A Concept for a Standardized DSM Product Automatically Derived from IRS-P5 Cartosat-1

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The DLR, GAF AG and Euromap cooperate regarding the development of digital surface model (DSM) products based on IRS-P5 Cartosat-1 in flight stereo data. The core of the DSM generation process is implemented as part of the DLR XDibias image processing system within the Euromap ground station facility in Neustrelitz.

IRS-P5 Cartosat-1 high resolution stereo satellite imagery is well suited for the creation of DSMs. A system for highly automated and operational DSM and orthoimage generation based on IRS-P5 Cartosat-1 imagery is presented, with an emphasis on automated processing and product quality. The proposed system processes IRS-P5 level-1 stereo scenes using the rational polynomial coefficients (RPC) universal sensor model. The described method uses an RPC correction based on DSM alignment instead of using reference images with a lower lateral accuracy, which results in improved geolocation of the DSMs and orthoimages. Following RPC correction, highly detailed DSMs with 5 m grid spacing are derived using Semiglobal Matching.

In order to guarantee the traceability of information and the data quality, the product is accompanied by several traceability and quality layers. The combination of a high-quality DSM and the generated quality layers is unique.

When processing larger areas, the relative alignment of DSMs and orthoimages is carried out via bundle block adjustment. This bundle block adjustment is currently tested in an area covering ~90,000 km^2 in the northern part of Italy (Po plain and surrounding areas). An area-wide accuracy assessment with a major focus on slope-dependent accuracy will be carried out with suitable reference data.
In addition, an evaluation in chosen test sites against independent ground truth measurements indicates a mean lateral error (CE90) of 6.7 m and a mean vertical accuracy (LE90) of 5.1 m.

1. INTRODUCTION

In May 2005 India launched its IRS-P5 Cartosat-1 satellite equipped with the PAN-Aft and PAN-Fore instruments which constitute 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. Cartosat-1 high resolution stereo satellite imagery is very suitable for the creation of digital surface models (DSMs).

In this paper, a system for highly automated DSM generation based on Cartosat-1 stereo scenes is presented. More details about Cartosat-1 are given in [9].
Cartosat-1 stereo scenes are furnished with a rational polynomial coefficient (RPC) sensor model [2], derived from orbit and attitude information. The RPCs have a much lower absolute accuracy than the ground resolution of approximately 2.5 m. Subpixel accurate ground control points (GCPs) have been used in previous studies to estimate biases or the affine RPC correction parameters required for the high quality geolocation of high resolution satellite images [6]. Such highly accurate GCPs are usually derived from a DGPS ground survey or high resolution orthoimages and digital elevation models.

For large scale and continent-wide processing, the establishment of a highly accurate GCP database with the density required for processing the relatively small Cartosat-1 scenes (810 km²) requires significant resources. For near real-time applications such as disaster assessment tasks in remote regions, highly accurate GCP data are often not available.

We propose the use of widely available lower resolution satellite data, such as the Landsat ETM+ and SRTM DSM datasets as a reference for RPC correction. The accuracy of these datasets is low compared to the high resolution Cartosat-1 images. The absolute lateral error of ETM+ Geocover is 50 m (CE90), the absolute lateral error of SRTM is between 7.2 m and 12.6 m (CE90, depending on the continent), with an absolute height error of 4.7 m to 9.8 m [8]. The traditional method of collecting lateral positions from a reference image and interpolating the corresponding heights from the DEM ignores the higher lateral accuracy of the SRTM dataset. Our method avoids this drawback by using an RPC correction based on DSM alignment, resulting in improved geolocation of the DSMs and orthoimages generated. In areas, where more accurate ortho mosaics are available (e.g. Euro-Maps 2D), they can potentially replace Landsat ETM+ as reference.

Digital surface models are derived from dense stereo matching and forward intersection, with subsequent interpolation into a regular grid. The first part of this paper describes the process used for DSM generation, with specific emphasis being placed on the georeferencing. The second part describes how the products standard quality can be assured by the generation of so called quality and traceability layers. The third part evaluates the processor using 22 Cartosat-1 stereo pairs for which high quality kinematic GPS transects are available.

Euromap's long-running experience with satellite data from India (IRS-1C/1D, IRS-P6 Resourcesat-1, IRS-P5 Cartosat-1), GAF AG's long-term experience in working with satellite data and elevation data from many different sources, and DLR's Remote Sensing Technology Institute's outstanding expertise in the field of photogrammetry and image analysis are combined during this cooperation. 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 DLR processor is operated successfully at Euromap premises**.**

2. CARTOSAT-1 STEREO PROCESSOR

The DSM generation process consists of the following main steps, implemented as part of the DLR`s XDibias image processing system.

1. Stereo matching in epipolar geometry
2. Affine RPC correction and alignment to reference DEM
3. Forward intersection and outlier removal
4. DSM interpolation
5. Orthorectification
6. Quality assurance
7. Generation of water masks
8. Bundle block adjustment

2.1. Stereo matching

Hierarchical intensity based matching is used for matching the stereo pairs and the reference image. This consists of two major steps, hierarchical matching to derive highly accurate tie points and dense, epipolar based stereo matching.

The initial matching step performs correlation, using a uses a resolution pyramid [7;5] 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 semiglobal matching (SGM) [4]. 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 [1]. On average, valid disparities are found for more than 90% of all image pixels representing ground features.

2.2. Georeferencing

Previous studies [6] 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 continent wide 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.

Landsat ETM+ Geocover mosaic and SRTM elevation data are readily available global reference datasets. The accuracy of these datasets is low compared to the high resolution Cartosat-1 images. The Landsat ETM+ Geocover mosaic is specified with a lateral error of 50 m. 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].

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.

2.3. RPC correction by DSM alignment

Following the alignment based on ETM+ and SRTM reference data, forward intersection residuals are significantly improved, but the lateral accuracy is still limited by the ETM+ Geocover reference. To take advantage of the higher accuracy of the SRTM dataset, a second RPC correction step is necessary. 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.

2.4. DSM and orthoimage

The result of the matching and forward intersection is a set of 3D points representing the Earth surface (including e.g. tree tops) acquired from the stereo images. To facilitate further applications, the irregular point cloud is converted to a regularly spaced grid with a spacing of 5 m. If multiple points fall into the same grid cell, their heights are averaged to form a new point. Remaining holes are filled with SRTM data, using the delta surface fill algorithm [3]. Orthoimages with a user defined datum and projection are created by orthorectification of the Aft image with the generated DSM and the affine corrected RPC

2.5. Quality assurance

In order to guarantee the traceability of information and the data quality, an IRS-P5 Cartosat-1 DSM is accompanied by several traceability and quality layers. This is necessary as background information for the user of the height data. The information is traceable pixel wise.

Metadata and quality layers are created highly automated within the processing chain.

The first layer (Source1) contains the information for each pixel's origin. The value 1 is allocated for IRS-P5, 2 for SRTM, 3-9 are reserved for other potential DEM sources (e.g. SPOT DEM, AsterGDEM), 10 is allocated for manually edited pixels, 11 stands for water masked pixels and 12-255 is reserved for other use. Below an example for this quality layer can be found, where IRS-P5 pixels are grey, SRTM pixels are red, edited pixels are yellow and water mask pixels are blue (see Fig.1).

Another quality layer (Source2) shows the number of IRS-P5 stereo pairs, which were used to create the DSM for every single pixel or 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 / 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.

The expected absolute vertical accuracy (LE 90) is specified in three slope classes (0-20%, 20-40% and > 40%). This layer is preliminary and will be finalized after testing the accuracy of DSMs area-wide and slope-dependent.

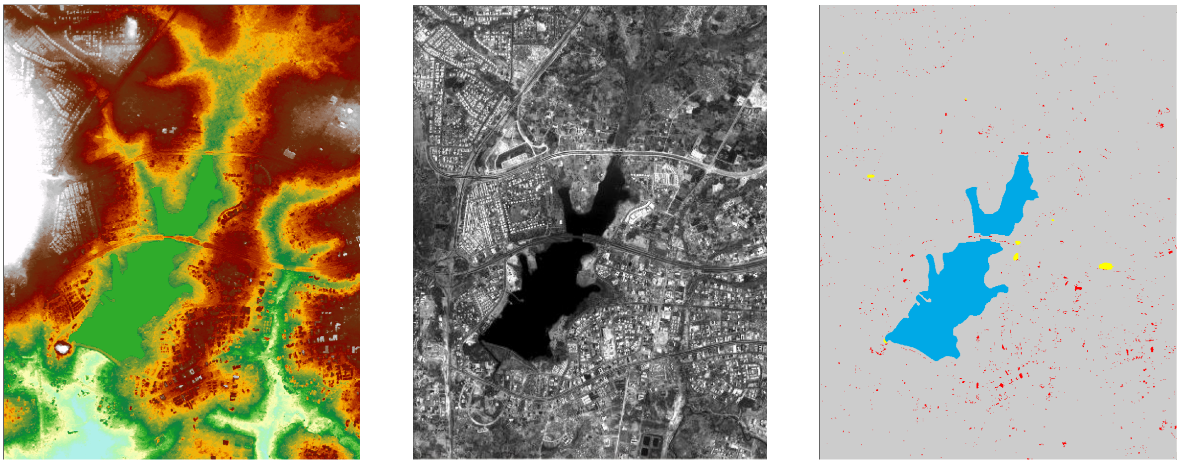

Figure 1: DSM, orthoimage and quality layer (Source1) of an area in Abuja, Nigeria (© 2010, Euromap, includes Antrix material)

2.6. Generation of water masks

By using a two-step approach, area-wide water masks can be generated automatically out of Landsat data and IRS-P5 orthoimages. 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 90m 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 orthoimages 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.

2.7. Bundle block adjustment

The DSM based georeferencing described in Section 2.3 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 consistency 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 scene based correction described in Section 2.3. Scenes in hilly or reliefed areas stabilize adjacent scenes located in flat terrain. This procedure is required in extend, flat areas, such as the Po plain in the northern part of Italy. Areas with weak geometry are detected, and are stabilized using additional GCP measurements.

3. EVALUATION

3.1. Evaluation strategy

For an independent examination of the horizontal and vertical accuracy of the digital surface models, kinematic GPS transects were used as a reference dataset at 22 test sites. The software used for accuracy assessment was developed by the GAF AG programming department. A two step procedure is followed in order to ensure the quality of the reference dataset: the first step involves the automatic detection and elimination of erroneous GPS measurements and the second step results in GPS points that are considered as not reliable, as they provide incorrect heights in comparison to the DSM (e.g. bridges, forest, ...), being deleted.

After eliminating incorrect GPS measurements the vertical accuracy is calculated by comparing the GPS height and DSM height for each pixel. The vertical accuracy (LE90) is subsequently computed for each test site.

As a next step, the horizontal accuracy is calculated by finding the minimum standard deviation of height differences of the track in the north-south and east-west directions and then calculating the CE90 based on the length of the resulting shift vectors (see Fig.2).

These results are checked by visually comparing the track with the orthoimage.

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. Various criteria were considered during the identification of test sites – e.g. good coverage by the GPS transect, a range of landscapes, such as urban areas, forested areas, agricultural areas, and dry areas, and also various types of relief (flat, hilly, mountainous).

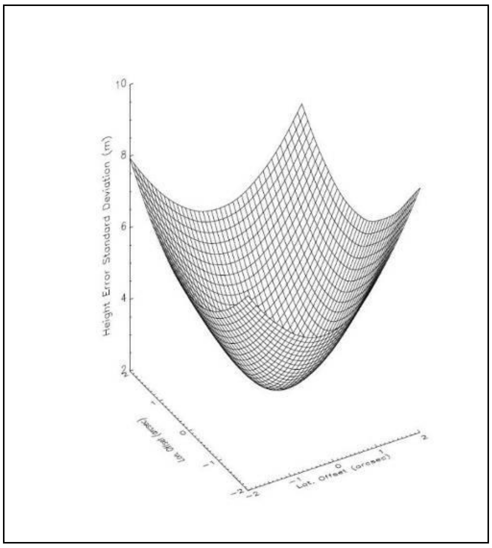

Figure 2: Surface plot of the standard deviation of the height error sampled along a kinematic GPS track over a mountainous SRTM cell [8]

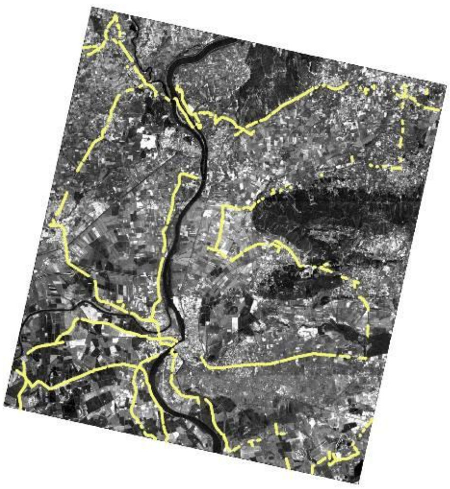

Figure 3: 2.5 m orthoimage from a test site around Arles (France) with the corresponding GPS transects

Additionally, the slope-dependent and area-wide accuracy will be tested for an area in the northern part of Italy covered by approximately 420 stereo pairs (Po plain, 90,000 km²). Such tests are also very important for examining the methods used for image block adjustment. In this case, the better horizontal accuracy of DSMs generated in more textured areas (Alps, Apennines) will be used for compensating (adjusting) the potentially worse horizontal accuracy in very flat and un-textured areas (Po plain).

3.2. Results

The accuracy tests, using 22 single IRS-P5 DSMs scattered across Europe which were processed individually, confirmed a horizontal accuracy (CE90) of 6.7 m and a vertical accuracy (LE90) of 5.1 m.

When comparing the LE90 values of the test sites with the LE90 values of the SRTM tiles and the continent-wide calculated CE90 values of SRTM, the IRS-P5 values are similar or even better.

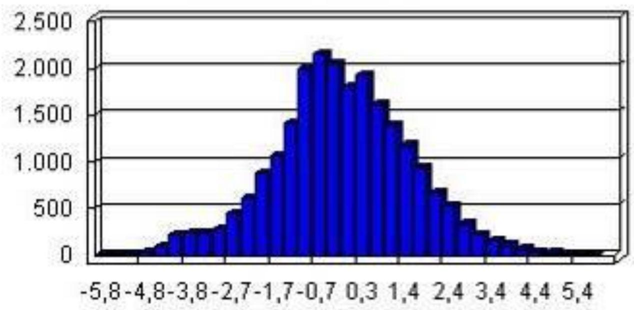

Figure 4: Frequency distribution of height differences between DSM and GPS height values in Arles (France)

Table 1: Vertical and horizontal accuracy at 22 test sites

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
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	Agriculture, forest, mountainous	6.4	7.4
Mostar	Agriculture, hilly	4.5	7.0
Trebinje	Agriculture, hilly	5.6	4.1
Relizane	Dry, flat	5.9	6.9
Gospic	Forest, hilly	8.4	3.1
Friedrichshafen	Agriculture, forest, flat	5.3	8.9

It should be noted that the accuracy assessment with GPS transects is only representative for certain areas and does not reflect the slope-dependent and land cover-dependent accuracy of the DSM. Further area-wide accuracy tests will therefore be carried out in the near future.

4. CONCLUSIONS

The results of the accuracy assessment of 22 well-distributed test sites show that the initially declared and expected DSM accuracy of approximately 10 m for both LE90 and CE90 can be reached without difficulty. In many of the areas, the values achieved are considerably better than the expected values.

Area-wide DSM-processing is currently being carried out for a test area in Northern Italy. A systematic accuracy assessment focusing on slope-dependent and land cover-dependent accuracies will be carried out at this test site. It is expected that the lateral accuracy of the mosaiced DSM will be improved significantly by triangulating large blocks containing several hundred scenes.

The IRS-P5 Cartosat-1 DSM product characteristic permits the usage within a wide range of geo-applications which depend on the input or processing of elevation data. Basically the DSM product provides ideal elevation reference information for any satellite image ortho-rectification procedure. Also its corresponding 2.5 m Cartosat-1 orthoimages implies an excellent geo-reference data set for VHR- and HR-satellite image orthorectification. Other potential fields of application are e.g. infrastructure and urban planning and monitoring, controlling and monitoring of open cast mining, flood modelling, Line-of-sight analysis, volume calculation, and telecommunication network planning.

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