Peer-reviewed version available at ISPRS Int. J. Geo-Inf. 2018, 7, 118; doi:10.3390/ijgi7030118

Type of the Paper (Short Note)

Validation of Pleiades Tri-Stereo DSM in Urban Areas

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Abstract: A very high-resolution DSM covering an area of 400km^2 over the Athens Metropolitan Area has been produced using Pleiades 1B 0,5m panchromatic tri-stereo images. Applied Remote Sensing and Photogrammetry tools have been used resulted in a 1x1m DSM over the study area. DSM accuracy has been evaluated by comparison with measured elevations with D-GPS and a reference DSM provided by the National Cadaster & Mapping Agency S.A. In addition, different combinations of stereo images have been prepared for further exploitation of the quality of the produced DSM by stereo *vs.* tri-stereo images. Results show that the produced by the tri-stereo images DSM has an RMSE of 1.17m in elevation (z), which is among the best reported in the relevant literature. Stereo based DSMs from the same sensor have worst performance to this end. Satellite Remote Sensing (SRS) based DSMs over urban areas provide the best cost-effective approach in comparison to airborne-based datasets due to high spatial coverage, lower cost and high temporal coverage. Pleiades-based high-quality DSM products can serve the domains of urban planning/climate, hydrological modelling and natural hazards, as major input for simulation models and morphological analysis at local scale.

Keywords: tri-stereo; DSM, validation; urban surface morphology

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1. Introduction

Satellite Remote Sensing (Optical and SAR) and airborne LIDAR technology have been exploited for their capabilities on the production of high resolution DSM for use in urban studies [1-5], in hydrological modelling [6] and natural hazards [7-9]. Both methods have their limitations and advantages [6] while open access datasets didn't provide the detailed information required for studies at local scales [10]. The first stereoscopic images that allowed the extraction of DSM over large areas were provided by SPOT in 1986 [11]. Since then, several Very High Resolution (VHR) satellites, that their sensors have the capability of taking stereo or tri-stereo pairs (table 1), have been launched during the last decade as the demand for high resolution and large area DSM extraction has increase. Among them, Pleiades-1 mission has attracted attention due to its unique tri-stereo image acquisition that provide almost simultaneously images from 3 different views (one backward looking, one forward looking, plus a third near-nadir image, figure 1) for the same area with a stereo angle varying between ~6° and ~28° and at the same spatial resolution. This configuration and in particular the use of the near-nadir image, allows a better retrieval of heights over terrains where the performance of classic photogrammetry with forward backward looking stereo pairs is limited [12]. Poli et al., [13] examine the capability of Pleiades 1A for DSM extraction over Trento test field. By using 15 control points extracted by a LIDAR based DSM, they achieve an RMSEz of 0,75, while Perko et al., [14] having similar approach over Innsbruck city, Austria with a direct comparison of the produced DSM over the city with a Lidar based DSM, they achieve a RMSEz of 2,4m. Bagnardi et al., [7] extract a DSM of 1m from Pleiades 1A to calculate lava flow volume after the eruption of Fogo Volcano in

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Cape Verde in comparison to a pre-eruption Satellite based SAR DSM from TanDEM-X. The Pleiades-1 mission consists of a constellation of two satellites for VHR panchromatic (PA) and multispectral (MS) optical observation of the Earth's surface. The Pleiades-1 (1A and 1B) mission is programmed to continue for several years [16], and the tri-stereo (or multistereo) acquisition mode is set to become a common feature in future satellite missions.

Table 1. VHR satellites with stereo and tri-stereo capabilities.

Satellite	Spatial resolution (panchromatic)	Stereo	Tristereo	Temporal resolution
Ikonos	0.82 m	y	n	3 to 5 days off nadir
Quickbird	0.61 m	y	n	1 to 3.5 days off-nadir
Pleiades 1A/B	0.7 m	y	y	4 days off-nadir
Worldview-1	0.46 m	y	n	5.9 days off nadir
Worldview-2	0.46 m	y	n	3.7 off nadir
OrbView-3	1 m	y	n	3 off nadir
GeoEye-1	0.46 m	y	n	2.8 off nadir
SPOT-5	2.5 m	y	n	2-3 days off nadir
SPOT-6 & SPOT-7	1.5 m	y	n	1 day off nadir
Resurs-DK1	0.8 m	y	n	6 days off nadir
ZY-3A	2.1m Nadir / 3.5m Forward-Backward	y	y	5 days off nadir
IRS Cartosat-1	2.5 m	y	n	5 days off nadir
IRS Cartosat-2	1 m	y	n	4 days off-nadir
IRS Cartosat-2 B	1 m	y	n	4 days off-nadir

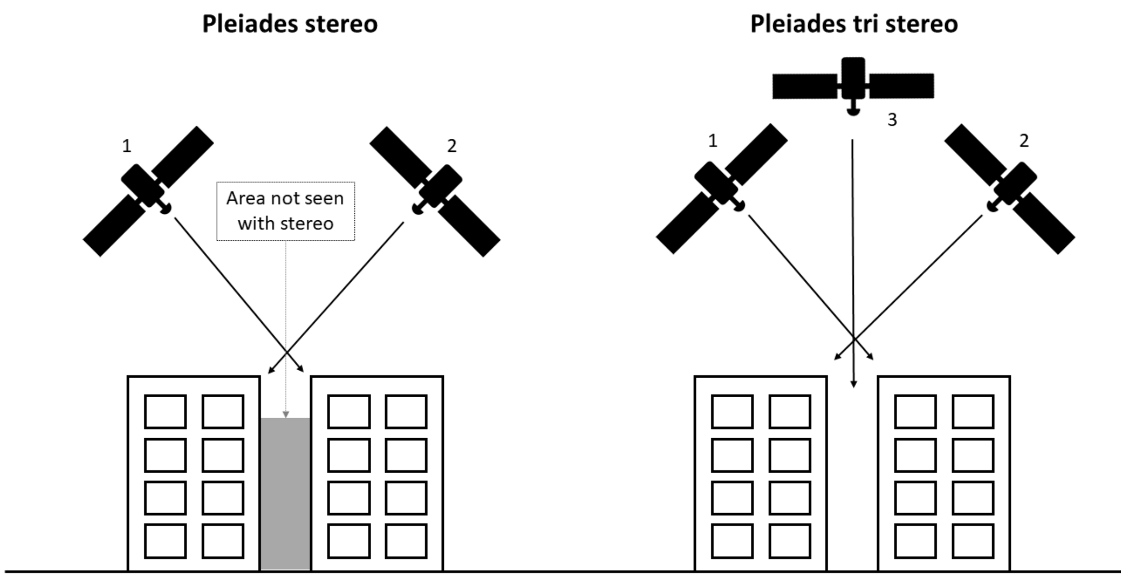

Figure 1. Stereo and tri-stereo views of Pleiades 1 mission.

To this end, the objective of the present study is to exploit the potential of the extraction of DSM over large urban areas, such as the Athens Metropolitan, Greece using Pleiades-1 stereo and tri-stereo images, to compare the results between the two approaches and to evaluate the results using the official VHR DSM from the National Cadaster & Mapping Agency S.A. as reference as well as measured point-based elevation data with D-GPS in absence of Lidar-based DSM.

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2. Materials and Methods

2.1. Study area

The study area covers the central part of Athens Metropolitan area, covering ~ 350 km2 in a dense cityscape surrounded by 2 mountainous massifs at the southeast and north-west part (figure 2). Athens is the capital and largest city of Greece dominating the Attica region. The topography of the studied area includes two mountains, Hymettus on the southeast and Aigaleo (Poikilon Oros) on the west-northwest side of Athens. The central part of the area is characterized by a low/ moderate relief with an average elevation of 400m in the urban area.

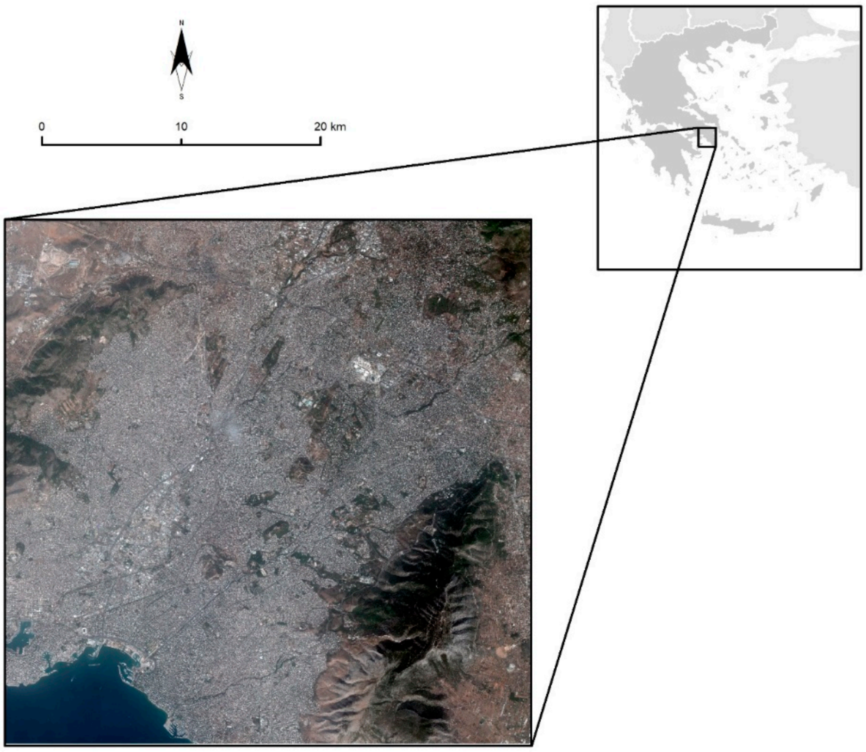

Figure 2. The study area in Athens city by Pleiades 1B multispectral image.

2.2. Data processing and analysis

Pleiades constellation is constituted by 2 satellites. The first satellite, Pleiades 1A was launched in December 2011, while the second satellite, Pleiades 1B was launched a year later, in December 2012. Both satellites, part of the French-Italian Optical and Radar Federated Earth Observation program for civilian and defense uses, fly in sun-synchronous orbits with 98.2° inclination and an offset of 180° from each other, which allows a minimum revisit time of 24h. The PA and MS images are acquired simultaneously at a nominal resolution of 0.7m and 2.8m, respectively [15]. Level 1B Pleiades cloud free tri-stereo image acquired at 16 October 2016 (table 2) has been processed using the Automatic Terrain Extraction with Dense Point Matching (eATE) of ERDAS Imagine Photogrammetry. Orbital pushbroom has been selected as Geometric model with classic point measurement tool for GCP preparations (figure 3). After the preparation of the GCP's, block triangulation has been used to check the quality of the GCP's. Afterthat, eATE process is activated, there the output spatial resolution of the DSM is defined, the interpolation method but also the smoothing factor.

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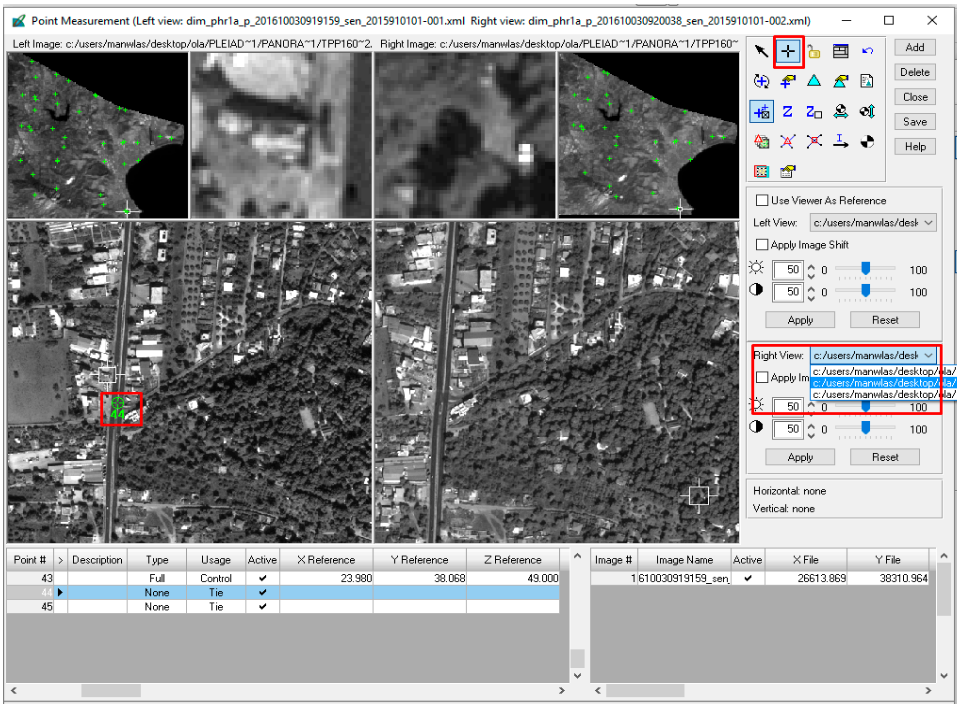

Figure 3. View of the ERDAS Imagine Photogrammetry for the GCP collection and preparation.

The set of the 3 panchromatic images have been visual inspected for radiometric inconsistences due to operational aspects of image acquisition, in combination with the landscape characteristics. Usually, such anomalies appear only in one of the images from a stereo pair or a tri-stereo acquisition due to the presence of reflective surfaces (e.c. metal roofs, water masses causing sun glint), in combination with the imaging incidence angle [13]. None of these effects were observed in the present set of Pleiades images. A set of ten GCPs has been extracted from the official orthorectified imagery basemap platform provided by the National Cadaster & Mapping Agency S.A. while the respected elevation has been extracted by the official DSM of the same area (figure 4). Both the orthorectified image and DSM have been produced for the year 2010 and are the reference data for the present study; the data gaps shown in figure 4 concern classified areas by the Hellenic Military Services. In absence of a lidar-based DSM, for the validation of the produced DSM, two different datasets have been prepared and used: a) 188 random check points with elevation data from the reference dataset in distance of more than 50m each other in order to avoid spatial autocorrelation following a rule of thumb that each point has to be in a distance of 40 times the size of pixel [17] and b) 26 well measured points across the project area using Trimble R-10 GNSS system and the ground reference stations of HEPOS (figure 4).

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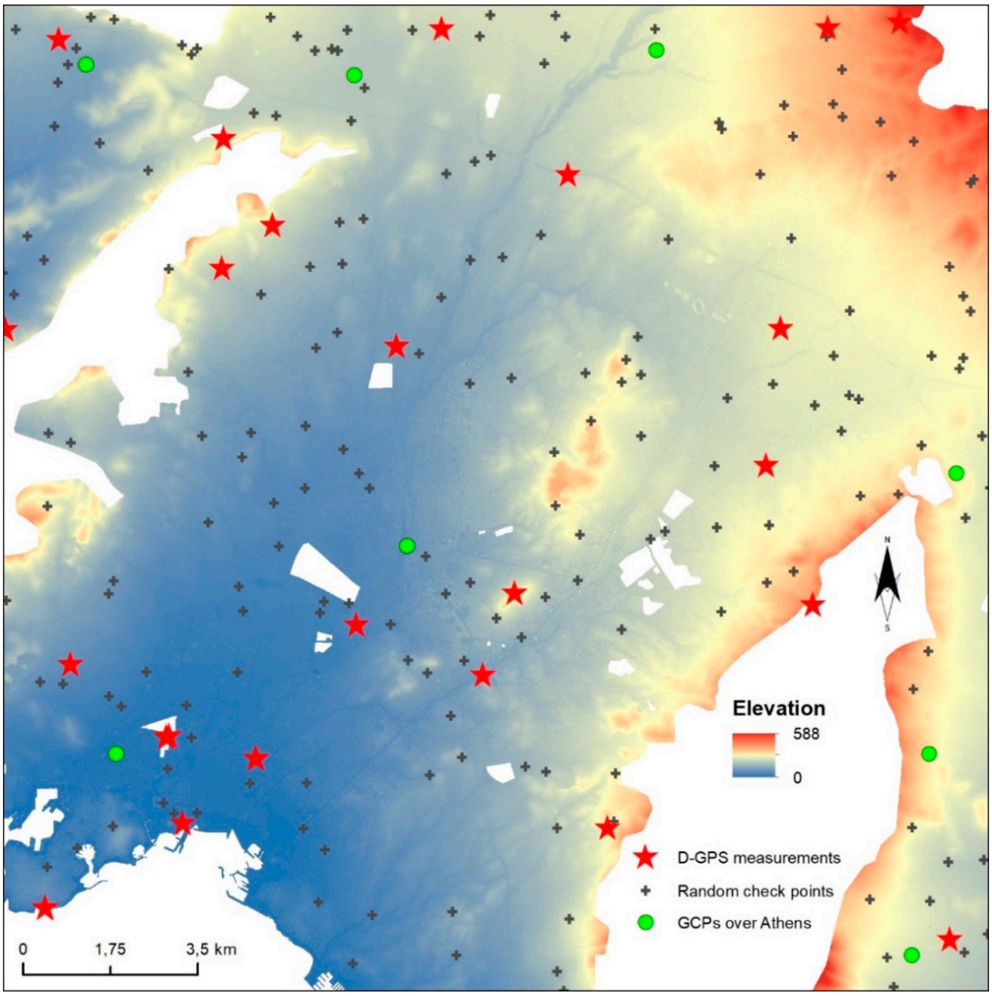

Figure 4. The project area with overlaid the reference DSM, the dataset of GCP's, the random check points and the D-GPS measured data.

RMSE, a a comprehensive statistic metric and easy to be implemented, has been selected as the evaluation metric of the accuracy of the produced DSM. Linear Error at 95% and 99 % confidence intervals (CI) have been calculated from the RMSE.

Table 2. The characteristics of the analyzed Pleiades tri-stereo acquisition.

	Image 1	Image 2	Image 3
Along-track (°)	13.84	3.17	-7.81
Across-track (°)	-4.01	-3.45	-2.86
GSD (m)	0.74 x 0.74	0.70 X 0.71	0.71 x 0.71
Size (columns)	39501	40000	40000
Size (rows)	38248	39956	39576
Acquisition time	9:19:36	9:19:56	9:20:16

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3. Results and Discussion

After the analysis of the tri-stereo imagery of Pleiades 1B, the produced DSM with a spatial resolution of 1x1 m, show excellent detail in the cityscape with minor issues related to "noise" in comparison to the reference dataset (figures 5 and 6). The majority of the "noise" issues appear on the road network (figure 6) or at streets with narrow canyons due to moving objects and shadow effects. It is worth noting that the produced DSM from Pleiades 1B has not been post processed using any type of filtering for noise and artefact removal. Checking the produced DSM with the measured by the D-GPS points, the RMSEz is at 1,8m. Tests on the stereo (fb= forward-backward, fn= forward-nadir) and tri-stereo DSM production from Pleiades shows that the tri-stereo has better performances in terms of RMSEz (tri-stereo = 1,17m, stereofb = 1,48m, stereofn=1,64m). From the RMSE of the tri-stereo DSM the LE95 is 2.29 m and LE99 is 3.02 m respectively. The RMSE is an aggregated measure of the vertical accuracy of the produced DSM. To assure its accuracy at local level, one may visualize how the difference ZPleiades – ZReference is distributed in space, hence one may depict the magnitude of this difference around each checkpoint. Differences among them have been calculated and histogram has been prepared (figure 7). Pleiades DSM as well as the reference DSM for study area show strong positive correlation. The results (figure 7), indicating strong correlation for the estimated elevation differences between the two DSMs, observations corresponding to slope are much smaller, but still positively correlated. The scatter plot of Pleiades DSM as well as the reference DSM values reflects this strong correlation (figure 8).

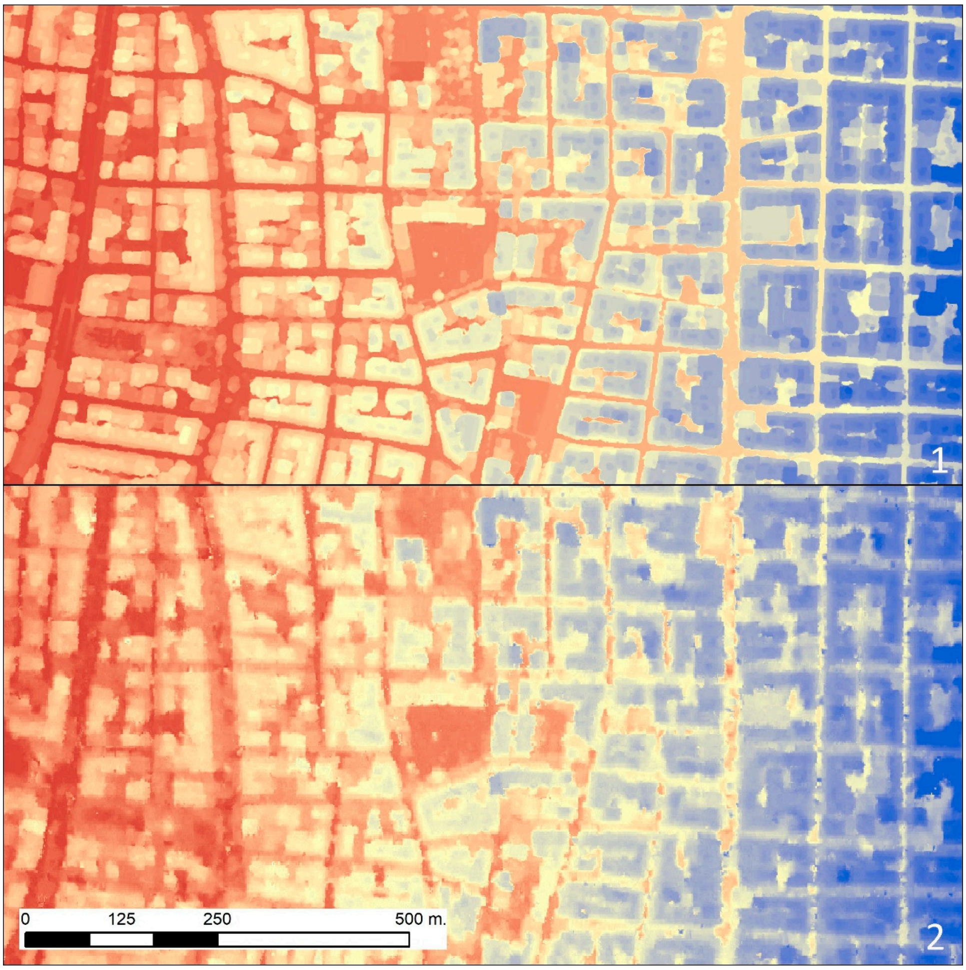

Figure 5. Details in the cityscape of Athens in the level of neighborhood from the reference dataset (1) and the produced DSM (2).

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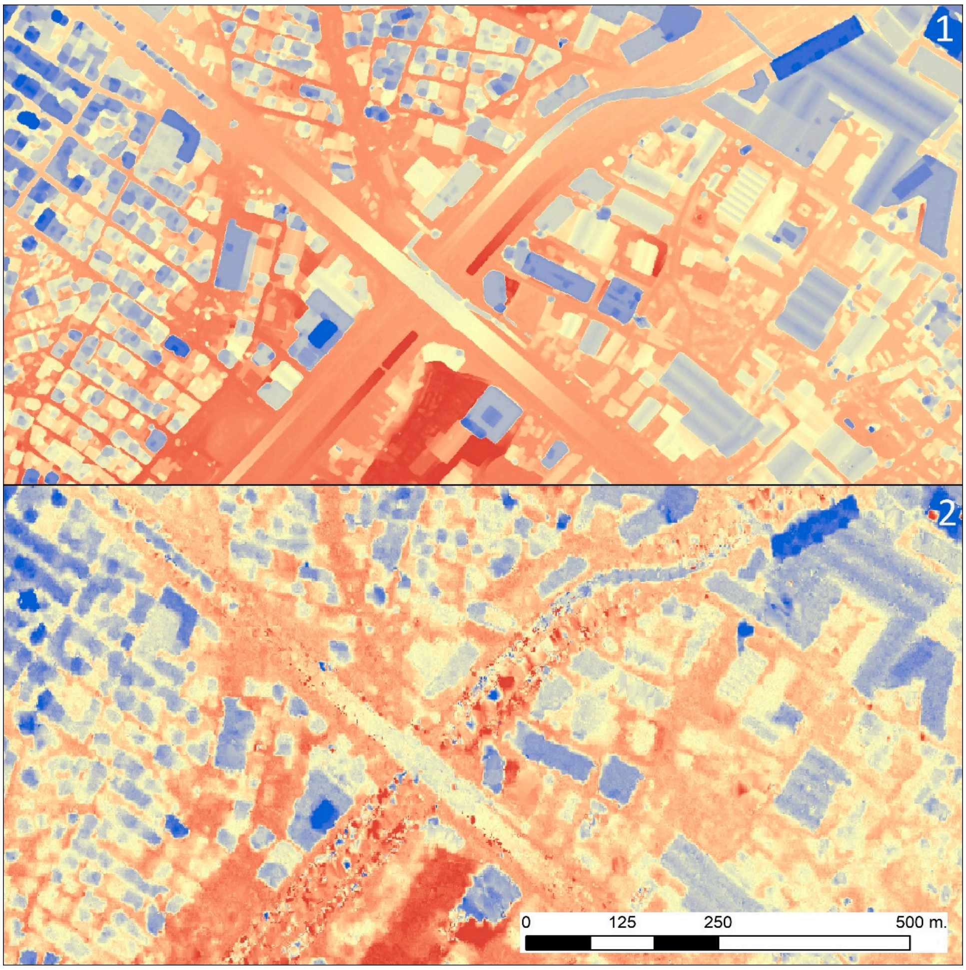

Figure 6. Details over a central road of Athens from the reference dataset (1) and the produced DSM (2). The noise over the road network is visible and is mainly caused by the small elevation differences in the terrain due to moving objects.

In order to check for elevation-caused bias, scatter plot of Pleiades DSM vs Reference DSM (figure 9) with elevation data from the Reference DSM has been prepared and shows that the majority of differences cluster around mean difference (avg=0,53).

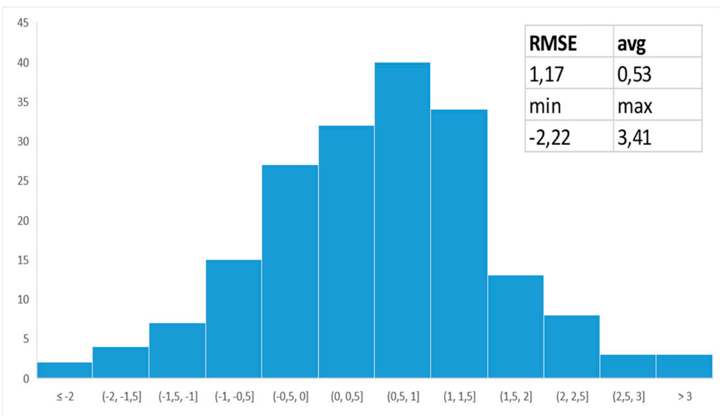

Figure 7. The probability distribution of error, the means correspond to biases (systematic effect) and the variances corresponds to random effects; values are in meters. RMSE is at 1.17m.

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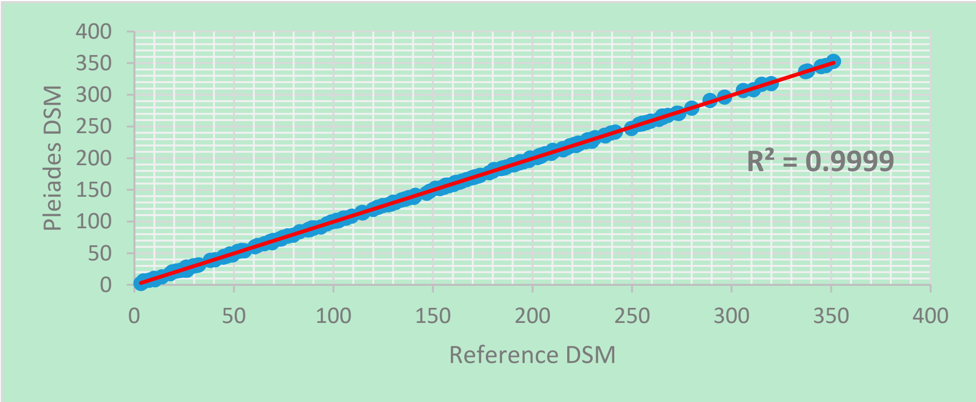

Figure 8. Scatter plot of Pleiades DSM vs Reference DSM for the 188 random points.

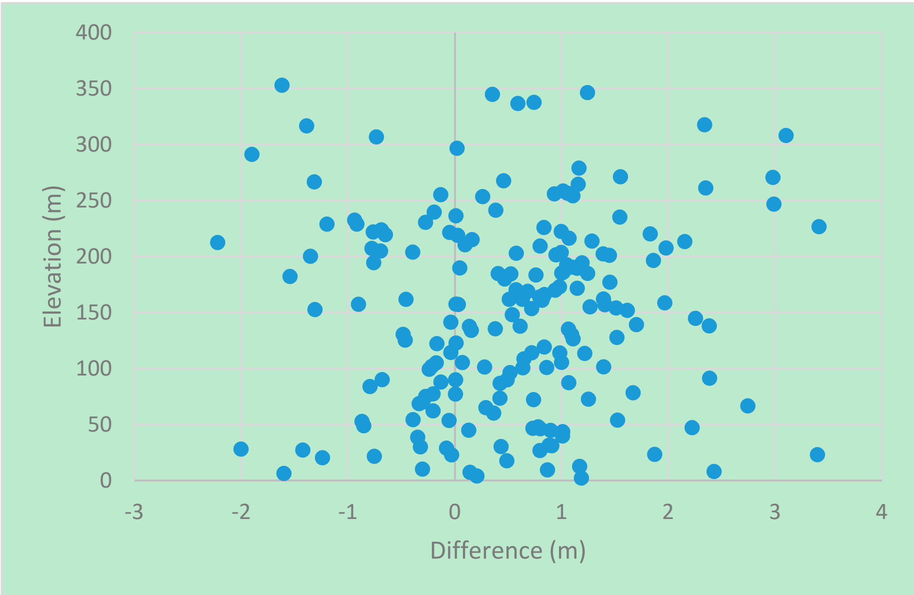

Figure 9. Scatter plot of Pleiades-Reference DSM difference vs elevation. No important bias is being observed.

Airborne LIDAR technology for the extraction of DSM provide unprecedented accuracy whilst the cost of that is quite high in comparison to the SRS methods, is spatially restricted over sensitive areas and the frequent update of such datasets are highly costly. SRS based methods, as the one of the present work, can provide an automated way to extract high resolution DSMs across the globe with a relative low cost, high accuracy and frequent temporal cover whilst the spatial coverage is quite large and there are no restrictions on the spatial coverage [18]. The reference DSM has been produced by using stereoscopic airborne camera with simultaneous image captions at elevation lower that the one of the Pleiades 1B satellite. The raw data have been captured at a resolution of 0,25m and the final DSM has been delivered at 0,8m. These reasons and the post process of the reference dataset has end up to a clear and smooth DSM in the cityscape of Athens. The produced one presents more noise, mainly over the road network because of moving items as well as from shadows in narrow street canyons. A previous study, using Pleiades 1A, show similar results [13], as the tri stereo images didn’t include a real nadir acquisition, as is also our case of image dataset. The temporal resolution between

 doi:10.20944/preprints201801.0030.v1

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the Pleiades 1B tri-stereo images according to the metadata is 2 minutes between each acquisitions, sufficient time for changes over the same scene for moving objects. Whilst GCP's have a crucial role in the production and the quality of the DSM, the number of them in each case study is related to the quality of them in terms of vertical and horizontal accuracy. The present study end up to 10 GCP's over an area of $400km^2$, resulted in a high accurate DSM with an RMSE of 1,17m, among the highest reported so far. DSM's are incorporated in the process of image classification in urban/rural areas, either for a holistic approach of land use/cover with improved results [19], for a targeted image classification, as in the case of urban green vegetation [3] or the extraction of buildings [20,21] which resulted in more accurate results. The incorporation of DSM's in mapping elements in urban environments can benefit current research improving the results as incorporate texture and shape information apart from the spectral one [22,23]. Important is the moving objects detection over same dataset resulted in advanced datasets important for studies in urban environments [24].

5. Conclusions

The goal of this paper is to validate the high-resolution DSM produced by the analysis of Pleiades 1B over a large area of the Athens Metropolitan Area. Tri-stereo image analysis provide the best results according to the RMSEz values in comparison to the stereo pair based DSMs. Ten evenly distributed GCP's across the study area have been used to produce the DSM, which turn out as a sufficient number for a total area of $400km^2$. Two independent datasets have been used for the evaluation of the products. GCP's evenly distributed across the study areas and z values coming from a reference DSM produced by aerial stereo images and measured points with D-GPS. The first dataset provides an RMSEz of 1,17m, which is among the lowest errors that have been provided in the scientific literature so far while the second dataset provide a slightly higher one (RMSEz=1,82). Both evaluation datasets provide results that are acceptable from SRS based DSMs. The present study shows that Pleiades constellation (1A/B) can provide the required terrain information over urban areas across the globe, in areas that Megacities are under development (e.c. China, India) with high accuracy, using applied remote sensing tools and methods, covering large areas with no spatial restrictions as is the case of airborne-based campaign data.

Acknowledgments: The authors are grateful to the EnCeladus Hellenic Supersite (http://www.earthobservations.org/gsnl.php) for the Pleiades data provision.

Author Contributions: All authors contribute equal to this work.

Conflicts of Interest: "The authors declare no conflict of interest."

Peer-reviewed version available at ISPRS Int. J. Geo-Inf. 2018, 7, 118; doi:10.3390/ijgi7030118

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