Digital Surface Models from ZiYuan-3 triplet: performance evaluation and accuracy assessment

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Abstract. At the beginning of 2012, a new optical satellite, called ZiYuan-3 (acronym ZY-3), was launched from the Taiyuan Satellite Launch Center. It carries three panchromatic cameras: the nadir camera has a spatial resolution of 2.5 m, whereas the aft and forward cameras, both tilted by 22° degrees, have a spatial resolution of 4 m; moreover this satellite carries a four multispectral bands camera with GSD of 10 m at nadir. The 50 km swath and the ZY-3 along track three-stereo imaging capabilities, allows to generate Digital Surface Models (DSMs) and to produce/update 1:25.000 orthophotos/maps. The goal of this paper is DSMs generation and assessment from a ZY-3 triplet acquired over the city of Bolzano (Alto-Adige province, northern Italy). Four different software (MATCH-T by Trimble, LPS eATE embedded in ERDAS, OrthoEngine embedded in PCI Geomatica software) were used at the moment, in order to investigate the effects of the orientation model and the matching strategies on the 3D reconstruction accuracy. In all cases the Rational Polynomial Functions orientation model was used, with Rational Polynomial Coefficients supplied by the vendors in the imagery metadata file. The accuracy the extracted DSMs were compared to the public LiDAR Digital Terrain Model – DTM, with a posting of 2.5 m and a mean elevation accuracy of 0.25 m. The preliminary obtained results show that the geometric potentialities of ZY-3 three-stereo images as regards DSMs generation is at the level of about 10 meters, similar for all software. A comparison, including also SISAR package (developed at the University of Rome "La Sapienza"), has been developed, and the global obtained results have been discussed in this paper.

Keywords. ZY-3 sensor, DSM generation and assessment, software comparison.

1. Introduction

Digital Surface Models (DSMs) have large relevance in many engineering, land planning and environmental applications for a long time. At present, the data required for the DSMs generation can be acquired by several sensors/techniques, among which airborne LiDAR, aerial photogrammetry, optical and radar spaceborne sensors play the major role. In this respect, the availability of new high resolution optical spaceborne sensors offers new interesting potentialities for DSMs generation, among which low cost, speed of data acquisition and processing and relaxed logistic requirements, quite important for the areas where the organization of aerial flights can be difficult for logistic motivations.

In this respect, China launched a first civil high-resolution stereo mapping satellite ZiYuan (ZY-3), on January 9, 2012. It is an optical satellite that carries three high-resolution panchromatic cameras and an infrared multispectral camera.

ZY-3 data have been widely applied in surveying and mapping, agriculture, forestry, environmental protection, disaster reduction, urban planning and other fields at present. It provides stable data source to plot 1:50.000 surveying and mapping products, updates 1:25.000 even larger scale maps, and carries out mapping and change detection of land resources. In addition, the image data provide emergency mapping services to help disaster management, and lend assistance to farming, ecological protection, national geographical state monitoring, etc.

The satellite can collect 6 to 8 image strips every day, and the imaging time per strip is about eight minutes with coverage area approximate 150.000 sq. km.

The ZY-3 multispectral camera collects four bands (blue, green, red, near infrared) and it has a spatial resolution of 5.8 m and 51.0 km ground swath.

The panchromatic cameras are positioned at the front-facing (forward camera - FWD), ground-facing (nadir camera - NAD) and rear-facing (backward camera - BWD) positions. Two cameras (forward and backward) have a spatial resolution (GSD) of 3.5 m and 52.3 km ground swath while the nadir camera has a spatial resolution of 2.1 m and 51.1 km ground swath. The forward and the backward cameras are tilted by 22° degree.

The goal of this work is to evaluate the accuracy of the DSM extracted by the new optical sensor ZY-3; despite the GSD is not at the same level of the second generation optical satellite like WorldView-1 and 2, GeoEye-1 (2.1 m GSD for the nadir ZY-3 camera vs. 0.5 m GSD for WorldView-1 and 2, GeoEye-1) the wide swath (50 km vs. 30 km) and especially the possibility to acquire the three images of the same area at the same time with different incidence angles make interesting the study of their potentialities and capabilities to 3D reconstruction.

In Section 2 the available data set and the software used are illustrated; in Sections 3 and 4 the strategies used for the DSM generation, and the evaluation results obtained with different software are described and discussed; finally, in Section 5 some conclusions and prospects are outlined.

2. Data set

The data set available are three along track panchromatic images (NAD, FWD, BWD) acquired by the three ZY-3 sensor cameras over the Bolzano area (Alto Adige province, northern Italy). The images have been acquired on September, 2012, and they are totally overlapped and cover an area of around 2500 km^2. The off nadir angles of the FWD and BDW images are about -22/+22 degrees respectively and the ground resolutions are around 2.1 m and 3.0 m for the NAD and FWD/BWD images respectively.

The acquired area is mainly mountainous (around 80%), with maximum elevations close to 2000 m, and only in the South-West part there is a flat enough area, including Bolzano city. Unfortunately, clouds cover some zones of the image in the East part (Fig. 1). The images have been supplied with metadata file and with relative RPCs file for the geolocation.

The ground swath is 50 km, but only a tile of about 10x10 km^2 has been selected (Figure 1) and over this tile the DSMs with eATE, MATCH-T and OrthoEngine software have been extracted and assessed; in details a global analysis and an evaluation on the bases of different morphologies (urban, flat and mountain) have been executed; as regards the additional investigation with the scientific software SISAR, just a sub tile (in the South-West part of the considered tile) was selected (Figure 2).

A LiDAR DTM with posting 2.5x2.5 m and 0.25 m elevation accuracy, freely available on the website “Provincia Autonoma di Bolzano” (http://www.provincia.bz.it/), has been used to assess the generated DSMs.

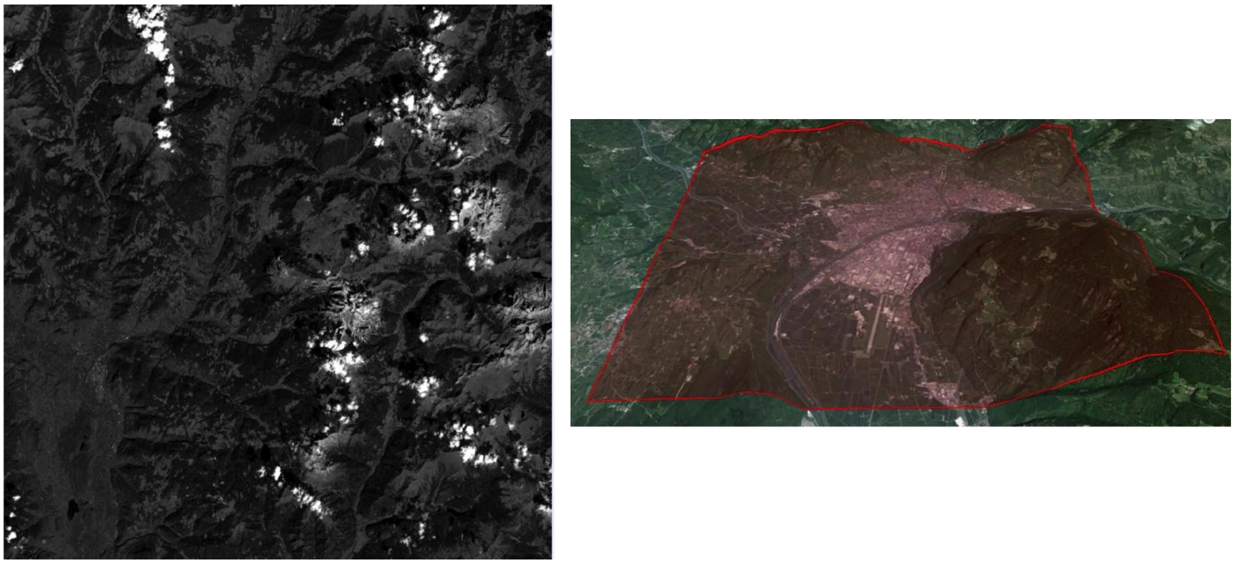

Figure 1: ZY-3 images (left) and tile selected (right)

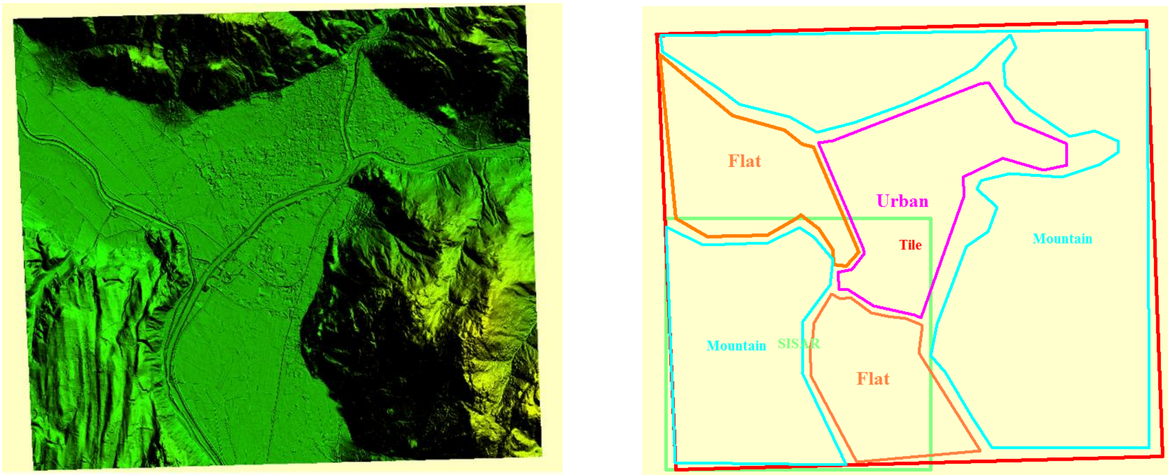

Figure 2: LiDAR (left), tile partitioning with different morphologies (right)

3. DSM generation

In order to generate DSMs from ZY-3 data four software were used: MATCH-T supplied by Trimble, LPS eATE embedded in ERDAS software, which are able to manage the three-stereo images, the commercial software OrthoEngine embedded in PCI Geomatica and the SISAR software, a scientific software developed at Geodesy and Geomatics division – University of Rome "La Sapienza". The latter two software are able to process the stereo images only. For all software DSMs have been extracted using the RPCs model, supplied by the image provider, without using GCPs for the orientation, so that the differences in DSMs extraction procedure among the four software are basically in their matching algorithms, which obviously have a marked impact on the DSMs quality.

3.1. RPCs orientation model

It is well known that the RPF models relate the object point coordinates (latitude φ, longitude λ and height h) to the pixel coordinates (I, J) in the form of ratios of polynomial expressions, whose coefficients (RPCs) are often supplied together with imagery:

$$I = \frac{P_1(\varphi,\lambda,h)}{P_2(\varphi,\lambda,h)} \quad J = \frac{P_3(\varphi,\lambda,h)}{P_4(\varphi,\lambda,h)}$$

where

$$P_n = \sum_{i=0}^{m_1}\sum_{j=0}^{m_2}\sum_{k=0}^{m_3} t_{ijk}\varphi^i\lambda^j h^k$$

with $0 \leq m_1, m_2, m_3 \leq 3$, $(m_1+m_2+m_3) \leq 3$ and where t_{ijk} are the RPCs.

In this respect, some companies supply the RPCs into the metadata delivered together with imagery, and the RPFs model available in several commercial software allows for a straightforward image orientation.

Generally, if unacceptable residual biases affect RPCs results, the orientation can be refined on the basis of few GCPs; usually a 2D shift (2 parameters) or a 2D affine (6 parameters) transformations are estimated, but investigations with new optical imagery clearly underlined that many RPCs are highly accurate, so that the GCPs refinement is becoming always more frequently not necessary [1], [2].

In our case, the orientations of the single ZY-3 images with the RPCs, without the use of GCPs, were checked. In details, quite similar shifts for the three images (FWD, NAD, BWD) were detected, in the order of about -5 m in East and + 25 m in North directions; these shifts are significant for the overall geolocation of the derived DSMs, but do not significantly affect the image relative orientation and the DSMs generation, due to their similarity.

3.2. Matching algorithms

For the commercial software MATCH T and LPS eATE the image matching technique used is not declared, therefore a briefly description of matching approach derived from some papers, cited in the references, is reported.

3.2.1. MATCH-T

MATCH-T DSM is a part of INPHO photogrammetric suite, a software of the Trimble geospatial solution family. MATCH-T module obtains very dense point clouds and high quality surface models directly from stereo imagery using image matching techniques. The automatic DSM generation approach in MATCH-T is mainly characterized by the feature-based matching technique, being hierarchically applied in image pyramids; in order to improve the matching precision, Least Squares Matching (LSM) is applied [3]. Multi-layered matching takes all locally overlapping images into account, achieving dense point clouds, even in urban and forested areas. With that dense matching technique, users can produce point cloud density up to 1 point per pixel, providing rich detail and sharp edges with sub-pixel relative accuracy. MATCH-T DSM can be used with orbital pushbroom or digital frame camera sensors, enabling 3D extraction also from triplet set of satellite images.

The generated DSM was obtained using the 5.5.1.43272 (64 bit) version of MATCH-T DSM, build on June 2013. Morphological and basics parameters can be set before surface generation: the first to improve the performance of automatic terrain generation (consideration of pre-measured morphological data as breaklines, 2D and 3D exclusion areas, borderlines) and the basics parameters to enhance surface model extraction (region type editor). For these latter, it is possible to choose: the region type such as flat, undulating, mountainous, extreme terrain type; four level of smoothing filter (low, medium, high and extreme); the feature density (dense, medium, sparse and very sparse) that regulate the amount of ground points that are automatically matched in the DSM generation process; the threshold value of parallax to define a search area for homologous points in overlapping images (for example, for the mountain terrain the search area must be larger than for the flat terrain). A regular point distribution in poorly textured image areas is guaranteed through auto-optimization of local parameters.

3.2.2. LPS eATE

LPS eATE (enhanced Automatic Terrain Extraction) extracts accurate, high-density elevation surfaces from overlapping imagery. The matching algorithm implemented in eATE is performed hierarchically through the image pyramids by means of NCC (Normalized Cross Correlation) and the matching results are refined by Least Squares Matching (LSM), again through all image pyramids The edge constrain and a filter of the matching candidates can be applied [4].

eATE's performance is based upon user-defined region strategies and parameters that control and guide the terrain processing. Traditional stereo pairs are the most common suitable image data, but eATE can also operate on any overlapping imagery with adequate convergent geometry. The final results can be in gridded format (TIF or IMG) and mass points or point clouds (3D ASCII, LTFx, 3D Shape, and LAS v1.2). Different strategies can be applied to all images in an eATE workspace or to user-defined AOIs. The Strategy Manager includes settings that can be changed according to the terrain type to be processed. Moreover, in order to reduce the overall processing time, eATE can run on multiple processors within a single computer.

In this study we used a group of parameterizations according to the region types of the considered area. Urban, mountainous and undulated terrain were investigated, applying different strategies: normalized cross correlation correlation algorithms, spike interpolation (to remove points identified as spikes based on the surrounding elevation data), LSM refinement, Edge constraint (to ensures that the interpolation and the matching processes do not cross edge boundaries), low "smoothing filter" and 3 pixel of additional parallax to widen the search area perpendicular to the epipolar line.

3.2.3. OrthoEngine

OrthoEngine is a photogrammetric tool designed to produce geospatial products. It supports images from standard aerial, SAR and optical satellite sensors.

OrthoEngine matching algorithm is based on cross correlation and it needs epipolar or semiepipolar image geometry to find the corresponding points, in order to increase the correlation process speed and reduce the possibility of incorrect matches. Stereo pairs are reprojected, ensuring that the left and right images have a common orientation, and matching features between the images appear along a common x-axis.

Three different parameters influence the final DSMs accuracy: epipolar down sample, details and DTM sampling pixel. The epipolar down sample represents the number of image pixels and lines that will be used to calculate one epipolar image pixel; the details parameter indicates the level of desired detail (high, medium and low) in the extracted DEM; the DTM sampling pixel is the number of image pixels and lines (sampling frequency) that will be used to extract one DSM pixel [5].

3.2.4. SISAR

The scientific software SISAR (Software per Immagini Satellitari ad Alta Risoluzione) has been developed and implemented by the research team of Geodesy and Geomatics division of the University of Rome "La Sapienza".

The software including original algorithms for the DSMs generation, starting from optical and SAR imagery acquired by high satellite sensors [6].

The image matching strategy is based on a hierarchical solution with a geometrical constrain, and the corresponding points (actually, so-called primitives) are searched using an Area Based Matching (ABM) criterion and analyzing the signal-to-noise ratio (SNR). In this sense, the peculiarity of the proposed algorithm is to use the image orientation model to limit the search area of the corresponding primitives, allowing a fast and robust matching. Primitives are searched directly in the object space re-projecting and re-sampling the stereo images on a regular grid in the ground geometry, that is in the ground reference system [6].

4. Analysis of results

4.1. Commercial software comparison

As mentioned before, a tile (about 80 km^2), characterized by different morphologies and land covers, has been selected and for this tile four DSMs have been extracted with eATE, MATCH-T and OrthoEngine software. OrthoEngine software operates with stereo pairs only, consequently for this software two DSMs have been extracted, one orienting the backward (BWD) and the nadir (NAD) images, and one orienting the forward (FWD) and the nadir (NAD) images.

The heights of the extracted DSMs are ellipsoidal with respect to the WGS84 ellipsoid; they were extracted at maximum resolution through each software, then they were resampled using a bilinear interpolation over a grid with 4x4 m cell size in order to perform the comparison with homogeneous products; the between the ellipsoidal and orthometric heights used in the LiDAR reference were computed using the Earth Gravitational Model EGM2008.

For the tile selected and for all software, both a global analysis and the specific investigations over the different morphologies and land covers have been performed. The height differences with respect to the LiDAR reference were computed on the grid of the extracted DSMs by resampling the LiDAR reference itself using a bilinear interpolation; the accuracy statistics (bias, standard deviation, RMSE) were evaluated at the 95% probability level, and the LE95 were computed too; note that the bias is negative when the extracted DSM is above the LiDAR reference. The software used for DSM accuracy assessment is DEMANAL, developed by Prof. K. Jacobsen – Leibniz University Hannover (Germany).

As regards the results, for all software, on the whole selected tile, the biases range within -6.5 to -9.6 m (this last value seems to indicate that a problem affects the OrthoEngine BWD-NAD solution); the standard deviations are close to 13 m, and the corresponding RMSE are around 15.5 m (note that this is approximately the mean value of the RMSEs related to the two OrthoEngine BWD-NAD and FWD-NAD solutions too) (Table). It has to be underlined that all extracted DSMs are above the LiDAR reference, with high biases since the LiDAR reference is a DTM, whereas the elevation data extracted are DSMs, so that the biases take into account of the overall effect of buildings and vegetation.

The selected tile has been divided on the base of different morphologies and land covers (flat, urban and mountain) and an additional assessment has been performed. The accuracy evaluation on the flat, basically cultivated, area is more representative of the behavior of the three software, because the comparison between DTM and DSM here is not impacted by the effect of buildings and vegetation.

The best accuracy is obtained by MATCH-T software (3.2 m), with a bias higher (about 1 m) but a standard deviation lower (about 2.3 m) than OrthoEngine FWD-NAD (
Table).

Note that the RMSE of the OrthoEngine BWD-NAD solution in the flat area is the order of 8.3 m, much higher than the other software. Also in the urban area this is the worst solution, confirming that it probably suffers for matching errors caused by different radiometric characteristics of the backward image (BWD) with respect to the nadir image (NAD) (
Table).

In the urban area the DSM accuracy of the MATCH-T and OrthoEngine FWD-NAD software is similar (8.2 m vs 8.9 m respectively); on the contrary in the mountain area the DSM generated with

OrthoEngine FWD-NAD is slightly better than the DSM generated with MATCH-T (RMSE is 17.6 m vs 19.3 m) (
Table).

An additional test was carried out with MATCH T software only, in order to investigate if it is possible to retrieve a global information about the mean canopy height, and therefore about the biomass. A tile of approximately 40 km^2, mainly covered by the forest, was selected in the South-East part of the area covered by the triplet, due to the fact that, in this area (Province of Trento), both a LiDAR DTM (2.5x2.5 m posting) and a LiDAR DSM (1x1 m posting) are freely available. The analysis shows that the standard deviations are similar for the two comparisons, while biases differ for more than 8 meters, being higher when MATCH T DSM is compared with DTM LiDAR; the difference between the two biases, is likely to be essentially due to the mean canopy height.

Table 1. DSMs assessment on the whole area of selected Tile

Software	Bias [m]	St.dev. [m]	RMSE Z [m]	LE95 [m]
eATE	-8.35	13.14	15.57	33.64
MATCH-T	-7.06	13.94	15.63	34.06
OrthoEngine BWD-NAD	-9.64	13.21	16.36	34.60
OrthoEngine FWD-NAD	-6.52	13.00	14.55	31.71

Table 2. DSMs assessment on different land covers of the selected Tile

Software	Bias [m]	St.dev. [m]	RMSE Z [m]	LE95 [m]
Flat Area				
eATE	-3.42	3.99	5.26	9.04
MATCH-T	-2.18	2.34	3.20	6.05
OrthoEngine BWD-NAD	-5.44	6.34	8.36	13.71
OrthoEngine FWD-NAD	-1.29	4.67	4.84	8.62
Urban Area				
eATE	-8.58	5.65	10.28	19.02
MATCH-T	-6.55	4.98	8.23	15.64
OrthoEngine BWD-NAD	-10.58	7.46	12.95	23.69
OrthoEngine FWD-NAD	-6.04	6.61	8.95	18.34
Mountain Area				
eATE	-9.88	15.94	18.75	30.28
MATCH-T	-8.80	17.18	19.30	34.19
OrthoEngine BWD-NAD	-10.76	15.62	18.96	29.36
OrthoEngine FWD-NAD	-8.39	15.46	17.59	29.06

4.2. Commercial software vs. scientific software SISAR

In order to investigate the potentiality to DSM extraction of the scientific software SISAR with the ZY-3 sensor, a further analysis was developed. Actually, since the software is not yet optimized to manage a large amount of data, a sub-tile (around 25 km^2) (Figure 2) of the selected tile was chosen and two DSMs (SISAR BWD-NAD and SISAR BWD-NAD) were extracted. Again, the comparison among different software (eATE, MATCH-T, OrthoEngine and SISAR) was carried out as before, focusing both on the whole sub-tile area and on the different morphologies and land covers (flat, urban and mountainous).

Also in this sub-tile MATCH-T has the best performance; as regards SISAR, it has good performances in flat and urban areas, worst only with respect to MATCH-T, but it is evident that the main problem with SISAR is related to the noise (standard deviation) of the extracted DSMs (
Table **1**, Table 2).

Table 1. DSMs assessment on the whole area of selected sub tile

Software	Bias [m]	St.dev. [m]	RMSE Z [m]	LE95 [m]
eATE	-5.70	7.53	9.45	20.31
MATCH-T	-4.70	6.59	8.09	19.02
OrthoEngine BWD-NAD	-7.84	9.11	12.02	24.15
OrthoEngine FWD-NAD	-3.97	7.78	8.73	20.16
SISAR BWD-NAD	-4.76	10.39	11.43	23.42
SISAR FWD-NAD	-5.09	10.61	11.77	22.72

Table 2. DSMs assessment on different land covers of the selected sub tile

Software	Bias [m]	St.dev. [m]	RMSE Z [m]	LE95 [m]
Flat Area				
eATE	-2.42	4.64	5.24	8.59
MATCH-T	-1.46	2.11	2.56	5.02
OrthoEngine BWD-NAD	-4.89	7.08	8.60	14.71
OrthoEngine FWD-NAD	-0.66	4.81	4.86	8.21
SISAR BWD-NAD	-2.07	3.67	4.21	8.51
SISAR FWD-NAD	-1.59	3.35	3.70	6.63
Urban Area				
eATE	-8.51	6.06	10.45	19.96
MATCH-T	-5.97	5.39	8.04	16.16
OrthoEngine BWD-NAD	-10.86	7.92	13.44	24.46
OrthoEngine FWD-NAD	-5.19	6.70	8.48	17.63
SISAR BWD-NAD	-6.77	6.21	9.19	18.83
SISAR FWD-NAD	-6.79	4.55	8.18	15.05
Mountain Area				
eATE	-6.81	8.75	11.08	23.06
MATCH-T	-6.22	7.96	10.10	22.32
OrthoEngine BWD-NAD	-8.69	10.22	13.42	26.29
OrthoEngine FWD-NAD	-5.47	8.81	10.37	22.71
SISAR BWD-NAD	-5.54	12.92	14.06	31.48
SISAR FWD-NAD	-6.30	12.92	14.37	28.59

5. Conclusions and prospects

ZY-3 is a first China civil high-resolution stereo mapping satellite. It is able to acquire along track three stereo imagery (triplets), with a swath of 50 km, since it is equipped by three cameras (BWD, FWD and NAD) with the spatial resolution of 2.1 m for the nadir camera and 3.0 m for the backward\forward cameras.

In this paper the capabilities and the potentialities for the 3D reconstruction of this new Chinese satellite was investigated. Several DSMs have been extracted using some commercial software (MATCH-T by Trimble, LPS eATE embedded in ERDAS, OrthoEngine embedded in PCI Geomatica), and a reduced test was carried out with scientific software SISAR, developed at Geodesy and Geomatics Division – University of Rome “La Sapienza”. The former two software are able to process triplets, whereas the latter two software operate with the stereo pairs only; consequently two DSMs were extracted through these software, considering respectively the BWD-NAD and the FWD-NAD pairs.

A tile of 80 km^2 was selected in order to evaluate the performances of the commercial software (MATCH-T, eATE, OrthoEngine); moreover a sub-tile of 25 km^2 was selected for extending the performances comparison to the scientific software SISAR, since this software is not yet optimized to manage a large amount of data at present.

DSMs assessment procedure, based on the comparison with a reference ground truth (LiDAR DTM) was carried out using the scientific software DEMANAL. For each tile both the global analysis and the DSMs evaluation over different morphologies and land covers (flat, urban and mountain areas) were developed, and the accuracy statistical indices (bias, standard deviation and RMSE at the 95% of probability level, LE95) were computed.

The best performance was obtained with MATCH-T in flat cultivated areas, where the comparison between the generated DSMs and the LiDAR reference DTM is substantially not impacted by buidings and vegetation; here, a RMSE of 3.2 m was achieved. On the other hand, the DSMs accuracy ranges between 8 m in the urban area and 19 m in the mountain area, where the effects of buildings and vegetation (mainly forests, in the mountain area) are clearly visible in the biases.

Concerning SISAR software, the results are already encouraging, but clearly indicates that it is necessary: to refine the matching strategy, in order to reduce the noise of the extracted DSMs; to improve the software efficiency both to manage wider images and to process triplets.

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