Accuracy Analysis of Digital Elevation Models from very High Resolution Satellite Imagery

ANA-MARIA LOGHIN¹, JOHANNES OTEPKA¹, WILFRIED KAREL¹, MARKUS PÖCHTRAGER¹ & NORBERT PFEIFER¹

Abstract: In recent years, the derivation of Digital Elevation Models (DEMs) from very high resolution stereo satellite imagery has become an interesting option and research topic, because the sub-meter GSD (Ground Sampling Distance) suggests that accuracy in the dm domain is possible. Current optical earth observation satellites are able to collect multi-view images of the same area during a single pass, and thus satellite imagery became an important source for 3D information extraction.

Photogrammetrically derived DEMs play a significant role in many engineering, land planning, geomorphology, forestry and infrastructure applications. To guarantee reasonable analyses in the multiple applications, surface models with high quality are needed. While previous research demonstrates the potential of Very High Resolution (VHR) stereo / tri-stereo satellite imagery for DEM reconstruction, questions about the accuracy of the derived models and their noise-induced roughness were not fully investigated. Therefore, the main focus of this contribution is to analyse and assess the potential in geometric quality of DEMs generated from high-resolution Pléiades and WorldView-3 stereo and tri-stereo scenes. We study 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 690 m a.s.l. 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). We focus on the assessment analyses in free, open and smooth areas, without any vegetation or artificial structures like buildings or infrastructure. For this, a mask derived from available LiDAR DSM and DTM was used. 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.

¹ Technische Universität Wien, Department of Geodesy and Geoinformation (GEO), Gu
ßhausstra
ße 27-29/E120, A-1040 Wien, E-Mail: [ana-maria.loghin, Johannes.Otepka, Wilfried.Karel, markus.poechtrager, Norbert.Pfeifer]@geo.tuwien.ac.at

1 Introduction

Digital Elevation Models (DEMs), mathematically describing the terrain surface topography, play an essential role in GIS and environmental modelling, having applications in agriculture, geomorphology, forestry, natural resources, disaster management, urban planning and engineering. To guarantee reasonable analyses for multiple applications, surface models with high quality are needed. Airborne Laser Scanning (ALS) active systems are the primary data source for accurate DEM extraction of high spatial resolution (CONTRERAS et al. 2017; HABIB et al. 2005) with reported height accuracy between 15-25 cm (AGUILAR & MILLS 2008; GATZIOLIS & ANDERSEN 2008; LIU et al. 2007). The great advantage of this technology 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 & MAAS 2010). Nevertheless, the major limitations of ALS data are related to access restrictions and low temporal resolution. On the other hand, multi view aerial imagery is the traditional and cost efficient method to acquire high resolution elevation data over large surface areas. Depending on the Ground Sample Distance (GSD) of the used sensor, the best vertical accuracies of airborne photogrammetrically derived DEMs vary between 0.44 and 2 GSD (BÜHLER et al. 2012; HOBI & GINZLER 2012; HOFFMANN & LEHMANN 2000; HU et al. 2008; RESSL et al. 2016). Since more than thirty years, the interest of the scientific community has turned to the potential of satellite imagery for DEM extraction in a timely and cost-effective manner, with the possibility of providing almost real time data. 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 (TOUTIN & CHENG 2002). Since 1999, thanks to the continuous development of the remote sensing systems, 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.

In this study, we consider two different VHR tri-stereo satellite systems, namely Pléiades and WorldView-3 for our analyses. The Pléiades constellation comprises two identical satellites, Pléiades-1A and Pléiades-1B, that were launched in December 2011 and December 2012, respectively. Both satellites are flying at 694 km altitude, in sun-synchronous orbits (98.2° inclination), with an offset of 180° from each other, which provides a daily revisit interval (ZHOU et al 2015). For the tri-stereo acquisitions, the B/H ratios (baseline/height) vary between 0.1 and 0.5 with corresponding stereo angles of ~6° to 28° (DE LUSSY et al. 2006). The sensor is able to collect panchromatic and multispectral images at nominal resolutions of 0.5 m and 2 m, respectively. The WorldView-3 high resolution commercial satellite was launched in August 2014. Operating at an altitude of 617 km, the sensor has an average revisit time of less than one day and is capable to collect up to 680 000 km² daily. WorldView-3 provides panchromatic, multispectral and short wave infrared imagery of 0.31 m, 1.24 m and 3.7 m resolutions, respectively, both in stereo (forward and back-ward view) and tri-stereo (forward, nadir and backward view) acquisition mode.

The potential of surface modelling from VHR satellite imagery and the advantages of using tristereo instead of stereo images for generating height models has been addressed in various publications. BERNARD et al. (2012) showed that by using tri-stereo configurations, reliable surface models can be obtained in urban areas. For a number of 295 ground control points, they report a Root Mean Square Error (RMSE) of 0.49 m in height. PERKO et al. (2014) assessed the mapping potential of Pléiades stereo/tri-stereo scenes, obtaining 3D geolocation accuracies of 0.5 m in planimetry and of 1 m in height. The results obtained by PANAGIOTAKIS et al. (2018) show that the DSM produced with tri-stereo analysis has better performances in terms of RMSEz (1.17 m), compared with the stereo-pair DSMs that perform worse (RMSEz of 1.48 m for forward-backward and of 1.64 m for forward-nadir). Additionally, DEMs derived by using Pléiades stereo/tri-stereo acquisitions were used for estimating lava flow volumes (BAGNARDI et al. 2016) and changes in height produced by earthquakes (ZHOU et al. 2015). After coregistration procedures based on crosscorrelation and iterative closest point, ZHOU et al. (2015) reported a 0.5 m standard deviation of heights, when comparing the Pléiades DEM with an airborne LiDAR DEM. The DSM extraction from WorldView-3 stereo-images is evaluated in Hu et al. (2016), where the elevation biases between the generated DEM and 7256 LiDAR check points are about 0.62 m.

In contrast to the previous research that demonstrates the capacity of Very High Resolution (VHR) satellite imagery for DEM reconstruction, in our study we investigate the potential of Pléiades and WorldView-3 stereo and tri-stereo scenes for DEM generation in open free, areas, where the DSM can be considered as DTM. Moreover, our study is, to the best to our knowledge, the first to assess the accuracy of DSMs derived from WorldView-3 tri-stereo scenes.

Specifically, our research study has as main purpose finding the answers to the folowing questions: (1) what is the impact of the different acquisition geometries (stereo / tri-stereo, ground sample distance, viewing and incidence angles) on DEM derivation, (2) which image combination produces the highest DEM accuracy and (3) what is the influence of spatial resolution and interpolation on the estimated surface roughness? To do so, we used Pléiades and WorldView-3 tri-stereo satellite imagery over a ~214 km² study area, located in Lower Austria. The absolute vertical accuracy of the photogrammetrically derived DEMs is evaluated against measured GCPs by means of Real Time Kinematic (RTK) and a LiDAR derived DTM. We focus on the assessment analyses in free, open and smooth areas, without any vegetation or artificial structures like buildings or infrastructure

2 Study area and Image Data Sets

The study area, located in Allentsteig, Lower Austria (48° 30' 30"N; 15° 08' 34"E; WGS84, 33N) is a hilly region with elevations between 300 m and 690 m a.s.l. The territory is covered mainly by arable lands and coniferous forests, the urban, suburban and rural areas being also present, but covering only a small area, compared with the entire extend. For the present study area, analyses were conducted using tri-stereo satellite images from two different VHR optical sensors: Pléiades-1B and WorldView-3 (Fig. 1). Each triple consists of three images, acquired from different along-track positions of the satellite: forward (F), close to nadir (N) and backward view (B).



Fig. 1: Study area and acquisition geometries of Pléiades (blue) and WorldView-3 sensors (orange) (view of the satellite positions and acquisition footprints in Google Earth)

The Pléiades tri-stereo data for Allentsteig area were acquired in the morning of 13 June 2017, around 10:10 a.m in North-South direction. Due to the high speed (~ 7.5 km/s) the sensor mounted on PHR1B platform was able to cover 159 km² within 23 seconds. The average viewing angles in along-track direction with respect to the nadir are 5.66°, 0.46° and -5.19°, respectively, for the forward, nadir and backward Pléiades images (Fig. 2). Based on the total travelled distance (167.8 km) and the orbit height (694 km), the baseline to height ratios (B/H) are of 0.13 (FN), 0.11 (NB) and 0.24 (FB) for each pairwise combination, with the corresponding convergence angles on the ground of 7.5° (FN), 6.3° (NB) and 13.8° (FB).

Sensor type			GSD	View	ing Angle/	es (°)		Conver-
& Acquisition date	Acquisition Time	View	(m) Along track	Across	Along	Overall	B / H Ra- tio	gence An- gle (°)
Pléiades 13-06-2017	10:09:51.5	Forward	0.71	3.15	5.66	6.47	0.13(FN)	7.5 (FN)
	10:10:03.7	Nadir	0.71	3.62	0.46	6.32	0.11(NB)	6.3 (NB)
	10:10:14.0	Backward	0.70	3.37	-5.19	3.41	0.24 (FB)	13.8 (FB)
WorldView-	10:22:07.0	Forward	0.32	7.70	11.00	13.50	0.22(FN)	12.7 (FN)
3	10:22:25.5	Nadir	0.31	7.23	-0.62	7.36	0.22(NB)	12.8 (NB)
08-04-2018	10:22:44.1	Backward	0.32	6.72	-12.20	13.97	0.45 (FB)	25.5 (FB)

Tab. 1 Acquisition properties for Pléiades and WorldView-3 data for the study area

To comparatively investigate the accuracy potential of DEM derived from VHR satellite imagery and the impact of the acquisition geometry, we tasked a new tri-stereo WorldView-3 dataset in the same area (100 km²), with an overlapping of 44.5 km² with the Pléiades images. According to the metadata, the acquisition was done on 8 April 2018, around 10:22, within 37 seconds. The alongtrack acquisition angles w.r.t. nadir are 11°, -0.6° and -12° for the forward, close to nadir and forward images, respectively (Fig. 2). Compared to Pléiades sensor, WorldView-3 platform flies at a lower altitude (617 km), a fact that leads to higher values for the B/H ratios, even if the satellite speed is almost the same. Thus, the B/H ratios for the FN and NB are both 0.22, whereas for FB is 0.45. The intersection angles of rays on the ground for each combination have higher values as well: 12.7° (FN), 12.8° (NB) and 25.5° (FB). The images were delivered in tiles: 8, 2 and 2 for nadir, forward and backward, respectively. The operational aspects of acquisition influence the radiometric characteristics of the images. The fast recording (less than one minute) guarantees same sun illumination conditions with no significant shadow changes in the scenes. From a visual inspection, some radiometric inconsistencies can be observed in the WorldView-3 forward image, i.e. saturation and spilling effects (Fig. 2), mainly caused by the reflective roof surface, in combination with the imaging incidence angle.

All optical satellite images were delivered as 16 bit pansharpened with four bands (Red, Green, Blue and Near-infrared). Their acquisition properties are given in Tab. 1. Depending on the viewing angle, the spatial resolutions (mean values for the GSD) for Pléiades images are varying between 0.70 and 0.71 m, whereas the WorldView-3 sensor provides images with higher resolutions, between 0.31 and 0.33 m (Fig. 2, magnified detail).



Fig. 2: Zoom in built-up area in the three Pléiades images (first row) and in the three WorldView-3 images (second row), acquired with forward-, nadir- and backward-viewing, with a magnified detail

3 Data Analyses and Processing

3.1 Reference Data

For the current analyses, we have used a number of 43 GCPs measured by means of Real Time Kinematic (RTK), with high accuracies (up to 1 cm). Additionally, reference data are based on a DTM and a DSM with 1 m spatial resolution, derived from an ALS flight measurement campaign in December 2015. These LiDAR models were used to compute a reference mask for the open, smooth surfaces. The LiDAR DTM vertical accuracy was checked against the RTK GCPs showing a σ_z of 0.12 m. The digital terrain model was used to compute the Pléiades and WorldView-3 nDSMs (normalized DSM) and to improve the absolute geolocation of the photogrammetrically derived DEMs. We used a digital orthophoto from 2017 at 0.20 m spatial resolution for defining the positions of new Ground Control and Check Points (CPs), whose corresponding heights were extracted from the LiDAR DTM, at the same location.

3.2 Satellite Image Processing and DEM derivation

3.2.1 Pléiades and WorldView-3 image processing

The workflow as applied in this study starts with satellite image triangulation and dense image matching, followed by 3D reconstruction, DEM interpolation, geolocation improvement and accuracy assessment (Fig. 3). The sensor model used for image orientation is based on eighty Rational Polynomial Coefficients (RPCs), available as metadata information. They are used as an alternative to the rigorous sensor model and allow the conversion between image and object space coordinates (POLI & TOUTIN 2012). The reported geo-location accuracy for the Pléiades RPCs is of 8.5 m CE90 (circular error at 90% confidence) corresponding to the nadir view (ASTRIUM 2012), whereas for the WorldView-3 is of 3.1 m CE90 (COMP & MULAWA 2015). For obtaining a submeter accuracy, the RPCs are refined by including GCPs in the workflow. In order to get a homogenous distribution over the entire area, besides the RTK GCPs, we additionally measured 7 and 14 GCPs in the reference orthophoto for Pléiades and WorldView-3 tri-stereo scenes, respectively. The target positions of these points correspond to fixed details on the ground, such as: corners of field and pavement boundaries, road surface changes and intersections. Their accuracy depends on the orthophoto planimetric accuracy (0.20 m) and on the DTM vertical accuracy (0.12 m). In total, we employed 50 GCPs for Pléiades and 36 GCPs for WorldView-3. During image orientation, Tie Points (TPs) are automatically extracted using a multi-ray image matching method.



Fig. 3: Workflow for the processing chain

Dense Image Matching was performed with the specialised Match-T DSM module of the Trimble Inpho software. During processing, a number of ten pyramid levels were generated: the higher seven levels adopt a Feature Based Matching (FBM), while the last three ones a Cost Based Matching (CBM) strategy. The CBM is similar to the Semi-Global Matching algorithm (HIRSCHMÜLLER

2008), that generates an object point for every pixel. The same processing chain was followed for both Pléiades and WorldView-3 triplets.

3.2.2 DEM derivation and geo-location improvement

Dense image matching was performed for all three images (forward-nadir-backward, FNB) of the triplet and for each stereo pair i.e., forward-backward (FB), forward-nadir (FN) and nadir-backward (NB). The object point coordinates were determined by forward intersections. In a last step, regular raster models of height values (i.e., DSM) at 0.5 m resolution are generated by using a robust moving planes interpolation. According to the input point density we have chosen this approach to be the optimal in terms of surface detail preservation.

After a quality checking, systematic errors were visible between the reconstructed DEMs and the LiDAR DTM. In order to reduce them, we applied a least squares matching (LSM) technique that estimates an affine 3D transformation between each pair of target DEM and the reference DTM over common open areas. We masked out the areas containing vegetation, rivers, lakes, buildings and other artificial objects on the ground, and only used smooth surfaces, which can be considered to be stable; here the differences in height are expected to be as low as possible. These areas were identified based on the absolute values of the reference nDSM LiDAR data that needed to be less than 10 cm. The percentage values of stable areas within each dataset are of approximately 37.8 % and of 32.8 % for Pléiades and WorldView-3 scenes. Subsequently, the resulted LSM parameters were used to transform each Pléiades and WorldView-3 point clouds, which were then reinterpolated into new DEMs. The DEM interpolation and geolocation improvement were conducted in the scientific software OPALS (Orientation and Processing of Airborne Laser Scanning) (PFEIFER et al. 2014).

3.3 Quality Assessment

For both tri-stereo scenes, in a first step, the orientation accuracy was assessed by considering the RTK GCPs and 50 CPs measured in the available orthophoto and LiDAR DTM.



Fig. 4: (a) Orthophoto visualised as true color RGB with overlaid RTK GCPs (red circles) and manually measured GCPs (red circles) (b) colour coded and (c) shaded reconstructed DEMs

Secondly, we evaluated the vertical quality of the resulted DEMs, from each image combination, against the available elevations of the ground checkpoints and the reference DTM in the open areas. Thus, the vertical accuracy in open areas was determined by (1) computing the RMSEs between reference and obtained Z coordinates in each generated DEM and (2) analysing the histogram of difference values that should be around zero. For this, the distribution histogram was investigated by deriving statistic parameters such as mean, standard deviation, a robust standard deviation (σ_{MAD}) and also RMSE.

4 Results and disscusion

4.1 Image orientation and matching results

For both scenes, the bundle adjustment was performed using all three images, RTK GCPs and automatically extracted Tie Points (TPs). To assess the image orientation result, we used the available RTK GCPs and 50 CPs homogenously distributed in each tri-stereo scene.

For Pléiades sensor, automatic tie point extraction identified 561, 552 and 582 TPs for Forward, Nadir and Backward images, respectively. The computed RMSE of the GCPs is at decimetre level, except the value in vertical direction which reaches 0.27 m (Tab. 2). For WorldView-3 images, 556, 585 and 554 TPs were automatically extracted in each image. The GCPs discrepancies are at sub-decimetre level in planimetry, whereas a larger value of 0.11 m was obtained in the vertical direction. The accuracy of the CPs for both sensors is similar, around 0.5 m. The standard deviations for the bundle adjustments are 0.54 and 0.46 pixels for Pléiades and WorldView-3, respectively.

Sensor type	No. of GCPs /	RM	IS Values (meters / pixe	els)
Sensor type	CPs	Х	Y	Z
Dláiadaa	43 GCPs	0.187 / 0.26	0.196 / 0.28	0.273 / 0.39
Pleiades	50 CPs	0.441 / 0.63	0.532 / 0.76	0.850 / 1.21
WorldView 2	22 GCPs	0.063 / 0.21	0.086 / 0.29	0.111 / 0.37
worldview-3	50 CPs	0.424 / 1.41	0.403 / 1.34	0.584 / 1.95

Tab. 2: RMSE values for GCPs and CPs after bundle block adjustment

Depending on the incidence angles combinations, four different dense 3D point clouds resulted for each dataset: FNB, FB, FN and NB (Tab. 3) in LAS file format. Image matching processes were performed using the same machine with a core of 3.50 GHz and 32 GB RAM.

	Pléia	ades		WorldView-3				
Scene	Matching	LAS file	No. of points	Scene	Matching	LAS file	No. of	
Comb.	Time (h)	(GB)	(mil.)	Comb.	Time (h)	(GB)	points (mil.)	
FNB	10	15	667	FNB	33	27	1049	
FB	9	15	582	FB	21	26	1048	
FN	10	15	584	FN	24	26	1048	
NB	10	15	597	NB	24	26	1048	

Tab. 3: Image matching results

In the case of Pléiades, the FNB triplet provides the largest point cloud (~667 million points), compared with the three stereo pairs having ~582 (FB), ~584 (FN) and ~597 (NB) million points. Approximately same number of 3D points are generated for all four WorldView-3 combinations

(~1048 million points). Overall, the reconstructed point clouds have a regular distribution, with one point per each image pixel and resulted densities of 4 points / m^2 for Pléiades and of 12 points / m^2 for WV-3.

The resulted photogrammetric point clouds are used as input for DEM derivation. Usually the transition from 3D points to 2.5D grid models is done through interpolation that tends to smooth the input elevation values. The accuracy of obtained models highly depends on the adopted interpolation strategy and the choice of grid resolution. We have used a robust moving planes interpolation that estimates a best fitting tilted plane for every point considering a search radius of 1 m. For minimizing the smoothness effect, we selected a small grid size of 0.5 m, 10 and 20 neighbours (within the 1 m circular neighbourhood) for Pléiades- and WorldView-3-derived point clouds, respectively. This interpolation strategy is actually a compromise between achieving fidelity to the true surface and respecting the limitations according to the density and accuracy of the data source. The nDSMs were derived by subtracting the reference LiDAR DTM from the Pléiades and WV-3 DEMs, respectively.

4.2 Influence of acquisition geometry on DEM quality

4.2.1 Quality assessment of Pléiades DEMs

For each Pléiades image combination, the vertical quality of the photogrammetrically derived DEMs is assessed using the available ground check points, before and after applying the LSM transformation (Tab.4). The RMSE values before LSM for GCPs vary between 0.27 m (FNB) and 0.35 (NB). The LSM transformation significantly reduced the RMSE values for both GCPs and CPs in each image combination, the smaller value being of 0.20 m (FNB).

No. of GCPs /	RMSE (meters)								
CPs		Before LSM At					ter LSM		
	FNB	FB	FN	NB	FNB	FB	FN	NB	
43 GCPs	0.27	0.28	0.30	0.35	0.19	0.20	0.23	0.25	
50 CPs	0.31	0.31	0.36	0.38	0.25	0.26	0.32	0.34	

Tab. 4: RMSE values in Z-direction for GCPs and CPs for Pléiades DEMs

Finally, the interpolated DEMs in open, free areas for each combination, were compared with the ALS reference data. From a visual inspection, after the LSM transformation we obtain a good agreement between DEMs and reference DTM (Fig.5).

Tab. 5 Accuracy assessment of Pléiades DEMs in open areas (values are in meters)

Scene		Befo	ore LSM					
Comb.	Mean	Std	σμαρ	RMS	Mean	Std	σμαρ	RMS
FNB	0.80	0.53	0.51	0.96	0.15	0.60	0.50	0.61
FB	0.77	0.53	0.51	0.93	0.13	0.58	0.50	0.60
FN	0.72	0.65	0.68	0.97	0.13	0.75	0.72	0.76
NB	0.78	0.70	0.73	1.04	0.17	0.79	0.80	0.81

The statistic results show that the DIM terrain heights are systematically shifted by ~ 1 m, but they are reduced to a median close to zero after applying the LSM transformation. The FNB and FB image combinations show a slightly better accuracy than the FN and NB (Tab. 5).



Fig. 5: Pléiades nDSM statistics for open areas, before (top) and after (bottom) LSM. Left: color-coded height differences (masked areas are shown in grey). Right: nDSM height distribution for all combinations



Fig. 6: Analysis of a section profile in along-track direction before and after LSM between pairwise difference models from Pléiades satellite imagery

When comparing the resulted DEMs to the ground truth LiDAR DTM and the three stereo combinations among them, the elevation differences show an undulation similar to waves that are visible in the along-track direction (Fig. 6), with a wavelength of ~4500 m. In this case, LSM transformation slightly reduces the maximum difference elevation values. Except the NB-FN difference model, the wave amplitude values reach ~1.5 pixels.

4.2.2 Quality assessment of WorldView-3 DEMs

In a first phase, the WorldView-3 DEM accuracy is estimated by contrasting the GCPs and CPs elevations with those extracted from the computed DEM (Tab. 6), with improved results after LSM (best accuracy for GCPs in the FNB combination, of 0.10 m). The resulted statistics for CPs have higher values when compared with GCPs, due to the influence of DTM accuracy ($\sigma_z = 0.12$ m), since this served as base for CPs height extraction.



Tab. 6: RMSE values in Z-direction for GCPs and CPs for WorldView-3 DEMs

Fig. 7: WorldView-3 nDSM statistics for open areas before (top) and after (bottom) LSM. Left: colorcoded height differences (masked areas shown in grey). Right: nDSM height distributions

Scene	e Before LSM					After LSM			
Comb.	Mean	Std	σμαρ	RMSE	Mean	Std	σμαρ	RMSE	
FNB	-0.16	0.33	0.33	0.37	0.03	0.24	0.19	0.24	
FB	-0.17	0.34	0.33	0.38	0.02	0.24	0.20	0.24	
FN	-0.17	0.37	0.34	0.41	0.03	0.33	0.34	0.33	
NB	-0.11	0.46	0.48	0.47	-0.01	0.34	0.34	0.34	

Tab. 7 Accuracy assessment of WorldView-3 DEMs in open areas (values are in meters)

Finally, the interpolated DEMs in open, free areas were compared with the ALS reference data. Like for the Pléiades analysis, here also the pairwise comparisons allow the computation of statistic parameters. The resulting non-Gaussian distributions of the normalized elevations (nDSM) for the tri-stereo and stereo images are shown in Fig. 7 before and after LSM. Initially with two peaks and a RMSE of 0.47 m, the histogram corresponding to NB combination is corrected by applying the LSM transformation, achieving a lower value of 0.34 m. Better and similar results are obtained for the FNB and FB image combinations after LSM (with RMSEs of 0.24 m), with lower dispersions around zero.

Similar to Pléiades, by a visual inspection of the computed nDSMs, we could see the same wave effect in the along-track direction, with a wavelength of ~1500 m and a maximum amplitude of ~1.5 pixels for the FB-FN and NB-FB difference models (Fig. 8). By applying the 3D transformation, this effect is reduced to less than 1 pixel, except for the NB-FN difference model.



Fig. 8: Analysis of a section profile in along-track direction before and after LSM between pairwise difference models from WorldView-3 satellite imagery

4.3 Comparative analysis of Pléiades and WorldView-3 DEMs

To complete the analysis, the DEM generated from the Pléiades triplet was compared to the model obtained from WV-3 triplet in the overlap area of about 44.5 km². The distribution histogram in open areas before LSM shows a positive shift, with a mean of 1.35 m, a robust standard deviation of 0.47 m and a RMS of 1.43 m, whereas after transformation the statistic parameters decrease to 0.02 m, 0.43 and 1.15 m.

Dreiländertagung der DGPF, der OVG und der SGPF in Wien, Österreich – Publikationen der DGPF, Band 28, 2019



Fig. 9: Height differences between Pléiades and WV-3 tri-stereo DEMs with distribution histograms before and after LSM (masked areas shown in grey)

5 Conclusions

In this study, we focus on the potential of both Pléiades and WorldView-3 tri-stereo pansharpened images for surface reconstruction in open, smooth areas, where the DSM can be considered same with the DTM. Satellite image orientation and dense image matching were performed in Inpho Trimble software, which employes a high automation process. GCPs were used for improving the direct sensor orientation available as RPCs. Eight digital elevation models derived from different pairwise combinations were assessed with regard to their vertical accuracy using geodetic measurements (RTK GCPs), CPs and an ALS DTM as reference data. The quality analysis of photogrammetrically computed DEMs showed systematic errors, as well as non-normal distributions and a wavy effect in the along-track direction. Apparently the present solution in Match-AT is not able to fully exploit the benefit of given GCPs and a 3D LSM transformation needs to be appended. In future work this problem should be further investigated. 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, our 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 (BÜHLER et al. 2012; HOBI & GINZLER 2012; HOFFMANN & LEHMANN 2000; HU et al. 2008; RESSL et al. 2016). When compared to 50 CPs, the elevation accuracies of the Pléiades DEMs (RMSEs of 0.31 m, 0.31 m, 0.36 m and 0.38 m corresponding to FNB, FB, FN and NB, respectively) are similar with the results obtained by BERNARD et al. (2012), who achieved a RMSE of 0.49 m. In accordance with the investigations reported by PIERMATTEI et al. (2018) and PANAGIOTAKIS et al. (2018), we obtain higher accuracies for the tri-stereo and forward-backward combination compared with the other two stereo pairs that perform worse. Compared with Pléiades, the small ground sampling distance (0.31 m) of the WorldView-3 images leads to higher accuracies, as the representation of details on ground surface is more reliable. Our vertical accuracy results agree with those reported by HU et al. (2016), of less than 0.5 m for 6001 ground LiDAR check points. The small acquisition convergence angles influence the vertical accuracy, as the images are very similar to each other, a fact that enables a better image matching, despite the decrease in geometric intersection quality. By careful georeferencing including LSM over stable areas,

change detection between Pléiades and WorldView-3 satellite images is limited by an accuracy of only 0.50 m. With accuracies comparable to airborne photogrammetrically derived DEMs, the VHR satellite images are an important alternative data source for high resolution digital elevation models derivation over large areas.

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