3D PROCESSING OF HIGH-RESOLUTION SATELLITE IMAGES

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Abstract: High-resolution satellite images at sub-5m footprint are becoming increasingly available to the earth observation community and their respective clients. The related cameras are all using linear array CCD technology for image sensing. The possibility and need for accurate 3D object reconstruction requires a sophisticated camera model, being able to deal with such sensor geometry. We have recently developed a full suite of new methods and software for the precision processing of this kind of data. The software can accommodate images from IKONOS, QuickBird, ALOS PRISM, SPOT5 HRS and sensors of similar type to be expected in the future.
We will report about the status of the software, the functionality and some new algorithmic approaches in support of the processing concept. The functionality will be verified by results from various pilot projects. We put particular emphasis on the automatic generation of DSMs, which can be done at sub-pixel accuracy and on the semi-automated generation of city models.
Key Words: Linear Array Imagery, DTM / DSM Generation, Sensor Model, 3D City Models.

1. Introduction

The recent generations of high-resolution satellite imaging systems, such as IKONOS, QuickBird and SPOT5 open a new era of earth observation and digital mapping. They provide not only for high-resolution and multi-spectral data, but also the capability for stereo mapping. The related sensors are all using linear array CCD technology for image acquisition. The processing of high-resolution satellite images also provides a challenge for algorithmic redesign and this opens the possibility to reconsider and improve many photogrammetric processing components, like image enhancement, multi-channel color processing, rectification, triangulation, orthophoto generation, DTM generation and object extraction in general.

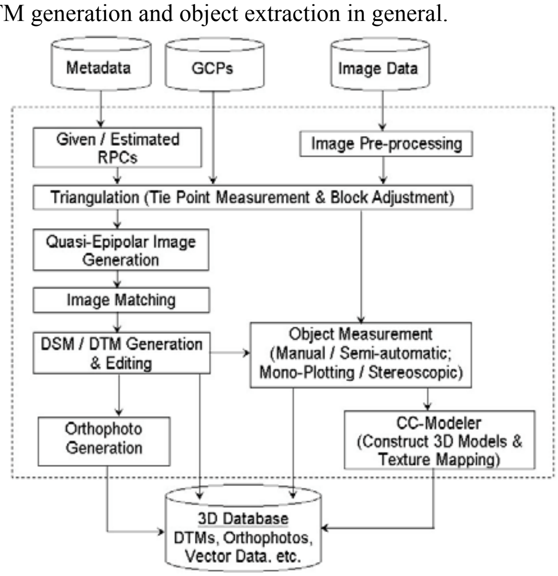

Figure 1: Workflow of the software system

Our group has recently developed a full suite of new methods and software for the precision processing of high-resolution satellite image data. The software can accommodate images from IKONOS, QuickBird, ALOS PRISM, SPOT5, etc. Figure 1 shows the workflow of this system.
The main components of the software include:

+ User interface for image handling and image measurement in mono and stereo, in manual and semi-automated modes
+ Sensor model adjusted to the particular sensor geometry
+ Orientation of single stereo models and triangulation of larger units. Tie point measurement in manual, semi-automated and fully automated modes
+ Derivation of quasi-epipolar images
+ Automated generation of Digital Surface Models (DSM)
+ Generation of orthophotos
+ Mono-plotting functions
+ Extraction of objects with particular emphasis on 3D city modeling

In this paper we put particular emphasis on the automatic generation of DSMs, which can be done at high accuracy and on the semi-automated generation of 3D city models. First we will briefly report about some key algorithms of our software system. Then we will show the results from the stereo processing of IKONOS and SPOT5.

2. Theoretical Foundation and Algorithms

1) Sensor Model and Block Adjustment

High-resolution satellite cameras use linear arrays that acquire a single image line at an instant of time, each with its own positional and attitude data. The imaging geometry is characterised by nearly parallel projection in along-track direction and perspective projection in cross-track direction.
A rigorous model is used to reconstruct the physical imaging geometry and transformations between the object space and the image space. Owing to the dynamic nature of satellite image acquisition, this kind of model is more complicated than in the single frame case. Moreover, high-resolution pushbroom cameras such as IKONOS have a very narrow field of view, resulting in near linear dependencies between many physical camera model parameters [3]. For example, the along-track and cross-track position errors are highly correlated with pitch and roll attitude errors so that they can not be separated and safely estimated.
Alternatively, Rational Function Models (RFM) can be used. These models don't describe the physical imaging process but use a general transformation to describe the relationship between image and ground coordinates. A RFM is generally the ratio of two polynomials and the parameters are derived from the rigorous sensor model with an approximate orientation ([3], [6]). IKONOS and QuickBird images are being released to the clients with Rational Polynomial Coefficients (RPCs) only.
For IKONOS we do not have information about the camera model, therefore we use the RFM concept. For SPOT and other satellite images, we use the rigorous physical sensor model. With the supplied RPCs from IKONOS, QuickBird or estimated RPCs, and the mathematical model proposed in [3], the block adjustment is performed. Accuracy tests have been made using SPOT5 HRS and IKONOS images. The results show that the orientation accuracy is on sub-pixel level.
For satellite images with a narrow field of view like IKONOS and QuickBird, the affine projection model and the projective

direct linear transform model DLT can be used. They are special cases of the RFM model. These models are geometrically and numerically more stable than the complex physical models [2].

2) Derivation of Quasi-Epipolar Images

Here the original satellite image data is transformed into quasi-epipolar form in order to remove/reduce the y-parallaxes. This is absolutely necessary for manual stereoscopic plotting, because otherwise the remaining parallaxes would disturb the stereo viewing. The procedure uses the orientation parameters estimated by least squares adjustment and projects the original images onto a pre-defined horizontal object plane. For the IKONOS quasi-epipolar resampled products this procedure can be skipped.

3) Automatic Generation of Digital Surface Model (DSM)

In order to extract the DSMs from the High-resolution satellite images, algorithms and a software package have been developed in our group [7].

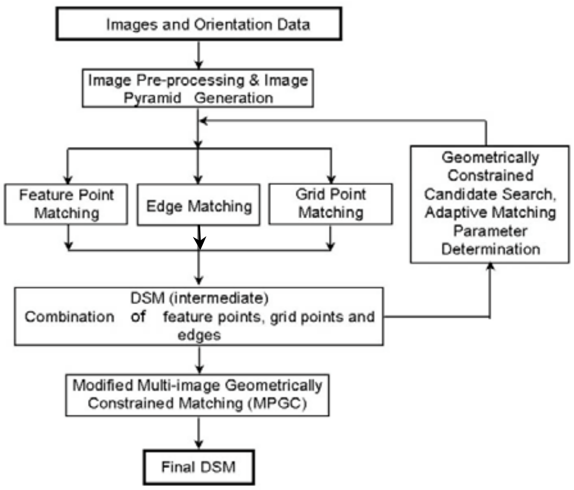

Figure 2: Flowchart of our image matching approach

The matching procedure for automatic DSM generation from high-resolution satellite images exploits the characteristics of the linear array imagery and its imaging geometry. It can provide dense, precise, complete and reliable results. The method uses a coarse-to-fine hierarchical solution with a combination of several image-matching algorithms (such as area-based matching, edge-based matching, global image matching with relaxation technique and geometrically constrained least squares matching) and incorporates automatic quality controls. After pre-processing of the images and production of the image pyramids, the matches of three kinds of features, i.e. feature points, grid points and free-form linear features, are found progressively, starting from the low-density features on the images with low resolution. An intermediate triangular irregular network (TIN) based DSM is constructed from the matches on each level of the pyramid, which in turn is used in the subsequent pyramid level for the approximations and adaptive computation of the matching parameters. Finally the modified Multi-Photo Geometrically Constrained (MPGC) matching ([1], [4]) is used to achieve more precise matches for all the matched features and to identify inaccurate and possibly false matches. A raster DSM can be interpolated from the original matching results. Figure 2 shows the flowchart of our image matching approach.

The algorithm generates not only a large number of mass points but also produces linear features, so that the terrain can be well captured and modeled. Figure 3 shows an example of the matched linear features, which provide for a very densely sampled DSM (Figure 4).

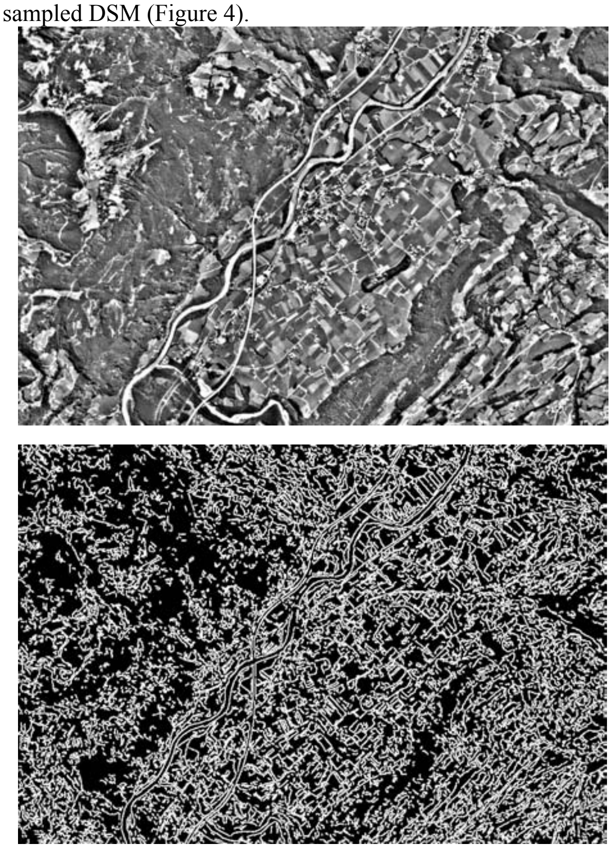

Figure 3: The top picture shows part of a SPOT5 HRS image and, the bottom picture shows the successfully matched linear features

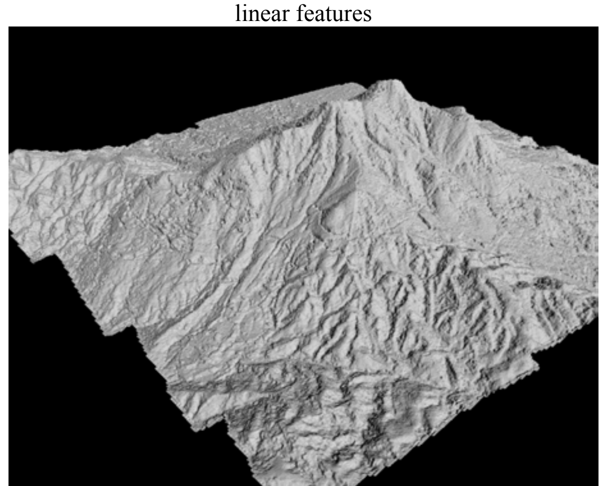

Figure 4: Shaded DSM extracted from IKONOS images of Japan’s Tsukuba area

4) Extraction of Objects and 3D City Modelling

Stereo measurement software is used for 3D object collection. Semi-automatic methods are available for some kinds of objects like buildings, roads and rivers. Given the DSM data, some objects can be measured with the monoplotting module by just using single images and the underlying DSM.

CyberCity Modeler (CC-Modeler) represents a methodology for semi-automated object extraction and modeling of built-up environments from images of satellite, aerial and terrestrial platforms. It is generic in the sense that it allows to model not only buildings, but all objects of interest which can be represented as polyhedral model, which includes DTM, roads, waterways, parking lots, bridges, trees and so forth (even ships have been modeled). As such it produces 3D city models efficiently, with a high degree of flexibility with respect to metric accuracy, modeling resolution (level of detail), type of objects and processing speed. The basic algorithm and related projects have been previously reported in [5].

With the mono/stereo measurement software the buildings, roads and other kinds of man-made objects can be measured manually or semi-automatically by using satellite images. The measurement procedure must follow the regulation of CC-Modeler, such that it can process this data directly.

Since the input data of CC-Modeler is just point clouds, it does not matter which sensor model is used to construct the 3D vector model. However, the sensor model must be identified if the full 3D model with texture mapping is required. In this case, the necessary modification of CC-Modeler is to extend the sensor model from the normal frame perspective projection to those of high-resolution satellite images. The procedure of texture mapping is to project the object faces from 3D space onto the satellite images and take the image patch that has the best resolution.

Figure 6 shows a visualization of the 3D city model Izmir, Turkey, derived from IKONOS images.

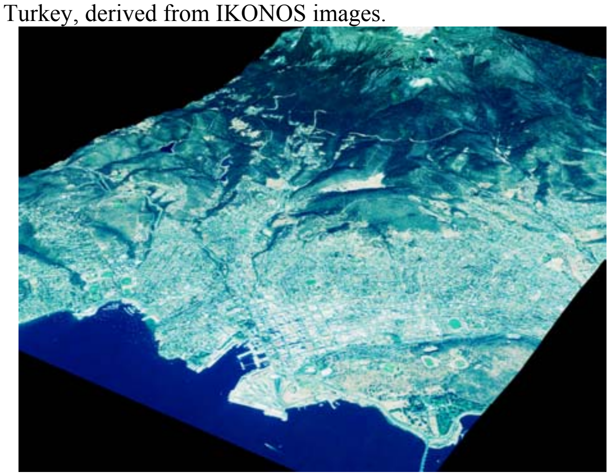

Figure 5: Textured DSM model of Hobart (Australia) area

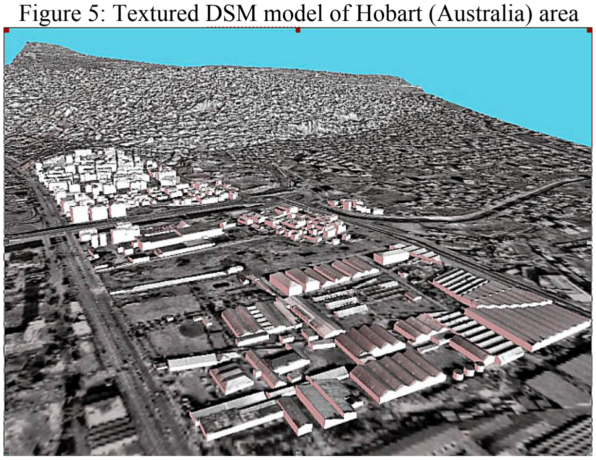

Figure 6: Visualisation of the textured 3D model of Izmir

3. Applications and Test Results

Hobart-Tasmania, Australia test area (IKONOS):

The image data of this test area includes IKONOS 1-meter Panchromatic Geo-Level and 4-meter Multi-spectral images. The images cover an area of about 12 × 16 km^2 and 111 well-distributed and highly accurate GCPs were measured on the ground and in the images. The elevation of the test area varies from 0 to 1200 meters.

The orientation results for the 1-meter images are shown in Table 1. A 5-meter interval DSM was generated by using the stereopairs of the Geo-Level Panchromatic images. To access the accuracy of the DSM, we used all the GCPs as reference points and interpolated their heights into the photogrammetrically determined DSM. The resulting height accuracy is about 0.9 meters. Figure 5 shows the 3D visualization of the DSM with the orthophoto generated from multi-spectral images.

Table 1: Image orientation results of IKONOS

Method	Number of GCPs + CPs	RMS in East (m)	RMS in North (m)	RMS in Height (m)
With RPCs	4+107	0.75	0.33	1.12
	8+103	0.52	0.34	0.90
	30+81	0.45	0.32	0.81
DLT without RPCs	8+103	0.50	0.83	1.37
	30+81	0.48	0.71	1.02
	111+0	0.43	0.65	0.97

Bavaria, Germany test area (SPOT5 HRS):

As a Co-Investigator of the HRS Study Team we work within the ISPRS–CNES Initiative towards DSM generation from SPOT5-HRS stereo-images. Here we report about our preliminary results.

The stereo-images of the test area cover South Germany and a part of Austria (ca. 120 × 60 km^2). The resolution of the images is 10 meter in cross-track direction and 5 meter in along-track direction. The test area includes about 81 GCPs, and the reference DSMs (derived from laser scanner data or contour lines) have height accuracies ranging from 0.5 to 5 meters.

For stereomodel orientation RFM parameters were computed by using the given interior and exterior orientation values without GCPs. Following this an 2D affine transformation was applied in order to remove large residual errors coming from inaccurately given orientation elements. Here only the bias in translation parameters in X and Y turned out to be significant. The orientation results are shown in Table 2 (43 GCPs were measured) and the DSM accuracy test results, based on this orientation, are shown in Table 3.

Table 2: Image orientation results of SPOT5 HRS

Number of GCPs + CPs	RMS in East (m)	RMS in North (m)	RMS in Height (m)
4 + 39	6.55	4.56	1.97
8 + 35	6.49	4.09	1.95
43 + 0	6.48	3.28	1.85

Table 3: DSM accuracy test results

DEM Name	Terrain Characteristic	Accuracy of Ref. DEM (m)	Number of Points	Average (m)	RMS (m)
DLR-DEM-01	Smooth, weakly inclined	0.5	53519	-1.35	4.91
DLR-DEM-02	Smooth, weakly inclined	0.5	48407	-0.92	5.09
DLR-DEM-03	Smooth, weakly inclined	0.5	45437	-0.51	4.06
DLR-DEM-04	Smooth, weakly inclined	0.5	46016	-1.23	4.97
DLR-DEM-05-1	Rough, strongly inclined	0.5	17035	-4.29	7.06
DLR-DEM-05-2	Rolling, strongly inclined	5.0	114422	-2.50	12.08
DLR-DEM-06	Rough, weakly inclined	2.0	170579	1.40	5.10

Izmir, Turkey test area (IKONOS):

The imagery comprised a stereopair of quasi-epipolar-resampled IKONOS Geo panchromatic images.

The area to be modeled is of 7 × 7 km^2 extension and covered by 7 GCPs, which were measured from 1:1000 digital maps. With the help of these GCPs an absolute accuracy of 1.2 m in planimetry and height could be achieved. After the orientation of the stereopair, a DTM and an orthoimage were generated.

About 440 buildings were measured and structured with CC-Modeler (5). Figure 6 shows a view on the textured 3D model.

4. Conclusions

We have reported about some components of our newly developed software package for the 3D processing of high-resolution linear array - based satellite images. We have basically three types of stereomodel orientation concepts at our disposal: (a) Physical sensormodel, (b) Rational Function Model (RFM) with given RPCs, and with possible affine postprocessing, and (c) simple affine or DLT models. The affine model alone is justified only for sensors with extremely narrow field of view, where the projective projection can be approximated by an affine one, as in case of IKONOS and QuickBird. Even without RCPs and only using the DLT we achieved in model orientation of IKONOS sub-pixel accuracy in planimetry and one pixel accuracy in height. In SPOT5 orientation we also achieved sub-pixel accuracy both in planimetry and in height. We also showed that DSMs could be produced fully automatically with an accuracy of slightly better than one pixel in cooperative terrain, both from SPOT and IKONOS imagery. We further showed that the proven semi-automatic concept of CyberCity Modeler [5] can well be used with IKONOS stereo images in order to produce 3D city models efficiently.

With our software package a powerful and flexible tool is available for accurate and automatic 3D processing of high-resolution satellite images.

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