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# PRECISE PROCESSING OF SPOT-5 HRS AND IRS-P5 STEREO IMAGERY – FOR THE PROJECT OF WEST CHINA TOPOGRAPHIC MAPPING AT 1:50,000 SCALE

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**KEYWORDS:** High-Resolution, Model, Adjustment, Image, Matching, DTM

**ABSTRACT:**

High-resolution satellite images (HRSI) at sub-5m footprint such as IKONOS, IRS-P5 (CartoSat-1) and SPOT-5 HRG/HRS images are the main data sources for the Project of West China Topographic Mapping (WChTM), which has been approved by the State Council of China in 2006 and will be completed at the end of 2010. Two procedures which are used for this project in practice, i.e. the block-adjustment procedure and automatic DTM generation procedure, are described in this paper. We firstly present an approach for block-adjustment based on Rational Function Model (RFM) with sparse GCPs by using satellite Images. Secondly, we present a matching approach for automatic DTM generation from HRSI.

To test the proposed approaches, they have been applied to SPOT-5 images over 1 test-fields, which covers eastern part of Tibet Plateau, China with variable terrain geomorphologic type. In another test we use 23 scenes of IRS-P5 images, which cover Beijing test area of about 21,000 square kilometers. From these experiments, it’s shown that with the proposed block-adjustment and DTM generation approach, by using SPOT-5 HRS/HRG and IRS-P5 imagery with small number of GCPs, satisfactory image orientation results and DTM product (after necessary manual editing) can be achieved with a little bit better accuracy than those requirements from the Chinese Surveying and Mapping regulations for 1:50000 topographic maps.

## 1. INTRODUCTION

A decade after early 1990s, remote sensing has stepped into a new stage which can supply various high-resolution observation data from space. At present, terrain information extraction, change detection, disaster monitoring, and topographic mapping by using the HRSI has become one of research hotspots. Meanwhile, HRSI has more and more applications in photogrammetry. The stereo remote sensing image with spatial resolution of meter-level or even sub-meter level has the capability to replace the aerial images which used for traditional topographic mapping or updating of geo-information at 1:50,000 and 1:10,000 scale (Zhang, et. al., 2004). Among these, GeoEye-1, IKONOS, SPOT-5 HRS/HRG, IRS-P5 images are well-known examples.

Due to the difficulties for aerial image acquisition, time limit of the project and other practical considerations, SPOT-5 HRS/HRG, IRS-P5 and other HRSI images are the main data sources for the project of Western China Topographic Mapping (WChTP) at 1:50,000 scale. Before 2006, up to 2.02 million $km^2$ are not mapped at 1:50,000 scale in western part of China, it includes Sorthern-XinJiang desert area, Qing-Tibet Plateau area and Heng-duan mountain ranges. This unmapped area covers about 20% of all areas of China; includes total number of about 5,032 sheets of 1:50,000 scale topographic maps. This situation greatly hiders the socio-economic development of this region, it also poses potential threat to national security. The project has been approved by the State Council of China in year 2006, and is dedicated to complete 1:50,000 scale topographic map and construct the national geo-spatial database for the region within next 5 years through year 2006 to 2010. The unmapped area

covers most unmans area of China, the very harsh natural conditions (average terrain elevation is more than 4000m) and difficult transportation conditions provide a very difficult situation for GCP measurement and other field works. In many areas, it’s even impossible for accessing or collecting enough GCPs, therefore, the project of WChTP should utilize some innovative and well-developed techniques, such as DGPS/IMU assisted aerial photogrammetry, high resolution satellite imagery mapping technique and radar image mapping technique, design and use mapping procedure with small number of GCPs, to complete the project. However, on one hand, the radar image processing technique, especially those methods for precise DTM generation from InSAR data, has not been well-developed and regularly used in China; on the other hand, very high resolution aerial images cannot be acquired within reasonable time due to the very harsh natural conditions and variable climate conditions, Therefore, in the project of WChTP, more than 90% areas will be mapped with SPOT-5 HRS/HRG and IRS-P5 imagery (including IKONOS and QuickBird images over some important cities and towns), the rest of areas will be mapped with SAR and aerial images only after enough research works and experiments.

The project of WChTP is a complicated project which first uses HRSI for topographic mapping in China In this paper, we firstly present a block-adjustment procedure based on Rational Function Model (RFM) for HRSI satellite images (Chapter 2). Secondly, we present a matching approach for automatic DTM generation. It can provide dense, precise and reliable results (Chapter 3). These two procedures have been successfully applied for block-adjustment of large-area SPOT-5 and IRS-P5 satellite imagery with small number of GCPs, and used in practice in production-line for the project of WChTP. The results show that with our approaches, by using SPOT-5 HRS/HRG and IRS-P5 imagery, with several GCPs, satisfactory image orientation results and DTM products (after necessary manual editing) can be completed with a little bit better accuracy than those requirements from Chinese Surveying and Mapping regulations for 1:50000 topographic maps (Chapter 4, 5).

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## 2. BLOCK-ADJUSTMENT WITH HRSI BASED ON RATIONAL FUNCTION MODEL (RFM) AND SPARSE NUMBER OF GCPS

Sensor models are fundamental for the photogrammetric processing, such as the stereo measurements and the image ortho-rectification. They are typically classified into two categories: the physical and the generalized models. In a generalized sensor model, the transformation between the image and the object space is represented as some general function without modeling the physical imaging process. The Rational Function Models (RFMs) is one of the generalized sensor models and have recently drawn considerable interest in the remote sensing community.

Almost all the high-resolution satellite cameras use Linear Array CCDs to acquire a single image line at an instant of time, each with its own positional and attitude data. The imaging geometry is characterized by nearly parallel projection in along-track direction and perspective projection in cross-track direction. The bundle adjustment approach, which has been well-developed in aerial photogrammetry, can also be applied for satellite images after appropriate alteration (Qian, et. al., 1990). Due to the dynamic nature of satellite image acquisition, this kind of model is more complicated than in the single frame case. Furthermore, due to very narrow field of view for HRSI images (e.g. SPOT-5 HRS is 8.3°, IKONOS only is 0.7°), many parameters in the physical sensor models are completely or highly correlated with other parameters so that they cannot be safely estimated through the triangulation procedure (Grodecki and Dial, 2003). According to the researches made by Tao and Hu (2001), The RFM can achieve an approximation accuracy that is extremely high both for aerial frame data and SPOT linear array data. Therefore, in this paper, we try to develop a block-adjustment approach with HRSI based on RFM. The procedure includes the following 2 steps:

### 2.1. Rational Function Model (RFM) parameter estimation

A RFM is generally the ratio of two polynomials with its parameters derived from the physical sensor model and the corresponding terrain information. In RFM, image pixel coordinates ($x$, $y$) are expressed as the ratios of polynomials of object coordinates ($\varphi$, $\lambda$, $h$), which in the case of the IKONOS RPCs correspond to latitude, longitude and ellipsoidal height. For an image, where $x_n$ and $y_n$ are normalised pixel coordinates and $\varphi_n, \lambda_n, h_n$ are normalised latitude, longitude and ellipsoidal height, the ratios of polynomials have the following form:

$$x_n = RPC_x(\varphi,\lambda,h) = \frac{f_1(\varphi_n,\lambda_n,h_n)}{f_2(\varphi_n,\lambda_n,h_n)}$$
$$y_n = RPC_y(\varphi,\lambda,h) = \frac{f_3(\varphi_n,\lambda_n,h_n)}{f_4(\varphi_n,\lambda_n,h_n)} \quad (1)$$

In equation (1), the maximum power of each object coordinate and the total power of all object coordinates are limited to 3.

Some commercial HRSI like IKONOS and IRS-P5, only supply RFM model coefficients to the user, however SPOT-5 HRS/HRG supplies orientation parameters through the metadata file (DIMAP format file).

Table 1: Accuracy test for SPOT-5 imagery RPC Estimation

| Image type | Image size (Row×Column) | Fitting RSME (pixel) |
|---|---|---|
| HRS 5×10m Pan | 50712×12000 | 0.00854 |
| HRS 5×10m Pan | 116264×12000 | 0.01017 |
| HRS 5×10m Pan | 114592×12000 | 0.01016 |
| HRS 5×10m Pan | 81928×12000 | 0.00978 |
| HRS 5×10m Pan | 116864×12000 | 0.01013 |
| HRG 5m Pan | 40208×12000 | 0.02557 |
| HRG 5m Pan | 51984×12000 | 0.02814 |
| HRG 2.5m Pan | 24000×24000 | 0.05495 |
| HRG 2.5m Pan | 24000×24000 | 0.05518 |
| HRG 10m MS | 6000×6000 | 0.01099 |
| HRG 10m MS | 6000×6000 | 0.01558 |

Through these parameters, the physical sensor model (details please refer to SPOTIMAGING, 2002) of SPOT-5 imagery can be established. Usually, the RFM can be computed based on the SPOT-5 physical sensor model. Tao and Hu (2001) gave a detailed description of a least squares solution of RPCs based on the physical sensor models and suggested using a Tikhonov regularization for tackling possible oscillations. In our procedure, this method was applied also for SPOT-5 image RPC estimation.

We applied comprehensive testing by using hundreds scene of SPOT-5 HRS/HRG images in order to evaluate the performance of RPC estimation method, part of the results are shown in Table 1. The results show that: a) For SPOT-5 HRS stereo image, fitting RMSE for physical sensor model usually is about 1/100 pixel, and it seems not related to the image size; for SPOT-5 HRS 5m panchromatic images, fitting accuracy is about 1/40 pixel, for SPOT-5 HRS 2.5m panchromatic images, fitting accuracy is about 1/20 pixel. b) The fitting RMSE for physical sensor model is roughly related to ground resolution of the images, which is roughly equal to 0.1m in ground. c) RFM can replace the physical sensor model in subsequent photogrammetric processing of SPOT-5 image, and the accuracy loss can be ignored in mapping at 1:50,000 scale.

### 2.2. Block-adjustment based on RFM

Actually, the RFM constitutes a re-parameterization of the physical sensor model. Errors in sensor interior and exterior orientation thus give rise to errors in the RPCs. Grodecki and Dial (2003) proposed a practical block-adjustment model for multi-strip blocks of the high-resolution satellite imagery described by RPC models and illustrated the method with an IKONOS example. With the supplied RPCs, the mathematical model used is:

$$x_k + a_{i,0} + a_{i,1}x_k + a_{i,2}y_k = RPC_x^i(\varphi_k,\lambda_k,h_k)$$
$$y_k + b_{i,0} + b_{i,1}x_k + b_{i,2}y_k = RPC_y^i(\varphi_k,\lambda_k,h_k) \quad (2)$$

where, $a_{i,0}$, $a_{i,1}$, $a_{i,2}$ and $b_{i,0}$, $b_{i,1}$, $b_{i,2}$ are the 6 adjusted parameters for image $i$, and ($x_k$, $y_k$) and ($\varphi_k$, $\lambda_k$, $h_k$) are pixel and object coordinates of the points $k$.

In our approach, we first used the RPCs to transform from object to image space and then using these values and the known pixel coordinates we estimated either two shifts $a_{i,0}$, $b_{i,0}$ (model *M_RPC2*) or all 6 parameters $a_{i,0}$, $a_{i,1}$, $a_{i,2}$ and $b_{i,0}$, $b_{i,1}$, $b_{i,2}$ (model *M_RPC6*). The basic least squares observation equations for these 2 models are:

$$v = A\Delta + l; \quad P$$
$$v = \left[v_x, v_y\right]_k^T; \qquad \Delta = \left[a_{i,0}, a_{i,1}, a_{i,2}, b_{i,0}, b_{i,1}, b_{i,2}, \Delta\varphi_k, \Delta\lambda_k, \Delta h_k\right]^T$$
$$\text{where} \quad A = \begin{bmatrix} 1, x_k, y_k, 0,0,0, \dfrac{\partial x_k}{\partial \varphi_k}, \dfrac{\partial x_k}{\partial \lambda_k}, \dfrac{\partial x_k}{\partial h_k} \\ 0,0,0,1, x_k, y_k, \dfrac{\partial y_k}{\partial \varphi_k}, \dfrac{\partial y_k}{\partial \lambda_k}, \dfrac{\partial y_k}{\partial h_k} \end{bmatrix}_i; \qquad l = \begin{bmatrix} x_k - RPC_x^i(\varphi_k, \lambda_k, h_k) \\ y_k - RPC_y^i(\varphi_k, \lambda_k, h_k) \end{bmatrix} \quad (3)$$

Here, $P$ is the weight matrix describing the image measurement precision. For a block of images, the image georeferencing can be performed with the solution of the least squares normal equations resulting from equation (3). From equations (2) and (3) it is apparent that model *M_RPC2* requires at least a single well-defined GCP, whereas an estimation of all six parameters in model *M_RPC6* would require a minimum of 3 appropriately located GCPs per image.

## 3. AUTOMATIC DTM GENERATION BY USING A MULTIPLE-PRIMITIVE MULTIPLE-IMAGE MATCHING APPROACH

We have developed an advanced matching approach for automatic DTM generation from HRSI. The approach uses a coarse-to-fine hierarchical solution with a combination of several image matching algorithms and automatic quality control. The approach essentially consists of 3 mutually connected components: the image pre-processing, the multiple primitive multi-image (MPM) matching and the geomorphologic refinement matching procedure. The overall data flow is shown schematically in Fig. 1.

The Multiple Primitive Multi-Image (MPM) matching procedure is the core of our approach for accurate and robust DTM reconstruction. In this procedure, we do not aim at pure image-to-image matching. Instead we directly seek for image-to-object correspondences. We have developed a new flexible and robust matching algorithm – Geometrically Constrained Cross-Correlation ($GC^3$) method in order to take advantage of the multiple images. The algorithm is an extension of the standard Cross-Correlation technique and is based on the concept of multi-image matching guided from object space and allows reconstruction of 3D objects by matching all available images simultaneously, without having to match all individual stereo-pairs and merge the results. For more details of our matching procedure, please refer to Zhang, (2005); Baltsavias, et. al., (2006).

It should mention that the results through matching two or more optical remote sensing images are actually the Digital Surface Models, i.e. DSMs. Post-processing of DSMs are necessary to generate DTMs through methods which can reduce the DSM points to bare earth in urban areas or heavily vegetated areas. Manual editing the DSMs through stereo checking is one of the options; however, it is a time-consuming job. In our procedure, a method which used for LIDAR data filtering was used. The filtering method is one of the so-called morphological filters, which use a small structure element, describing admissible height differences as a function of the horizontal distance. This method was modified, implemented and integrated into our matching procedure as a post-processing option. For details of this filtering method, please refer to Vosselman, G., (2000).

## 4. BLOCK-ADJUSTMENT TESTING AND ACCURACY ANALYSIS

In order to evaluate the performance of block-adjustment approach presented in this paper. We selected several test areas to apply extensively accuracy test, the results show that only using small number of GCPs, we can meet the requirements of topographic mapping at 1:50,000 scale in China for large coverage of SPOT-5 HRS and IRS-P5 stereo images.

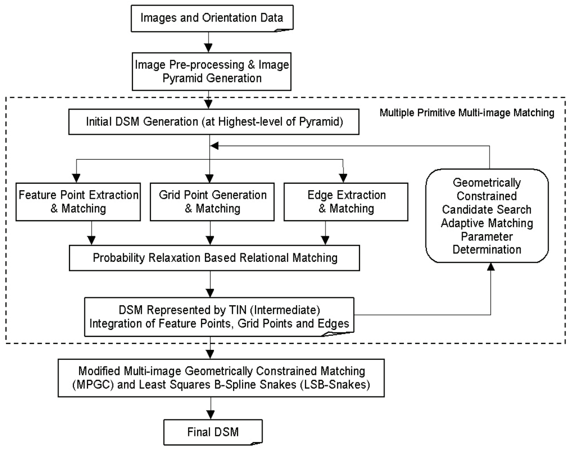



Figure 2. Workflow of the proposed automated DTM generation approach.

### 4.1 SPOT-5 HRS Imagery in Eastern Tibet Plateau and Eastern Talimu Basin

The block-adjustment with SPOT-5 HRS images in areas of eastern Tibet Plateau and eastern Talimu basin have been completed in 2006 and 2007. The test area in eastern Tibet Plateau covers 1234 topographic maps at 1:50,000 scale with the area of about 530,000km$^2$, where contains large-area of seasonally and perennially frozen soil, glacier and perennial snowfield and unman area; The test-field in eastern Talimu Basin and North Slope of Aerjin Mountain ranges covers 325 topographic maps at 1:50,000 scale with the area of about 130,000km$^2$, where covers large-area of desert with fixed/fluid dunes, arid salt desert, gobi, badland and yardang landforms. Therefore it is quite difficult for surveying field-works with these kinds of harsh nature environment, meanwhile, poor-texture image areas caused by large areas of desert and gobi result in another difficulties for GCP collection and precise measurement in both image and object space.

Field works such as GCPs surveying and image annotation have been completed in the test areas by over 500 surveyors and 120 vehicles from 7 production units including Shanxi, Heilongjiang and Sichuan Surveying and Mapping Bureau, Chongqing Surveying and Mapping department, and Surveying and Mapping Bureau in Qinghai, Xinjiang and Gansu provinces since 2006. About 700 GCPs and checking points are measured by differential GPS. The measurement accuracy was better than 1m in planimetry and 1.2m in height. The GCPs are well-distributed in the test area, their average ground distance is about 100-150km (in order to ensure reliable GCP at the in-home designed location, two- or three-point layout plan would be utilized at the designed location, and all of them would be recorded in the number of GCPs). According to the coverage of the SPOT-5 HRS satellite images and the distribution of GCPs, also considering the terrain type, block-adjustment of the whole test area will be divided into 4 sub-testfields (Fig. 3): (B1) Testfield in zone of headstream of Three rivers, Tibet Plateau, China: In this area, 13 SPOT-5 HPS stereo image strips which cover about 120,000km$^2$ are involved. The GCP measurement was completed in 2006, there are large number of GCPs because this area is the first working area of the WChTM project.

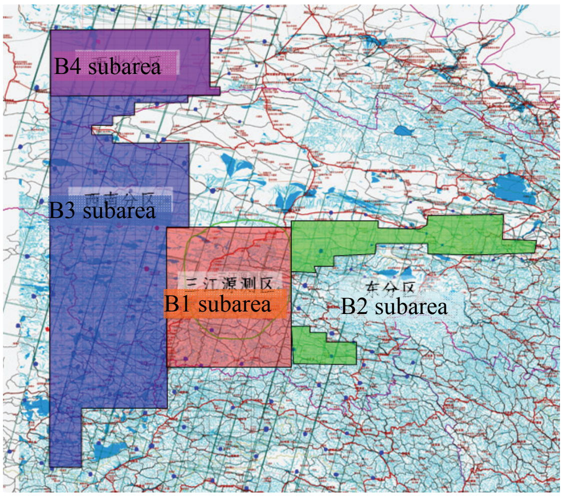



Figure 3. Overview of test-fields in eastern part of Tibet Plateau and eastern Talimu Basin, China

Finally, there are total 157 points were used in block-adjustment procedure except certain number of necessary tie points, in which contain 59 GCPs and 98 checking points. The block-adjustment results are shown in Table 4.

(B2) Test-field of northeast in eastern Tibet Plateau, this area has 26 SPOT-5 HPS stereo image strips which cover about 200,000km$^2$. There are 209 points were used in block-adjustment for this test-field, in which contain 81 GCPs and 128 checking points. The block-adjustment results are shown in Table 4.

(B3) Test-field of southwest in eastern Tibet Plateau, this area has 26 SPOT-5 HPS stereo image strips with coverage of about 300,000km$^2$. Finally there are 273 points were used in block-adjustment, in which contain 115 GCPs and 158 checking points. The block-adjustment results are shown in Table 4.

Table 4. Accuracy reports for block-adjustment in test-field of eastern part of Tibet Plateau and eastern part of Talimu Basin, China. The unit is in meters

| | $\sigma_0$ (pixel) | RMSE of GCPs | | | RMS of CPs | | | Max error of GCPs | | Max error of CPs | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | X | Y | Z | X | Y | Z | X-Y | Z | X-Y | Z |
| B1 | 0.79 | 4.9 | 5.2 | 1.4 | 8.9 | 6.9 | 2.1 | 13.4 | 4.3 | 23.2 | 4.3 |
| B2 | 0.68 | 5.3 | 4.6 | 2.1 | 7.8 | 6.7 | 2.5 | 16.2 | 5.9 | 17.4 | 6.1 |
| B3 | 0.62 | 5.2 | 5.6 | 1.6 | 8.4 | 7.2 | 2.4 | 15.8 | 4.1 | 18.2 | 5.0 |
| B4 | 0.54 | 4.4 | 4.5 | 1.2 | 5.2 | 6.3 | 2.1 | 11.6 | 2.2 | 11.7 | 3.6 |

(B4) Test-field of eastern Talimu basin, this area has 5 SPOT-5 HPS stereo image strips with coverage of about 60,000km$^2$. There are 92 points were used in block-adjustment, in which contain 51 GCPs and 41 checking points. The block-adjustment results are shown in Table 4.

As shown in Table 4, the block-adjustment accuracy of the test areas in eastern Tibet Plateau and eastern Talimu basin are quite good (in sub-pixel level) compared to the resolution of SPOT-5 HRS images, and it can meet the block-adjustment accuracy requirements regulated in mapping standard at 1:50,000 scale with small number of GCPs. Comparing to block-adjustment with the traditional aerial photos, block-adjustment with SPOT-5 HRS stereo image has some different features. For example, the resolution is quite different, the scale of aerial photos used for mapping at 1:50,000 scale normally is 1:35,000-1:50,000, the ground resolution of image usually is in sub-meter or meter level. According to experience of the tests made as above, for block-adjustment with SPOT-5 HRS stereo images, the following problems should be noted specially in GCPs/tie-point measurement, block- adjustment computation and accuracy checking:

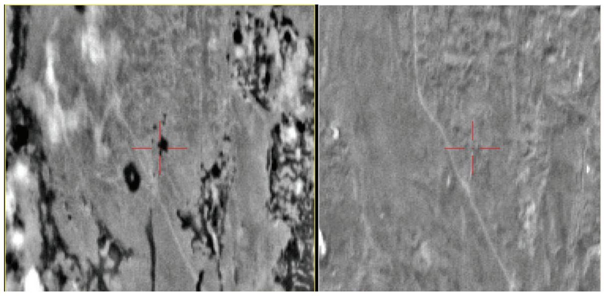


Figure 5. Example of radiometric difference between adjacent SPOT-5 HRS images caused by different acquisition time

(1) For satellite images, the radiometric differences caused by different imaging time between adjacent stereo images must be considered while making the GCP layout plan and measurement. GCPs should be located and can be measured precisely in all (or as more as possible) satellite images. Take example in Fig. 4 for instance, the GCP in left image will be very hardly or even can not be measured/transferred to the adjacent right image if we do not take the temporal difference into account.

(2) For SOPT-5 HRS stereo images, the image resolution of is 5m in along-track and 10m in cross-track direction, this means that measurement accuracy is different in different direction of SPOT-5 HRS images, thus we have to pay much attention when we make the point measurement in cross-track direction.

(3) The requirement of block-adjustment residual errors for GCPs and checking points in existing Chinese mapping standard of aerial image is regulated for tolerance. Sometimes, it might be very difficult to observe image points and carefully modify point location to reach the tolerance requirement. For example, assume the residual error of an image point is 3.2m or 3.5m, but if the tolerance is 3.0m, this means that the modification of this point is in 1/25 or 1/10 pixel level for SPOT-5 HRS image; Therefore it suggests that precise stereo observation must be applied for SPOT-5 HRS images to insure firstly, the residual error of this point in image space is less than 1.5 pixel, meanwhile, it suggests that the residual errors of 5%-10% GCPs or Check points are allowed over requirement of tolerance but they must be less than 1.5 times of the tolerance.

### 4.2 IRS-P5 Stereo Images and Accuracy Analysis

The test-field is an area around the city of Beijing, China. It consists of a steep mountainous region in the north-western part and flat regions in the middle and southern parts. The city of Beijing is located in the lower part of the study area. The whole area is about 70 × 210 km$^2$. The site has an average terrain height of 300m and an elevation range of more than 1100 m.

Over the test area, totally 23 scenes of IRS-P5 stereo images were collected. In order to precisely georeference these images, about 66 well-distributed GCPs were collected with differential GPS in 2006. The measurement accuracy was better than 0.5m in planimetry and 1m in height. The GCPs are well-distributed in the test area, their ground intervals are about 30km, and most of them are located at the center of road intersection which can be precisely measurement both in image and object space.

According to works made by Lutes, J. (2006), most orientation errors in IRS-P5 stereo images are either biases or linear in line/sample direction. This suggests that at least 4-6 GCPs are required for orient an IRS-P5 stereo pair (with corresponding RPCs) to achieve good enough results. Other works which made by Jocobsen, et. Al (2008) also show that with model *M_RPC2* (RPCs plus biases correction) can achieve good enough orientation results. However, based on our own test with IRS-P5 images in China, for each scene of stereo image, at least 4 GCPs are necessary to remove all biases and linear trend errors.

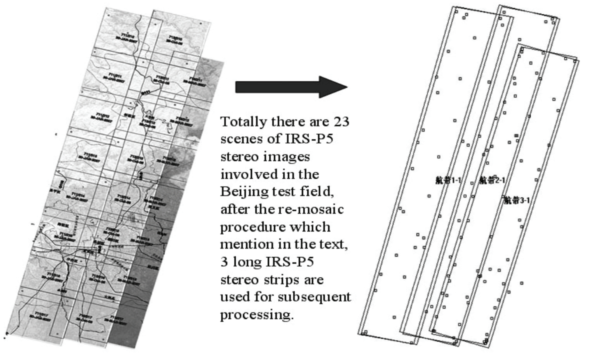



Figure 6. In Beijing test-field, there are 23 scenes of IRS-P5 stereo images. In order to facilitate the subsequent processing, we use the re-mosaic procedure based on metadata to combine these 23 stereo images into 3 long stereo strips.

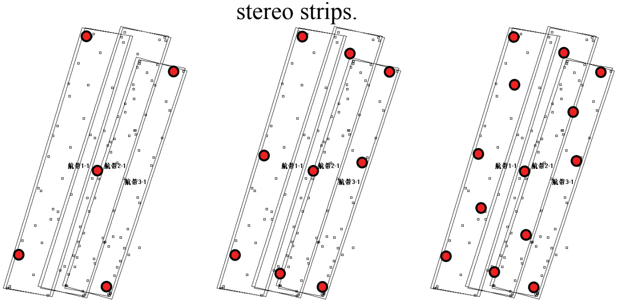


Figure 7. Different distribution of GCPs for different block-adjustment test phase (with 5, 9, 13 GCPs respectively) with IRS-P5 imagery

Normally, we could commercially get so-called IRS-P5 “standard scene” of images, which have 12000 × 12000 pixels and cover 30 × 30km$^2$. Basically the standard scenes could be sub-images of a long IRS-P5 strip. They are just subdivided from a long IRS-P5 strip for commercial reason and normally they have 5%-15% overlap between adjacent scenes. We develop a procedure to re-mosaic adjacent IRS-P5 standard scenes into a long stereo strip (Fig. 4) in condition that these scenes are sub-images of the original long IRS-P5 strip. After this re-mosaic procedure, 23 IRS-P5 scenes of the Beijing test-field are re-mosaic into only 3 IRS-P5 long stereo strips.

We select different numbers and distribution layout of GCPs for accuracy test, which includes 4 GCP, 9 GCPs, 13 GCPs and all of control points (see Fig. 5), the results are shown in Table 8. Test results show that: (a) with the increase number of GCPs, there is certain degree of improvement for both planimetry and elevation accuracy, but the improvement is not so significant; (b) adjustment accuracy in teat area can meet the requirement of block-adjustment in surveying criterion at 1:50,000 scale even with only 5 GCPs located at corners of the test-field. According to this result, the proposed re-mosaic procedure is quite important for both reduce the number of GCPs and reduce the measurement error accumulation. For single long-strip IRS-P5 images, only 4 GCPs at the image corners are enough to achieve good accuracy under the condition that the length of strip is below 150km; for multiply long-strip IRS-P5 stereo images even less GCPs are required to reach the requirement of topographic map surveying at 1:50,000 scale in China.

Table 8. Accuracy test for block-adjustment in Beijing test-field, with IRS-P5 stereo images. The unit is in meters

| Test phase | GCPs+CPs | RMSE-X | RMSE-Y | RMSE-Z |
|---|---|---|---|---|
| 5 GCPs | 5 + 61 | 1.70 | 1.96 | 2.49 |
| 9 GCPs | 9 + 57 | 1.64 | 1.93 | 2.50 |
| 13 GCPs | 13 + 43 | 1.61 | 1.86 | 2.37 |
| 66 GCPs | 66 + 0 | 1.43 | 1.68 | 1.98 |

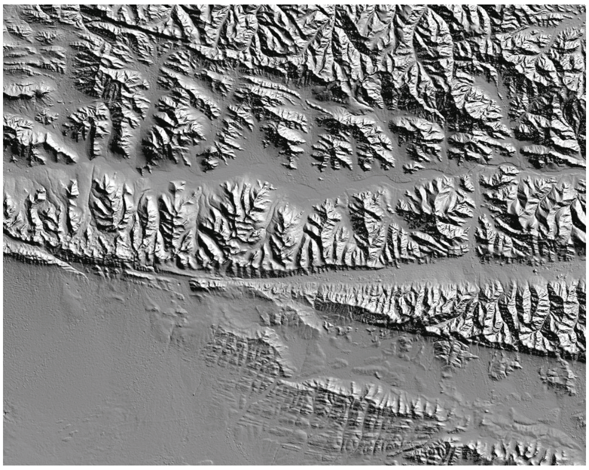
## 5. PERFORMANCE EVALUATION ON AUTOMATIC DTM GENERATION APPROACH

In order to evaluate the performance of our approach for DTM generation it has been verified extensively with several HRSI datasets, such as IRS-P5 and SPOT-5 HRS/HRG images, over different terrain types, which include hilly and rugged mountainous areas, rural, suburban and urban areas. In the following, we will report in detail about 1 experiment over test area in Zone of headstream of Three rivers, Eastern Tibet Plateau, China. Other processing and evaluation results of IKONOS and SPOT5 HRS/HRG can be found in Poli et al., 2004; Baltsavias et al., 2006 and Poon et al., 2005.

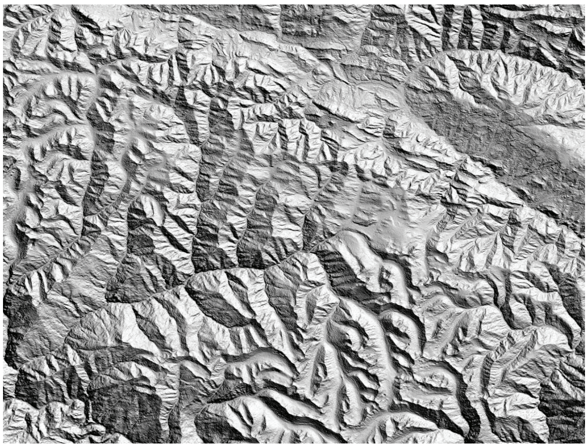
The test area in Zone of headstream of Three rivers, Eastern Tibet Plateau, China covers 250 topographic maps at 1:50,000 scale with the area of about 12,000km$^2$, where contains large-area of seasonally and perennially frozen soil, mountain/valley glacier and perennial snowfield and large area of unman area. The test-field is the headstream of Yangtze River, Yellow River and Lancangjiang River, and the QingZang railway and national road cross the region from north-east to south-west. The average elevation is 4000m in test-field. Main geological structures are in trend of nearly east-west direction. The various landforms in study area provides better environment for DTM automatic generation.

Over the test area, totally 11 pairs of 10 × 5m SPOT-5 HRS and nearly twenty 5m HRG images were acquired. These images were used to generate DTM over the whole test area. In particular, for DTM accuracy analysis, 2 SPOT-5 HRS satellite image pairs imaged in Nov 2003 and 6 HRG images, which can form the SPOT-5 stereo triplets, have been selected. The images have the fine quality and have no cloud coverage, which provide good data sources for DTM automatic generation and accuracy analysis.

After the block-adjustment, the proposed DTM generation approach was applied to 2 SPOT HRS stereo image strips and 6 HRG images simultaneously. As a result, 25m grid-spacing DTM of the accuracy study area has been generated automatically after about 26 hour. As results, about 90 millions feature points and 5 millions feature lines have been matched which is equivalent to match a 4 × 4 density grid on the original image, and it is good enough for generation of DSM with 25m interval. Since our DSM generation approach not only generates a large number of mass points but also produces line features, which are necessary for the modeling the rugged mountainous terrain. Finally, post-processing of the DSM by using a slope based filtering method was applied and worked well, since the average height of the test area is above 4000m and it is unman area, man-made structures and vegetation don not pose big problems. Parts of DTM results are shown in Fig 6. It can be seen that the resulted DTM reproduced quite well not only the general features of the terrain relief but also small geomorphologic and other features visible in the SPOT-5 images.



(a): Shaded DTM of arid/semi-arid mountainous terrain.



(b): Shaded DTM of high-plateau mountain ranges

Figure 9. The shaded terrain models of 25m over 2 sub-areas in test area. The resulting DTM reproduced quite well not only the general features of the terrain relief but also small geomorphologic and other features visible in the images.

Since the study area is within the WChTM project covered area, there are not good enough reference data, we apply the following three accuracy evaluation methods for DTM accuracy evaluation:

(1) Overlay the automated generated DTM onto the stereo image pairs to apply manual visual checking under stereoscopic display device. Checking results show a good enough match between DTM and stereo images expect some small blunders within shadow areas, which have to apply necessary manual editing.

(2) Accuracy checking by using GCPs and check points measured by differential GPS. Upside of Table 10 give the DTM accuracy evaluation results by using this method. We computed the differences as GCPs minus the interpolated heights from our generated DTM. The accuracy of the DTM is between 1.7 – 6.7 m depending on the terrain relief and land cover.

(3) Accuracy checking by using 1489 manually measured checking points which were acquired on digital photogrammetric workstation. We computed the differences as these points minus the interpolated heights from our generated DTM. The accuracy of the DTM is between 3.6 – 4.5m depending on the terrain relief and landform. Since the DTM generation and point measurement procedure share the same image orientation results, the errors of the DTM would be from the stereo image matching, which is directly relate to the matching accuracy. Detailed accuracies are shown in Table 10 downside.

According to the experiment results, the following conclusions can be made: (a) DTM at 1:50,000 scale can be generated automatically from SPOT-5 HRS/HRG stereo/triplet-stereo images by using the automatic DTM generation approach proposed in this paper. The elevation accuracy can roughly be 50% better than requirements of the Chinese national surveying regulation; (b) simultaneously matching SPOT-5 HRS/HRG triplet stereo strips and matching both feature points and feature-lines are quite necessary for deeply incensed mountainous area and rugged terrain, such as arid and semi-arid broken mountains in northern part and rugged mountain ranges in southern part of the study area; (c) the proposed automatic DTM generation approach can largely increase the working efficiency, however, necessary filtering of the DSM to generate DTMs, careful manually stereoscopic checking and editing are still necessary to remove some small matching blunders, which are in most cases within shadow and gully/rill/ steep-valley well-developed areas.

Table 10: DTM accuracy evaluation results with SPOT-5 HRS/HRG imagery

| Reference data | Map sheets | Num. of check points | Height accuracy (RMSE) | Accuracy requirements of 1:50,000 scale 1$^{st}$/2$^{nd}$ level DTM | Type of terrain |
|---|---|---|---|---|---|
| GPS points | 3 | 99 | 6.7 m | 14.0 m/19.0 m | Mountainous area |
| | 1 | 26 | 3.6 m | 8.0 m/11.0 m | Mountainous area |
| | 2 | 64 | 1.7 m | 5.0 m/ 7.0 m | Hilly area |
| | 3 | 127 | 2.8 m | 3.0 m/ 4.0 m | Flat/hilly area |
| Manually measured points | 47 | 937 | 3.6 m | 5.0 m/ 7.0 m | Hilly area |
| | 21 | 367 | 4.5 m | 8.0 m/11.0 m | Mountainous area |
| | 8 | 185 | 4.4 m | 14.0 m/19.0 m | Mountainous area |

## 6. CONCLUSIONS

In this paper, we firstly present an approach for block-adjustment based on Rational Function Model (RFM) with sparse GCPs by using satellite Images. To test the proposed approach, it has been applied to SPOT-5 images over test-fields, which covers eastern part of Tibet Plateau, China. The test-fields are with variable terrain geomorphologic type and several tens of GCPs and check points measured by DGPS. The block-adjustment results show that with SPOT-5 HRS images and a small number of GCPs we can achieve 5-9m in planimetric and 2-3m in height direction. In another test we use 23 scenes of IRS-P5 images, the test area covers Beijing area and about 21,000 square kilometers. In this test-field, the block-adjustment result shows that only with 5 GCPs we could achieve 2.0 m in planimetric and 2.5m in height direction. From these experiments, it's shown that with the proposed block-adjustment approach, by using SPOT-5 HRS/HRG and IRS-P5 imagery with several GCPs, satisfactory image orientation results can be completed with a little bit better accuracy than those requirements from Chinese Surveying and Mapping regulations for 1:50000 topographic maps.

Secondly, we have reported about an advanced matching approach for automatic DTM generation from high-resolution satellite images. The proposed approach has been applied to SPOT-5 HRS/HRG images over a test-field in Zone of headstream of Three rivers, Tibet Plateau, China with variable terrain geomorphologic type. The accuracy tests were based on the comparison between as many as 160 accurate GPS check points, more than 1400 manually measured check points and the automatically extracted DTMs. The RMS errors for the whole area are 2-7 m, while for flat/hilly areas the accuracy is about 2-3 m or even better. From the experiment, it's shown that with the proposed automatic DTM generation approach, by using SPOT-5 HRS/HRG and IRS-P5 imagery, satisfactory 1:50000 DTMs can be completed with a better accuracy than those requirements from Chinese Surveying and Mapping regulations.

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