ground and targets, Digital Surface Model (DSM) instead of DEM is generated. To transform the DSM to DEM, particular manual editing and post-processing are needed for some regions within the model.
- Quantitative accuracy evaluation of DEM is done by comparing the WV-3 stereo-images derived DEM with the elevation of corresponding points already derived by TS observations.

RESULTS AND ANALYSIS

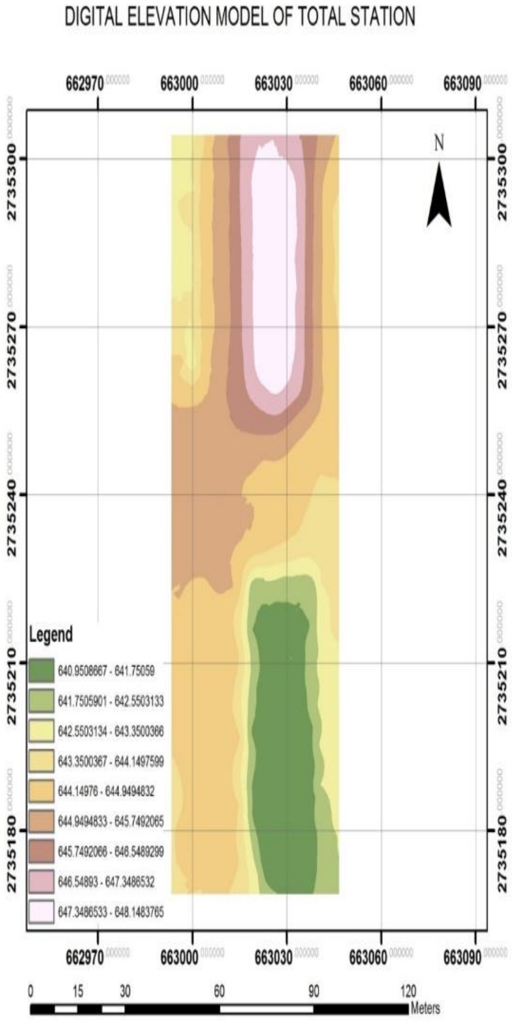


Fig. 5: TS DEM.

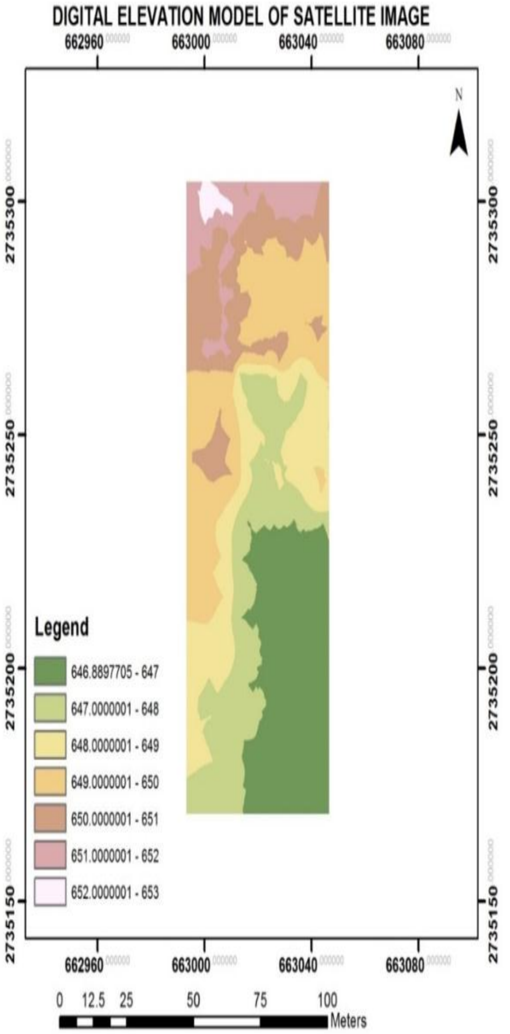


Fig. 6: WV-3 DEM.

DEM from TS Observations and WV-3 satellite stereo imagery are depicted by figures 5 and 6, respectively. In the former one, land elevation varies from 640.9m in the southern region of the test area to 647.3m in the north. In DEM from WV-3 imagery land elevation varies from 646.9m in the east-southern region of the test area to 651.m in the north.

Difference between DEM produced from TS and WV-3 imagery is produced by GIS program as in figure 7. Differences vary between 0.96m to 6.01m. Maximum variation appears to be in the south-east part of the test area. The statistical results are shown in figure 8.

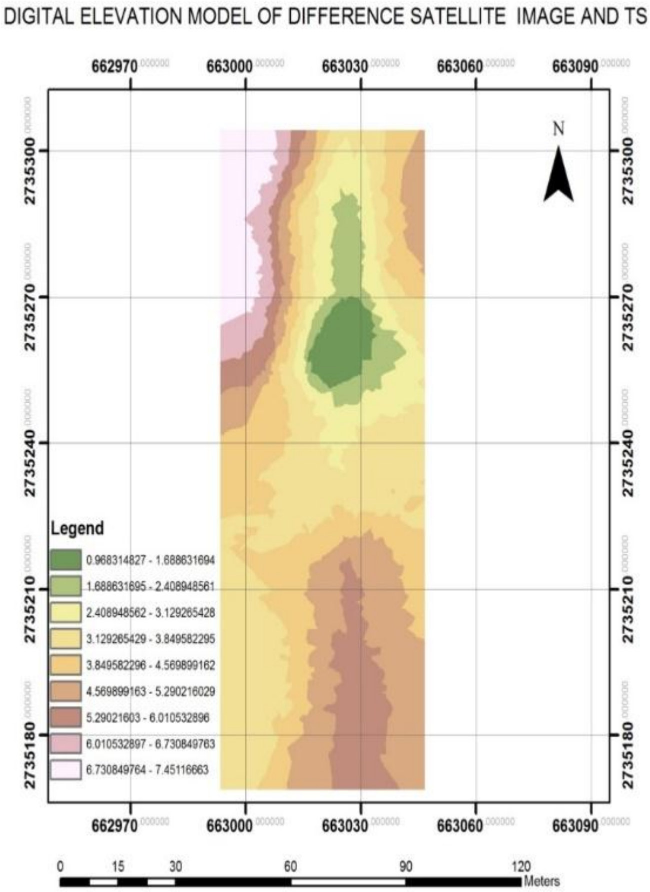
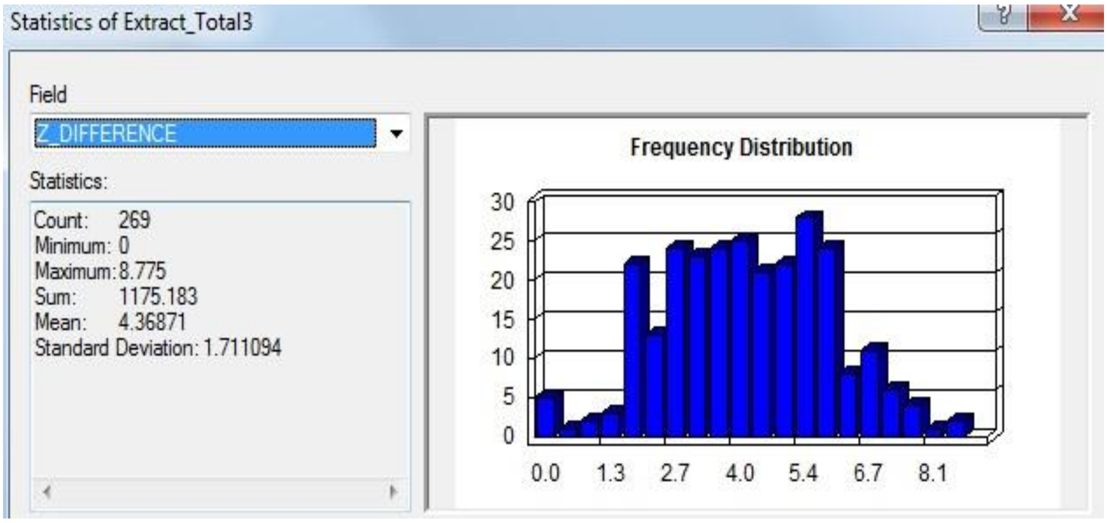


Fig. 7: Variations in DEMs between WV03 Imagery and Total Station.



Count: 269
Minimum: 0
Maximum: 8.775
Sum: 1175.183
Mean: 4.36871
Standard Deviation: 1.711094

Fig. 8: Statistical Results.

From statistical analysis minimum difference in elevation obtained using TS and WV-3 is 0.0m, while maximum difference is 8.8m. Root mean square error of difference is 4.3m and standard deviation of results from WV-3 imagery is 1.7m as compared to TS derived elevations.

In a previous study Hu, et al, 2016 carried out on testing height accuracy of WV-3 stereo imagery when forming DEM as compared to results from LIDAR and obtained mean error of vertical accuracy of 1.6m and standard error of 0.49m.

CONCLUSIONS

Test results in this study showed that the mean difference between elevations produced by WV-3 satellite stereo imagery and that from total station is 4.37m with standard deviation of 1.71m. According to Linear Map Accuracy Standard (LMAS) this height accuracy is capable of producing topographic maps of scale 1:5000 and smaller (Petrovic et al, 2017). This same conclusion was derived by Hu, et al, 2016.

Production of digital elevation models (DEM) from various stereo satellite sensors including the WorldView-3 satellite sensors at 30cm resolution can be very useful for project planners, emergency operation managers, and logistics managers to plan field operations in a computer environment, ensuring that the best terrain conditions and access is provided to achieve project objectives.

Elevation is a critical component of any earth observation, whether you're using a bare-earth digital terrain model or a detailed digital elevation model with ground features. As the accuracy of elevation observations have increased, on an ever-broadening scale, this data has grown in importance and utility.

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