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FEASIBILITY OF VERY HIGH RESOLUTION OPTICAL SATELLITE (VHROS) STEREO IMAGERY FOR TOPOGRAPHIC MAPPING

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ABSTRACT

The importance of Ground height determination is valid for various applications, especially in the fields of earthwork calculations needed for different constructions such as highways, railways and many other infra structures and in contour map production as well. Topographic maps and Digital Elevation Models (DEM) covering large areas can be generated by means of optical images taken from space. Very high resolution optical satellite stereo pairs of ground resolution better than one meter are now available and were tested for height determination accuracy. This paper is an attempt to collect and analyze test results of Very High Resolution Optical Satellite (VHROS) images as far as ground height accuracy and to validate their potentials in producing large scale topographic maps. Such VHROS include IKONOS, QUICKBIRD, Worldview-3, Pleiades and GeoEye-1 Satellite imagery.

KEYWORDS: Optical images, topographic mapping, DEM, stereo-pairs, Height Accuracy, GIS, VHRS.

INTRODUCTION

It is well known that position accuracy of plotting topographic maps is within 0.1mm in map scale. For example, a map of scale 1:25 00 requires position accuracy no larger than 0.25m on ground. For topographic mapping, height accuracy limit is governed by the following statements: Ninety percent (90%) of all elevations derived from solid line contours shall not deviate from true elevation by more than half a contour interval. The remaining ten percent (10%) shall be accurate to within a whole contour interval. Ninety percent (90%) of all plotted spot elevations shall be accurately positioned to within one fourth a contour interval. The remaining ten percent (10%) shall be accurate to within half a contour interval. NJDOT, 2009.

Stereo photogrammetric method is the traditional and cost efficient method, compared to ground surveying techniques, to acquire high accuracy elevation data over large surface areas. In stereo photogrammetric model, height of point measurement can be determined with accuracy ±0.08 per thousand of flying height above ground surface (Dörstel, 2003).

For stereo images acquired from altitude of approximately 5000 m above the mean ground level which lead to 50 cm ground sample distance (GSD), the root mean square error (RMSE) values of the adjusted ground point elevation is 1.187m (Tanhuanpää, et al, 2017).

As an example, Muller, et al, 2014 studied the absolute vertical accuracy of DEMs generated by the High Resolution Stereo Camera-Airborne (HRSC-A), the Leica Airborne Digital Sensors 40/80 (ADS40 and ADS80) and the analogue camera system RC30. The photogrammetrically derived DEMs are evaluated against geodetic field measurements and an airborne laser scan (ALS). The results show that all four sensor systems produce DEMs with similar accuracy despite their different setups and generations. The ADS40 and ADS80 (both with a Ground Sampling Distance (GSD) of 0.50 m) generate the most accurate DEMs in complex high mountain areas with a RMSE of 0.8 m. They also show the highest accuracy relating to flying height (0.14‰). The pushbroom scanning system HRSC-A produces a RMSE of 1.03 m. The analogue camera system RC30 produces DEMs with a vertical accuracy of 1.30 m RMSE (0.17‰ accuracy of the flying height and two times the GSD).

The preceding technique of Airborne Laser Scanning (ALS) provided the primary data source for very accurate DEM extraction of high spatial resolution with reported height accuracy between 15-25 cm (Aguilar and Mills 2008). The great advantage of this technology compared to aerial photogrammetric approach is the ability of capturing directly three-dimensional information in object space, based on the flight of a light signal between the sensor and the target (Vosselman and Maas, 2010). Nevertheless, the major limitations of ALS data are related to access restrictions and low temporal resolution.

Since more than three decades, the interest of photogrammetric community has turned to study the possibility of using satellite imagery for DEM extraction and topographic mapping in a timely and cost-effective manner, especially after the appearance of new various Very High Resolution Satellites. Compared with airborne remote sensing, the major advantages of satellite imagery is the large area coverage within a very short time (seconds), the worldwide availability without any limitations or access restrictions and the high temporal resolution (few days interval).

The possibility of DEM extraction from satellite stereoscopic images started in 1986, with the launch of the first SPOT series satellites. Since 1999 spatial resolutions in the range of less than one meter can now be achieved by means of satellite-supported images. Very High Resolution (VHR) optical sensors are able to acquire images comparable with those provided by aerial imagery, in terms of high GSD values (0.30 m). Moreover, they are able to collect not only stereo, but tri-stereo images for the same area during a single flight pass. Due to their short revisit time and stereo/tri-stereo capability, today, the new generation of VHR pushbroom satellite sensors, e.g., QuickBird, SkySat, Ziyuan-3A, GeoEye-1, Pléiades 1A/1B, WorldView-1,-2,-3 and -4 are used for DEM extraction and topographic maps production (Loghin, et al, 2019).

Therefore, a comprehensive comparison for scientific and commercial clients to choose appropriate satellite images and methods of topographic mapping and generating digital elevation models to obtain optimum results is urgently needed.

This article will thus give a review about the specifications of some VHR optical satellites. Then it will discuss the height accuracy capabilities for plotting and reviewing topographic maps and forming DEMs by introducing and comparing results obtained from VHRS imageries by different researchers.

Ground Spatial Resolution (GSR)

Ground Spatial Resolution (GSR) or Ground Sample Distance (GSD) is defined as the distance of the center of neighbored pixels projected on the ground (www.euspaceimaging.com/true-30-cm-imagery/) and refers to the smallest size an object or detail can be represented in an image. For example, 30cm resolution satellite imagery can capture details on the ground that are greater than or equal to 30cm by 30cm (Setyawan, 2019). Figures 1 and 2 illustrate the difference in GSR.

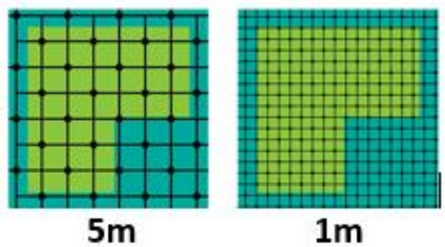

Figure 1: Comparison between 5m and 1m GSR.

Image of 30cm GSR **Image of 1m GSR**

Figure 2: Oil Refinery Taranto (www.euspaceimaging.com/true-30-cm-imagery/).

The optical images (photo images) to be used for mapping, therefore should have ground sampling distance (GSD) or GSR no larger than 0.5m which is satisfied by what is called Very High Resolution Satellites (VHRS).

The accuracy of products of processing VHRS imageries depends mainly on GSR of the image and on chosen geometrical sensor models. The geometrical sensor models of VHRS imageries is very important for improving processing of VHRS imageries. The polynomial models, physical or parametrical models which provide a simple, generic set of equations to represent the indirect relationship between the ground and its image can be found in, Luong and Woniewick, 2006. Many mathematical models, image processing software, algorithms and techniques are available to extract such information from VHRS images (Fareed, 2014; Jianya, et al, 2017; Liu, et al, 2018).

The Era of VHRS Imagery

The advent of very high resolution (VHR) optical satellites capable of producing stereo images led to a new era in extracting digital elevation model (DEM) and reviewing topographic maps. This commenced with the launch of IKONOS followed by QuickBird, WorldView-1 and WorldVew-2 launched by DigitalGlobe. Advanced Land Observing (ALOS) and GeoEye-1 were launched by Japan and GeoEye, respectively. In addition to aforementioned satellites, India initiated its own constellation by launching CartoSat-series. The availability of all so-called satellites make a huge market of stereo images for extracting of DEM and other correspondent applications such as, producing orthorectifcatin images and updating topographic maps (Deilami, et al., 2011).

Some of the VHRS (such as European Pleiades, Indian CartoSat-3 and American WorldView) that can produce imagery of better than 0.5m ground sampling distance (GSR) and which can allow height accuracy that may suit topographic map production have characteristics shown in Table 1 (Jacobsen, 2013).

Table 1: VHROS and GSR (from Jacobsen, 2013).

Satellite	GSD [m]	Archive
Pléiades Neo 3	0.30	2021
Cartosat-3	0.28	2019
WorldView-4	0.31	2017
WorldView-3	0.31	2014

The first VHROS imagery was obtained by the American Space Image IKONOS in 1999, providing 1 meter ground spatial resolution (GSR), opening the way for a series of VHRS such as Quickbird, ERS and OrbView, Luong and Wolniewicz, 2006. These are then followed by

VHRS images of better than 1 meter GSR. Table 2 shows USA VHRS specifications (Deilami, et al, 2011).

Table 2: USA VHRS (from Deilami and Mazlan, 2011).

Images	Company	Date of Launch	GSD (m)	Flying Height (km)
IKONOS 2	Space Imaging	1999	0.82	680
Quickbird 2	Digital Globe	2001	0.61	450
WorldView 1	Digital Globe	2006	0.50	770
OrbView 3	OrbImage	2002	1.00	470
OrbView 5	OrbImage	2006	0.41	470

The pixel size of IKONOS satellite image of pixel size 15µm contains information corresponding to the aerial images in scale 1:80 000 and information content of QuickBird image with 11µm pixel size are compared with the aerial images in scale 1:50 000. Therefore, IKONOS and QuicBird images can theoretically be used to topographic mapping up to map scale 1: 10 000 and 1:6 000, (Jacobsen, 2005).

Results and Discussion of Height Tests of VHRS Imageries

IKONOS: Geometric accuracy of IKONOS images was verified by Grodecki and Dial, 2001 and 2002, during the On-Orbit Acceptance Test (OOAT), using the San Diego test range consisting of 140 ground control points (GCP) over a 22 by 22km area [Grodecki and Dial, 2001]. The OOAT results indicated that the absolute horizontal and vertical accuracy of uncontrolled IKONOS stereo images – block adjusted without GCPs – was better than 6 m. The absolute horizontal and vertical accuracy of GCP-controlled stereo images was determined to be better than 2 m. Residual errors after bias and drift correction are 0.5 meters RMS (Grodecki and Dial, 2002). There are different studies of accuracy assessment of IKONOS, for instance, the mapping accuracy of the stereo images with GCPs was reported as 1.32m RMSE in horizontal direction and 1.82m RMSE in vertical direction by Grodecki and Dial, (2002). The mathematical model, presented in Toutin (2002), is based on the collinearity condition and represents the physical realities of the full viewing geometry and the platform-sensor- Earth relations with using 13 panchromatic and multispectral IKONOS images over seven study sites. Gruen, et al, 2005 proposed multi image matching, an advanced image matching approach for automatic DSM generation which can provide precise and reliable results. The outputs showed the accuracy of 2-3m RMSE error for the whole area while for bare ground was about 1m or even better.

IKONOS and QUICKBIRD: Eisenbeiss, et al, 2004 described the processing of IKONOS and QUICKBIRD imagery of two different datasets in Switzerland for analyzing the geometric accuracy potential of these images for 3D point positioning, and orthoimage and DSM generation. The first dataset consists of panchromatic and multispectral IKONOS and QUICKBIRD images covering the region of Geneva. In the second area around Thun with a ground height range of 1650 m, the dataset consisted of a triplet and a stereo pair with an overlap of 50 %. GCPs with an accuracy of 0.2-0.4 m have been used in both sites. The investigations for 3D point positioning included 4 different sensor models, different GCP measurement, variable number of control points and area covered by them. The results showed that the Rational Polynomial Coefficient (RPC) model compared to 2D and 3D affine models are more general and can model sufficiently imaging modes that depart from linearity. This is particular so for QUICKBIRD which needs after the use of RPCs an additional affine transformation in order to reach accuracies of 1m or less. With sufficient modeling, the planimetric accuracy was 0.4 – 0.5 m, even for few GCPs and only partly covering the images. Orthoimages were generated from both QUICKBIRD and IKONOS with an accuracy of 0.5-0.8 m, using a laser DTM. A sophisticated matching algorithm was employed in Thun. In spite of various difficult conditions like snow, long shadows, occlusions due to mountains etc., the achieved accuracy without any manual editing, was 1-5 m depending on the land cover type, while in open areas it was about 1 m. Under normal conditions, this accuracy could be pushed down to about 0.5 m. Thus, IKONOS, and to a lesser degree QUICKBIRD, could be an attractive alternative for DSM generation worldwide. A summary of results of testing IKONOS imagery is also given in Table 3 (Rozycki, & Wolniewicz, 2007). It is deduced that the larger number of GCPts the better is the height accuracy.

Table 3: Comparison of RMSE of Different Number of GCP (Rozycki, & Wolniewicz, 2007).

Number of GCP	**0**	**5**	**10**	**15**	**18**	**21**	**25**
RMSE on CP (m)	7.7	3.8	3.0	2.7	2.39	2.14	2.01

GeoEye-1 is the other member of GeoEye constellation which can collect images with a ground resolution of 0.41-meters in black and white mode. The GeoEye-1 satellite sensor was successfully launched by Digital Globe on September 6, 2008 and is capable of acquiring image data at 0.46 meter panchromatic (B&W) and 1.84 meter multispectral resolution. It also features a revisit time of less than three days, as well as the ability to locate an object within just three meters of its physical location. This sensor is optimized for large projects, as it can produce over 350,000 square kilometers of pan-sharpened multispectral satellite imagery every day. GeoEye-1 has been flying at an altitude of about 681 kilometers and is capable of producing imagery with a ground sampling distance of 46 centimeters, meaning it can detect objects of that diameter or greater.

During late summer of 2013 the orbit altitude of the GeoEye-1 satellite sensor was raised to 770 Km/ 478 Miles. GeoEye-1 new nadir ground sample distance (GSD) is 46cm compared to the previous GSD of 41cm. Meguro and Fraser 2012 investigated the georeferencing accuracy attainable from the GeoEye-1 satellite, and specifically the 3D accuracy achievable from stereo imagery. Both direct georeferencing via supplied RPCs and indirect georeferencing via GC and bias-corrected RPCs were examined for a stereo pair of pansharpened GeoEye-1 Basic images covering the Tsukuba Test Field in Japan, which contains more than 100 precisely surveyed and image identifiable GCPs. The results obtained, indicated that the direct georeferencing accuracy obtained was within that specified for GeoEye-1, namely a 2m Circular Error 90% (CE90) in planimetry and a 3m Linear Error 90% (LE90) in height. The use of a few GCPs improved geopositioning accuracy to around 0.35m (0.7 pixel) in planimetry and 0.7m (1.4 pixel) in height. Meguro and Fraser (2010) reported an accuracy of 0.35m in planimetry and 0.7m in height, Fraser and Ravanbakhsh (2009) reported an accuracy reaching 0.10m in planimetry and 0.25m in height. Fraser and Ravanbakhsh, 2009 described an experimental assessment of the accuracy of georeferencing from GeoEye-1 imagery. A stereo panchromatic image pair covering the Hobart HRSI test field in Australia was utilized in the testing. They highlighted the fact that with bias-corrected RPCs and a single GCP, the RMSE georeferencing accuracy reaches the unprecedented level of 0.10m (0.2 pixel) in planimetry and 0.25m in height. Saldana, et al, 2012 carried out an accuracy assessment test on the DSMs extracted from a GeoEye-1 stereopair captured in August 2011. A LiDAR derived DSM taken at the same month that the satellite imagery was used as ground truth. Different sets of GCPs ranging from 7 to 45, two sensor models and two geoids (EGM96 and EGM08, the last adapted for Spain vertical network by the Spanish's National Geographic Institute) were tested in this work. The photogrammetric software package used was OrthoEngine from PCI Geomatica v. 10.3.2. OrthoEngine implements both sensor models tested: (i) the physical model developed by Toutin (CCRS) and, (ii) the Rational Function Model using Rational Polynomial Coefficients supplied by the vendor and later refined by means of the zero order linear functions (RPC0). When high accurate and well-distributed GCPs were used, the planimetric and vertical accuracies of DSMs generated from the GeoEye-1 Geo stereopair were always better than 0.5 m. Using only 7 GCPs and RPC0, a vertical accuracy around 0.43 m measured as standard deviation was attained. The geoid used by OrthoEngine (EGM96) produced similar results that the EGM08 adapted for Spain vertical network.

QuickBird launched by The Digital Globe offers most agile and sophisticated constellation of high-resolution commercial earth imaging satellites with several technical advantages such as, outstanding geolocation accuracy and a global collection of panchromatic and multispectral images. Quickbird is a sun-synchronous satellite, placed on the altitude of 450 km and provides the revisit time of 2-3 days with an in-track / across –track viewing angle. QuickBird Basic Stereo Pairs are collected in-track, generally at 30º off-nadir (fore-aft) and within 10º of the ground track. (Digital Globe, 2003). A test has been conducted to evaluate the mean accuracy of two Digital Surface Models (DSMs) respectively extracted from a Quickbird in-track Basic Stereo imagery and from two Quickbird Standard Orthoready imageries partially overlapped acquired during two different orbital tracks by Crespi et al. (2006). The two tests showed that accuracy at 1 meter level or better may be achieved in DSM extraction from Basic Stereo. Further, DSMs extracted from pairs of Standard Orthoready imagery acquired on different tracks may reach accuracy at 2 meter level, provided the acquisition geometry is good. In addition, the extracted DEM of QuickBird stereoimages showed an averaged difference of 3m for gentle to moderate terrain and up to 30 m for rugged terrain in vertical values (Cheng and Chaapel, 2008).

Yanalak, et al, 2012 investigated the accuracy of Digital Elevation Models (DEMs) generated from two different satellite data namely OrbView-3 with 1 meter GSD and IKONOS stereo images using 21 GCPs (Ground Control Points), 182 CPs (Check Points). Two DEMs were generated from OrbView-3 and one DEM from IKONOS stereo data. The results were analyzed with the empirical accuracy criterion for heights on analog maps (Table 4).

Table 4: Accuracy of DEMs from IKONOS and OrbView Imageries (Yanalak, et al, 2012).

SAT	IKONOS (DEM1)	OrbView (DEM2)	OrbView (DEM3)
Max Error (m)	2.4	1.8	2.7
RMSE (m)	0.80	0.80	1.1

The same results were obtained by Elif, et al, 2012 who investigated the accuracy obtained from the DEMs created from IKONOS and OrbView-3 stereo images, where RMSE values for heights were calculated for DEM1 (IKONOS), DEM2 (OrbView 3) and DEM3 (OrbView 3) with RMSEs of 0.90m, 0.90m and 1.10m and maximum errors of 2.6m, 2.0m and 2.7m respectively.

WorldView-1 (WV-1) and WorldView-2 (WV-2) are the initial members of DigitalGlobe series. Worldview-1 images the earth in sun-synchronous orbit, 496 km above the earth which has an average revisit time of 1.7 days at 1 m GSD or less and 5.4 days at 25° off-nadir or less (59 cm GSD). In comparison, WorldView- 2 was placed on the altitude of 770 km with the revisit frequency of 1.1 days at 1 meter GSD or less and 3.7 days at 20° off-nadir or less (0.52 meter GSD). On August 13th, 2014, DigitalGlobe has launched Worldview-3 (WV-3) which is the inheritance and development of Worldview-2 into orbit. Worldview series became so popular because they offer the potential to extract high quality DSM/DEM (Digital Surface Model /Digital Elevation Model) products from their stereo-images. Hu, et al, 2016 validated the potentials of WV-3 satellite images in large scale topographic mapping, by demonstrating that, for Worldview-3 stereoimages the planimetric accuracy without GCPs is about 2.16 m (mean error) and 0.55 (std. error), which is superior to the nominal value, while the vertical accuracy is about -1.61 m (mean error) and 0.49 m (std. error); with a small amount of GCPs located in the center and four corners of the test area, the systematic error can be well compensated. The std. value of elevation biases between the generated DEM and the 7256 LiDAR check points are about 0.62 m. It is concluded from the results hat WV-3 has the potential for 1:5000 or even larger scale mapping application. Elhassan, 2020 compared height results from WV-3 stereo pair and those from total station, using 180 check points. Results showed standard deviation difference of 1.71m. Loghin, et al, 2019 reported that the vertical accuracy 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 WV-3.

The excellent performance of geometric positioning of a newly Chinese launched satellite will greatly broaden its application field. Launched on January 15, 2020, the Hongqi-1-H9 wide-range satellite is the largest sub-meter-level satellite worldwide and the first ton-level commercial remote sensing satellite in China, with a resolution of less than 1 m and a swath width of 136 km. Song, et al, 2021 assessed the geometric positioning accuracy of this newly launched satellite considering three aspects, namely, the circle error accuracy, rational polynomial coefficient-based direct geometric positioning accuracy and ground control point-based absolute positioning accuracy under urban, plain, and mountainous areas, with different topographies. It has been found that Hongqi-1-H9 wide-range satellite exhibits the highest geometric positioning performance in the plain area, with a positioning accuracy of 3.24 m, 1.66m, and 1.75 m in the latitudinal, longitudinal, and elevation directions, respectively, when using the five GPS points. For the urban area, the positioning accuracy is slightly poor: 3.48 m, 4.48 m, and 2.73 m in the latitudinal, longitudinal, and elevation directions, respectively. Specifically, for areas with a low topography and few surface structures, the geometric positioning accuracy of the Hongqi-1-H9 wide-range satellite imagery can be less than 4 m and 2 m in the planimetry and elevation directions.

The Indian Space Research Organisation (ISRO) on Wednesday placed into orbit its most sophisticated and advanced earth imaging and mapping satellite Cartosat-3 with the highest camera resolution of 25 cm. The satellite, which is the ninth in the series and will replace the Indian Remote Sensing Satellite (IRS) series, was launched from Satish Dhawan Space Centre's (SDSC) Sriharikota at 9.28 am along with 13 commercial nano-satellites from USA. The satellite was placed into orbit 17 minutes and 46 seconds after lift-off at 9.28 AM (Titarov, 2008). Titarov, 2008 tested Cartosat-1 stereo imageries using RPC model resulting in DEM of accuracy 2m RMSE for flat area and 7m for mountainous area and created orthoimage of geometric accuracy that allows 1:10000 scale maps. Ashutosh, 2013 evaluated the accuracy of triangulation, DEM and orthoimage generated from Cartosat-1 satellite stero Panchromaic data for various terrain features, using Rational Polynomial Coefficient (RPCs) and 18 GCPts obtained by Differential Global Positioning System (12 used as Control Points and 6 as Check Points). Results showed height accuracy of 3.72m and planimetric accuracy of 2.72m. Radhadevi, et al, 2018 assessed the mapping potential of high-resolution Cartosat-1 and Cartosat-2. The geometric accuracy achieved from Cartosat-1 and Cartosat-2 images for topographic feature capture are good enough for making 1:10000 scale maps. Geometric accuracy and feature detectability of Cartosat-2 indicate that it is capable of making 1:7000 scale maps. Giribabu, et al, 2013 compared DEMs generated from Cartosat-1 data using forward, reverse and other possible synthetic stereo pairs for two different types of topographies. Stereo triplet was used to generate DEM for Himalayan mountain topography giving planimetric and height accuracy RMSE of less than 2.5 m and 2.95 m respectively. For rugged terrain and steep slopes of Himalayan mountain topography simple stereo pairs may not provide reliable accuracies in DEMs due to occlusions and shadows. Stereo triplet from Cartosat-1 was used to generate DEM for mountainous topography. This DEM shows better reconstruction of elevation model even at occluded region when compared with simple stereo pair based DEM. Planimetric and height accuracy (RMSE) of nearly 3 m were obtained and qualitative analysis shows reduction of outliers at occluded region. Cartosat-3 launched in November 2019 continued its successful run of using the Polar Satellite Launch Vehicle (PSLV) to place satellites in space. The panchromatic imager onboard can capture the Earth’s surface at resolutions up to 25cm. Unfortunately no height test results for CartoSat-3 imagery are obtained yet.

The European Pléiades satellite system is a dual system comprising the two identical satellites Pléiades-1A and Pléiades-1B. They have been launched in December 2011 and in December 2012, respectively, both providing VHR image data. The satellites operate in the same orbit with an offset of 180 degrees to offer a daily revisit capacity. They also share the same orbit as the satellites Spot-6 and Spot-7 but are positioned 90 degrees phase shifted. They are supplied with remarkable agility, as the pointing angles can be triggered in a range of ±47 degrees (standard mode ±30 degrees). The sensors are capable of acquiring a panchromatic band (470–830 nm) with 0.7 m GSD at nadir and four multi-spectral bands (blue: 430–550 nm; green: 500–620 nm; red: 590–710 nm; near-infrared: 740–940 nm) with 2.8 m GSD. Images of the Pléiades sensor get delivered as a bundle of a panchromatic band upsampled to 0.5 m GSD and multi-spectral bands at 2.0 m GSD in GeoTIFF or JPEG format. Thus, a variety of data sets showing different acquisition scenarios are gathered, all over comprising 24 Pléiades images. First, the accuracies of the 2D and 3D geo-location are analyzed. Second, surface and terrain models are evaluated, including a critical look on the underlying error metrics and discussing the differences of single stereo, tri-stereo and multi-view data sets. Overall, 3D accuracies in the range of 0.2 to 0.3 m in planimetry and 0.2 to 0.4 m in height are achieved with respect to ground control points. Retrieved surface models show normalized median absolute deviations around 0.9 m in comparison to reference LiDAR data. Multi-view stereo outperforms single stereo in terms of accuracy and completeness of the resulting surface models. (Perko, et al, 2019). Poli, et al, 2015, tested 3 of the HRS images: GeoEye-1, WV-2 and Pleadis-1. They have arrived to the results shown in Table 5.

Table 5: Plan and Height Accuracy of VHRS images: GeoEye-1, WV-2 and Pleadis-1 (Poli, et al, 2015).

Image	Geo-Eye-1	WV-2	Pleiades1
Plan (m)	7.1	7.4	6.5
Height (m)	7.9	8.5	8.5

Perko, et al, 2018 presented methodologies and workflows within the fields of remote sensing and computer vision that are used (1) to densely reconstruct digital surface models (DSM), (2) to derive digital terrain models (DTM), and (3) to generate multi-spectral ortho-rectified products. An assessment was performed on two distinct test sites discussing the initial 2D geo-location accuracy of the given sensor models. An optimization scheme is presented to adjust the given RPC models yielding 3D geo-location accuracies of 0.5 m in planimetry and 1 m in height. In their work, Perko, et al, 2019 introduced an end-to-end workflow for very high-resolution satellite-based mapping, building the basis for important 3D mapping products: (1) digital surface model, (2) digital terrain model, (3) normalized digital surface model and (4) ortho-rectified image mosaic. Their workflow was demonstrated for the Pléiades satellite constellation. The second aim of their study was a detailed assessment of the resulting output products. Thus, a variety of data sets showing different acquisition scenarios are gathered, all over comprising 24 Pléiades images. First, the accuracies of the 2D and 3D geo-location were analyzed. Second, surface and terrain models are evaluated, including a critical look on the underlying error metrics and discussing the differences of single stereo, tri-stereo and multi-view data sets. Overall, 3D accuracies in the range of 0.2 to 0.3 m in planimetry and 0.2 to 0.4 m in height are achieved with respect to ground control points. Retrieved surface models show normalized median absolute deviations around 0.9 m in comparison to reference LiDAR data. Multi-view stereo outperforms single stereo in terms of accuracy and completeness of the resulting surface models. Similar to the present VHR missions of Ikonos and WorldView, stereo data can be acquired during one overflight (single pass) through an appropriate forward and backward arrangement of the sensor. A significant innovation and advantage of Pléiades, however, is provided through the capability to acquire even three images for an area, taken from the same orbit at along track forward-, nadir- and backward-view of the sensor and through the possibility of an across track swipe. Such image triplets are also denoted as tri-stereo data sets. In addition to that, the Pléiades sensors are also able to steer in across track direction such that they can collect images over the same scene on ground from different orbits yielding also across track stereo pairs.

The second test is based on the Ljubljana set, where the 3D geo-location accuracy is evaluated using GCPs and ICPs found to be within 1 m in height. After adjustment, the majority of pairs yield high accuracies for the GCPs in planimetry of 0.2 m to 0.3 m and also in height of 0.2 m to 0.4 m. Actually, an accuracy at this level was never achieved before and is based on the highly accurate reference data. The statistics of ICPs are, as expected, a bit worse but no overfitting is observed. Figure 3 (Perko, et al, 2018) shows the 3D errors for GCPs and ICPs sorted w.r.t. the ICPs.

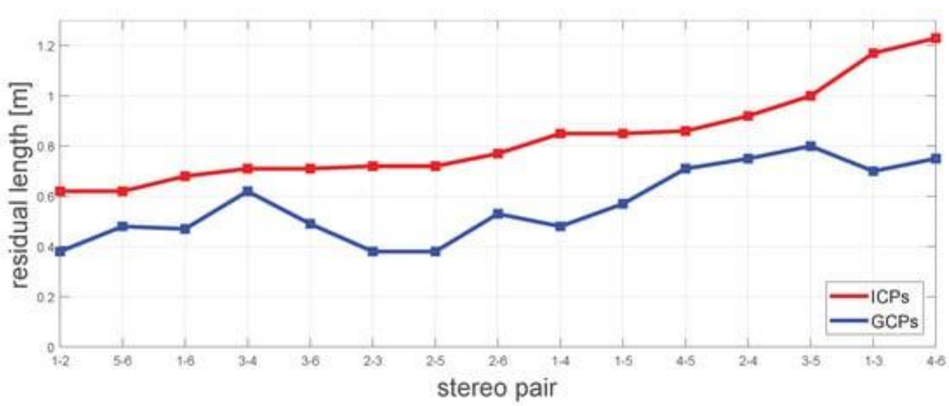

Figure 3: The 3D length discrepancies for the Ljubljana set sorted from lowest to highest ICP error. ICP values are given in red and corresponding GCP values in blue (Perko, et al, 2018).

Xiongwei, et al, 2018 described the processing carried out on Pleiades, ZY-3, TH-1, ALOS and SPOT6 in a geometric accuracy test field. All the results are compared under conditions both without and with GCPs, and whether in orientation with single image or in block adjustment. The performance of Pleaides is the best. Four GCPs laid in the corners is a good layout scheme, and is thus recommended.

Loghin, et al, 2019 analyzed the vertical quality of the reconstructed DEMs derived from the tri-stereo combination of Pleiades and WV-3 imageries 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 WV-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. The application of the affine 3D transformation brought improvements in the vertical accuracy of the tri-stereo DEMs from 0.96 m (1.4 pixels) to 0.61 m (0.9 pixels) for Pléiades and from 0.37 m (1.2 pixels) to 0.24 m (0.7 pixels) for WorldView-3. For both sensors, the computed RMSE values vary from 0.77 to 1.15 GSD after applying the LSM transformation. These are comparable with the reported vertical accuracies for airborne photogrammetrically derived DEMs, which are between 0.44 and 2 GSD. Results obtained by Postelniak, 2014 on testing Pleiades stereo imagery showed that a strong positive correlation between reference-derived elevations and DSM-derived elevations can be observed, and the orthorectified image accuracy, generated using that DSM, approximately equal to 1 m can be achieved using a bias compensation sensor model. The georeferencing accuracy of Pleiades stereo imagery was also estimated by Topan, et al, 2019 resulting in a 3D standard deviation of ± 0.44 m in X direction, ± 0.51 m in Y direction and ± 1.82 m in the Z direction. The generated digital surface/terrain models were achieved with ± 1.6 m standard deviation in Z direction in relation to a reference digital terrain model. Tampubolon, et al, 2020 concluded that height accuracy from VHRS WV-3 and Pleiades are 3.5m and 5.0m respectively. Pleiades Neo

Satellite Sensor Specifications was launched on 28th of April 2021, resolution 30cm, with 7 spectral bands and swath width of 14km at Nadir and expected life span of 10 years would be expected to give better height accuracy.

Summary of height accuracy from VHRS stereo imageries of given GSD as reported in the present article from various researches is given in Table 6.

Table 6: GSD, Height RMSE and RMSE/GSD ratio for VHRS Stereo Imageries.

Satellite	GSD (m)	RMSE (m)	RMSE/GSD
IKONOS	0.81	0.80	0.99
QuickBird	0.62	0.80	1.3
OrbView-3	1.00	0.80	0.8
Worldview-3	0.31	0.24	0.8
GeoEye-1	0.41	0.25	0.6
Pleiades	0.70	0.20	0.3

CONCLUSIONS

VHROS stereo images (with GSD less than 1m) can fairly be used to produce topographic maps with 2m contour interval, which is suitable for town planning topographic maps of scale 1:10000.

Height accuracy obtained from VHROS stereo imageries is not exactly directly proportional to GSD, since there are other factors that affect height accuracy like the mathematical model used. GSD, however is a good indicator to height accuracy that can be achieved from VHRS stereo imageries.

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