EURO-MAPS 3D – A TRANSNATIONAL, HIGH-RESOLUTION DIGITAL SURFACE MODEL FOR EUROPE

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ABSTRACT

Euro-Maps 3D is a homogeneous 5 m spaced digital surface model (DSM) semi-automatically derived by Euromap from 2.5 m in-flight stereo data provided by the Indian IRS-P5 Cartosat-1 satellite. This new and innovative product has been developed in close co-operation with the Remote Sensing Technology Institute (IMF) of the German Aerospace Center (DLR) and is being jointly exploited. The very detailed and accurate representation of the surface is achieved by using a sophisticated and well adapted algorithm implemented on the basis of the Semi-Global Matching approach. In addition, the final product includes detailed flanking information consisting of several pixel-based quality and traceability layers also including an ortho layer. The product is believed to provide maximum accuracy and transparency. The DSM product meets and exceeds HRE80 qualification standards. The DSM product will be made available transnational in a homogeneous quality for most parts of Europe, North Africa and Turkey by Euromap step-by-step. Other areas around the world are processed on demand.

1. INTRODUCTION

In May 2005 India launched its IRS-P5 Cartosat-1 satellite equipped with the PAN-Aft and PAN-Fore instruments which form a dual-optics 2-line along-track stereoscopic pushbroom scanner with a stereo angle of 31° and the very interesting resolution of 2.5 m. More details about Cartosat-1 are given in [1]. Because of its optimized and fixed stereo configuration and the very good worldwide coverage Cartosat-1 high resolution stereo satellite imagery is very suitable for the creation of digital surface models (DSMs). In this paper, a system for a highly automated DSM generation (including several quality assurance steps) based on Cartosat-1 stereo scenes is presented.

The generation of Euro-Maps 3D arises from a long-standing, intensive cooperation which combines the outstanding expertise in the field of photogrammetry and image analysis of the Remote Sensing Technology Institute (IMF) of the German Aerospace Center (DLR), GAF AG's long-term experience in working with satellite data and elevation data from many different sources, and Euromap's long-running experience with Indian satellite data from IRS-1C/1D, Resourcesat-1/2, and IRS-P5 Cartosat-1. The intensive cooperation and exchange of research and development expertise, regarding and incorporating user's requirements, and permanent communication between the partners result in high level products meeting customers' needs. Since July, 2010 the CATENA processor developed by DLR and described in detail in [2] is integrated within an overarching, semi-automated processing chain, and operated successfully at Euromap premises**.**

This paper focuses on the description of the Euro-Maps 3D DSM processing workflow, the product itself and the several corresponding quality assurance steps. Furthermore the evaluation strategy is described in detail.

2. WORKFLOW WITHIN SEMI-AUTOMATED PROCESSING CHAIN

The DSM generation process is implemented in Euromap's Production Management System (PMS), which controls the different processors as well as manual editing and quality control processes of the whole, semi-automated production workflow. This workflow consists of the following main steps, whereby the steps 2, 3 and 5 are implemented as part of DLR`s CATENA image processing system.

1. Automated IRS-P5 scene selection
2. Single scene stereo matching and disparity image check
3. Bundle RPC correction and alignment to reference DEM
4. Bundle analysis and accuracy assessment
5. DSM and ortho layer creation
6. Water mask creation, DSM editing and quality layers update
7. Final QC

2.1. Automated IRS-P5 scene selection

Available and suitable stereo pairs for usually up to three coverages are automatically selected from the archive according to parameters like e.g. raw data quality, cloud cover, adequate sun elevation and acquisition date.

2.2. Single scene stereo matching

Hierarchical intensity based matching is used to derive highly accurate tie points between the images of the stereo pairs, and for the dense, epipolar based stereo matching.

The initial matching step performs correlation, using a resolution pyramid [7, 6] to accommodate large stereo image distortions resulting from carrier movement and terrain. Local least squares matching results in a sparse set high quality tie points. Strict thresholds on correlation coefficient and bidirectional matching differences are used to select reliable and very accurate stereo tie points.

An epipolar stereo pair, with epipoles corresponding to the image columns, is generated by aligning the columns of the Fore image with the Aft image, using very accurate matches from the pyramidal matching step. Dense stereo matching is performed on the epipolar images, using semi-global matching (SGM) [6]. SGM avoids using matching windows, and is thus able to reconstruct sharp object boundaries.

Several consistency checks and outlier removal steps are applied in order to remove almost all remaining matching outliers. Finally, the content of the resulting disparity image is statistically analyzed for being sufficient to contribute to the further processing.

2.3. Bundle RPC correction

Previous studies [7] have shown that the Cartosat-1 RPC ground accuracy is in the order of several hundred meters. Furthermore, forward intersection performance without RPC correction is poor and results in large residuals in image space. The estimation of affine RPC correction parameters requires well distributed GCPs with subpixel accuracy. In many application scenarios, such as reconstruction or crisis support applications, acquiring the required GCPs is a time consuming task or might even be impossible, if a fast response is required. Therefore an iterative, fully automated approach has been developed for GCP matching and RPC correction.

Reference datasets used by default are the Landsat ETM+ Geocover mosaic and SRTM elevation data as they are readily available globally. Additionally, for some European countries Euro-Maps 2D, a 5 m seamless mosaic created from IRS-P6 images with a CE90 of 10 – 15 m, or user provided high resolution digital reference images can be used to further increase accuracy.

The Landsat ETM+ Geocover mosaic is specified with a lateral error of 50 m. The accuracy of this dataset is low compared to the high resolution Cartosat-1 images and not sufficient to contribute to the final product, but it is suitable for a preliminary affine RPC correction that makes the entire workflow more reliable.

GCPs are collected by transferring highly accurate tie points from the Cartosat-1 Aft and Fore images to the Landsat reference image and then extracting the corresponding height from SRTM. Preliminary affine RPC corrections for both Aft and Fore images are then estimated using these GCPs [9].

The absolute lateral error of SRTM amounts to 7.2 m - 12.6 m (CE90, depending on the continent), with an absolute height error of 4.7 m to 9.8 m [8].

To take advantage of the higher accuracy of the SRTM dataset, a second RPC correction step is performed. A 3D point cloud is calculated by forward intersection of a subset of the stereo tie points. The point cloud is aligned to the SRTM DSM, and used as input for the final estimation of the affine RPC correction parameters.

The DSM based georeferencing is reliable only in areas with significant relief, as flat areas do not provide the horizontal constraints required for the RPC correction.

To ensure a consistent and high-quality horizontal accuracy of all scenes, RPC correction coefficients are computed with a bundle block adjustment, using large blocks of Cartosat-1 scenes. The reference DSM is used as main control information, similar to the described scene-based correction. Scenes in hilly or rough-textured areas stabilize adjacent scenes located in flat terrain. This procedure is required in extend, flat areas, such as the Po Plain or the Great Hungarian Plain [9].

2.4. Bundle analysis and accuracy assessment

The results of the bundle block adjustment are manually checked by analyzing special bundle reports, which provide very detailed descriptions of the residuals of the GCPs and TPs used for georeferencing and RPC correction. If areas with weak results are detected, a reprocessing can be forced to use more suitable local reference data (e.g. Euro-Maps 2D or VHR reference images) or additional manually derived GCPs measurements.

2.5. DSM and ortho layer creation

The results of the matching and forward intersection are sets of 3D points representing the Earth surface (including e.g. tree tops, buildings) acquired from each single stereo pair. To facilitate further applications, the irregular point clouds are combined and converted to a regularly spaced grid with a spacing of 5 m. If multiple points fall into the same grid cell, their heights are calculated with median, to form a new point. Remaining holes are filled with SRTM data or other usable digital elevation models, using the delta surface fill algorithm [5]. The 5 m DSM is accompanied by several quality- and traceability layers, including an ortho layer with a user defined datum and projection created by orthorectification of the near-nadir image with the generated DSM and the affine corrected RPCs. Additionally the 5 m DSM is accompanied by several quality- and traceability layers.

Finally, accuracy assessment is carried out by using available vector and raster reference datasets. More details regarding accuracy evaluation can be seen in Section 4.1.

2.6. Water mask creation, DSM editing and quality layers update

Area-wide water masks are generated either automatically or semi-automatically, depending mainly on the visual appearance of the water areas (e.g. riverine sediments). As a first step a water mask is generated based on Landsat data by using ratios of certain channels and by additionally using a slope function based on SRTM 90 m data. The water mask is classified into three classes: land, potential water, water. The class potential water often contains areas with shadows, which can be excluded afterwards to improve the quality of the initial Landsat-derived water mask. This can be done by using segmented IRS-P5 ortho layers as input for the sharpening of the water mask.

The major advantage of this approach is that a globally available reference dataset can be used for the initial derivation of the water mask. The threshold values only have to be adapted marginally in different regions of the world.

In problematic areas, a semi-automated approach is carried out by using a region-growing algorithm on the basis of the IRS-P5 ortho layer. Therefore seed pixels are set into the water areas and depending on the chosen threshold grey values and other optional parameters the pixels are spread until a terminal point.

Areas with artifacts like wells and peaks are detected manually through visual inspection by experts or automatically by calculating difference images or deltaH values.

Metadata and quality layers are created highly automated earlier within the processing chain. The necessity to manually edit artifacts like spikes implies that also the quality layers have to be updated. A detailed description of the resulting layers is found in Section 3.1.

2.7. Final QC

During the final QC the plausibility of the DSM height values and the water mask is checked systematically by DSM experts. Also cross checks to the geometry of the finally edited DSM that have been accuracy assessed, are performed.

Additionally all the quality layers are checked regarding format and consistency.

3. EURO-MAPS 3D DSM PRODUCT

3.1. Specifications

The DSM has a resolution of 5 m and an absolute horizontal (CE90) and vertical accuracy (LE90) between 5-10 m for areas with slopes $\leq$ 20%. The vertical resolution of the DSM is 1 m.

The file format is 16-bit GeoTIFF and the product is delivered in 0.5° x 0.5° tiles.

The spatial reference system is either UTM, geographic or another projection based on WGS84.

The height reference system is EGM96.

In order to guarantee the traceability of information and the data quality, a Euro-Maps 3D DSM product includes several traceability and quality layers. This is necessary information for the user, as DSM values alone are often difficult to interpret. The information is traceable pixel wise.

The first layer (Source) contains the information about each pixel's origin. The value 1 is allocated for IRS-P5, value 2 for SRTM, values 3-9 are reserved for other potential DEM sources (e.g. CosmoDEM, SPOT DEM, AsterGDEM), value 10 is allocated for manually edited pixels, value 11 stands for water masked pixels and values 12-255 are reserved for other use.

Another quality layer (Number) shows the number of IRS-P5 stereo pairs that were used to derive the height value. The value 0 illustrates height values not derived from IRS-P5. The number of IRS-P5 stereo pairs used can be an important quality feature for the DSM.

The quality control layer is set to 1 for each pixel or height value which is derived from IRS-P5 data and which was rated by the quality control procedures of the production process to meet or exceed the product specifications. A pixel set to 0 does not meet or is not sure to meet the quality.

In the accuracy layer the expected absolute vertical accuracy (LE90) is specified in three slope classes (0-20%, > 20-40% and > 40%) to give a better overview of the distribution of accuracies across slope-classes.

3.2. Production strategy

The major focus for the production of the first final products lies on the Euromap footprint which is shown in Figure 1 and where coverage with stacks of up to 10 stereo pairs exists for many countries and regions.

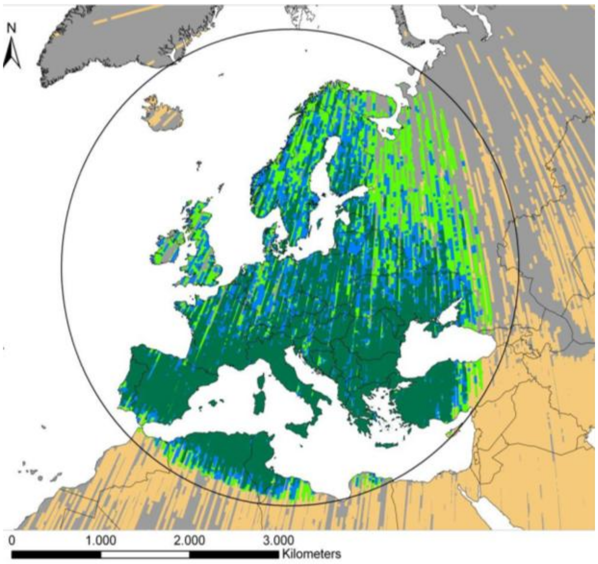

Figure 1: Euromap footprint and IRS-P5 Cartosat-1 stereo multiple coverage (dark green ≥ 3; blue = 2; light green = 1)

South-Eastern European countries like Kosovo (see Figure 2), Greece, Albania, and Slovenia are already processed as final products.

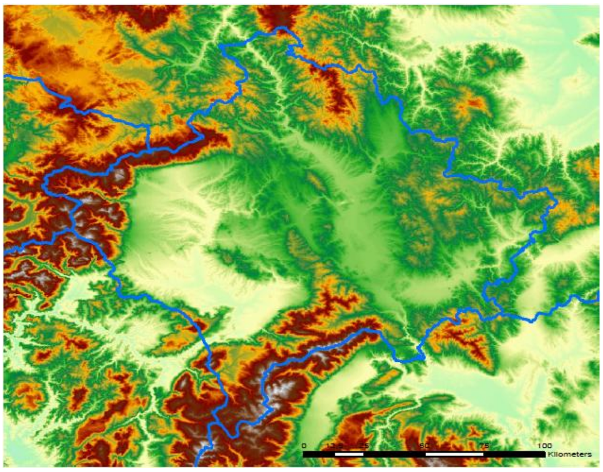

Figure 2: Euro-Maps 3D DSM of Kosovo and adjacent areas, derived from 138 stereo pairs with up to 8 stereo pairs overlapping each other

Other areas in regions such as the Near- and Middle East, Asia and America can be processed with the same quality on request.

4. PRODUCT EVALUATION

4.1. Evaluation Strategy

For an independent examination of the horizontal and vertical accuracy of the digital surface models, kinematic GPS transects, LIDAR reference points and aerial images were used as a reference datasets at several well-distributed test sites. Major parts of the horizontal and vertical accuracy assessment of the Euro-Maps 3D DSM was performed using a software, developed by the GAF AG programming department, capable of using either vector (GPS Track) or raster (reference DEM) data as reference data. For the horizontal check against aerial images another GAF software, the Correlator was used.

In order to ensure the quality of the GPS tracks, potentially erroneous GPS measurements were detected automatically (PDOP / HDOP value > 5) and manually (visual inspection) and were then eliminated, as they provide incorrect heights in comparison to the Euro-Maps 3D DSM (e.g. bridges, forests) [9].

The vertical difference (deltaH) was then calculated by comparing the GPS height or the reference DEM height with the height of the Euro-Maps 3D DSM. The vertical accuracy (LE90) was subsequently computed for each test site.

The horizontal accuracy was calculated by finding the minimum standard deviation of height differences between the GPS height or the reference DEM height and the Euro-Maps 3D DSM in the north-south and east-west directions and then calculating the CE90 based on the length of the resulting shift vectors.

These results were also checked by visually comparing the GPS tracks with the ortho layers.

22 test sites from within the Euromap IRS-P5 acquisition footprint and well distributed across Europe, Turkey and North Africa were chosen for the accuracy tests. The test sites were identified according to various criteria, such as good coverage by GPS transects, a range of landscapes, e.g. urban areas, forested areas, agricultural areas, and dry areas, and various types of relief (flat, hilly, mountainous) [9].

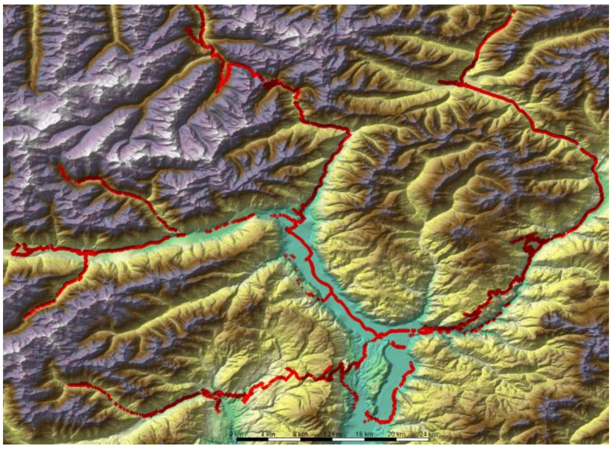

Figure 3: Euro-Maps 3D DSM of Bozen, Italy, with the corresponding GPS transects

Additionally, the slope-dependent and area-wide horizontal accuracy was tested over 15 test sites located in the northern part of Italy and covered by a DSM processed from approximately 420 stereo pairs (Po Plain, 90,000 km² (see Figure 4 from [4]). To avoid potential problems with georeferencing in very flat and untextured areas (Po Plain), the more textured surrounding areas (Alps, Apennines) were used to achieve a good horizontal accuracy.

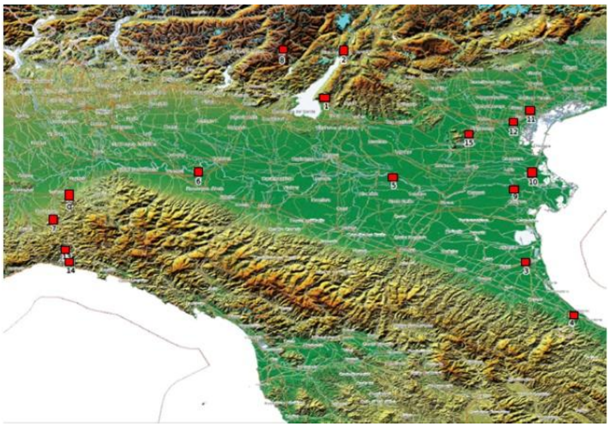

Figure 4: AOI of the Po Plain in Italy with 15 test sites

4.2. Results

The accuracy tests for 22 IRS-P5 DSMs individually processed from single scenes scattered across Europe confirmed a horizontal accuracy (CE90) of 6.7 m and a vertical accuracy (LE90) of 5.1 m (see Table 1).

Table 1: Vertical and horizontal accuracy of 22 DSMs processed individually from single scenes

Test area	Description	LE90 (m)	CE90 (m)
Ankara	Urban, hilly	3.9	4.2
Kastamonu	Urban, hilly	3.4	2.2
Uzunköprü	Agriculture, flat	8.3	4.0
Aydin	Agriculture, forest, mountainous	5.5	5.9
Arles	Wetlands, agriculture, flat	2.6	9.4
Nebelhorn-north	Mountainous	3.9	4.6
Nebelhorn-south	Mountainous	4.1	5.8
Munich	Urban, agriculture, flat	6.3	4.3
Heidelberg	Forest, urban, agriculture, hilly	5.2	5.8
Koblenz	Forest, urban, open cast mining, hilly	7.1	5.6
Friedrichshafen	Forest, flat	5.3	8.9
Relizane	Dry, flat	5.9	6.9
Gospic	Forest, hilly	8.4	3.1
Tunis	Urban, hilly	4.4	6.0
Le Kef 1	Dry, flat	3.9	5.7
Le Kef 2	Dry, flat	4.0	7.8
Sfax	Dry, very flat, salt lake	4.0	7.9
Gafsa	dry, flat	3.6	7.4
Mlawa	Forest, agriculture, flat	8.4	5.1
Nowy Targ	Forest, agriculture	6.4	7.4
Mostar	Agriculture, hilly	4.5	7.0
Trebinje	Agriculture, hilly	5.6	4.1

Three test areas near Barcelona, Spain, were examined with LIDAR reference points [3]. The results of these tests are shown in Table 2, whereby the statistics for different landcover types were computed on the Terrassa area.

The NMAD is a very robust estimated measure for the mean height difference and therefore not influenced by outliers, which is especially important during accuracy assessment of DEMs.

Table 2: Statistical evaluation of the Euclidian distance between LIDAR reference points and the Euro-Maps 3D DSM

Test area	Mean	Med	Std	NMAD	AQ68	AQ95
Terrassa	0.03	0.00	3.44	2.07	2.29	6.83
Vacarisses	-0.16	0.07	4.05	2.80	2.97	7.45
La Mola	-1.21	-0.03	8.18	3.69	3.90	12.64
Field	0.19	0.13	1.99	1.25	1.31	3.90
Bridge	1.22	0.28	4.86	2.12	2.27	12.18
Industrial	-0.10	-0.10	3.11	2.33	2.49	6.19
Residential	0.49	-0.08	3.90	2.64	2.88	8.28
City	-0.56	-0.64	5.63	3.88	4.16	10.36

For the 15 test sites located within a DSM covering roughly 90,000 km² of the Po Plain and surroundings in Northern Italy and processed with bundle adjustment from approx. 420 stereo pairs and available GCPs for the most flat areas, an overall CE90 of 9.4 m against RealVista aerial ortho images, provided by e-Geos, was calculated. Like expected previously, the accuracy was better in hilly and textured areas than in very flat areas next to the Adria coast.

It should be noted that the accuracy assessment with GPS transects is only representative for certain areas with moderate slopes and does not reflect the slope-dependent and land cover-dependent accuracy of the DSM.

5. CONCLUSIONS

During the long-term experience with Euro-Maps 3D processing, increasing evidence was seen, that quality assurance steps before and after processing and also after each processing step (if possible fully automated) are indispensable. Within the CATENA and PMS processing chain, many QA steps are integrated in the meantime and this leads to a more reliable and better DSM product.

The results of the accuracy assessment exercises show that the initially declared and expected DSM accuracy of approximately 5-10 m for both LE90 and CE90 can be reached in areas with less than 20% slope. In many of the areas, the values achieved are considerably better than the expected values.

Area-wide DSM-processing was tested for a large test area in Northern Italy. A systematic accuracy assessment focusing on slope-dependent and land cover-dependent accuracies was carried out at this test site. It is shown, that the lateral accuracy of the final DSM is improved significantly by triangulating the calculated 3D point clouds derived from several hundred scenes and by additionally using available GCPs for the most flat areas.

In the meantime the bundle block adjustment integrated in the CATENA software was enhanced, resulting in better accuracies, and therefore new accuracy tests will be carried out in the near future. In the newest version of the accuracy assessment tool it is also possible to check horizontal accuracy between two DEM datasets. This is done by using cross-correlation for many points in the corresponding DEMs.

6. REFERENCES

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