GEOMETRIC PROCESSING OF IKONOS GEO IMAGES WITH DEM♥

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ABSTRACT

Thirteen Pan or XS IKONOS Geo-product images over seven study sites with various environments and terrain were tested using different cartographic data and accuracies using a parametric modelling developed at the Canada Centre for Remote Sensing. The objectives were to track the error propagation during the full geometric correction process (bundle adjustment and ortho-rectification). When ground control points (GCPs) are less than 3-m accurate, 20 GCPs over the full image is a good compromise to obtain 3-4 m accuracy in the bundle adjustment. When cartographic co-ordinates are better than 1-m, 10 GCPs are then enough to increase to 2-3 m accuracy with either panchromatic or multiband images. The remaining error is due to GCP definition and plotting. Quantitative and qualitative evaluations of ortho-images were performed with independent check points or digital vector files. Positioning accuracy of 2-4 m is achieved for the ortho-images depending of the elevation accuracy (DEM and grid spacing). To achieve a better final positioning accuracy, such as 1 m, 1-2 m accurate DEM with fine grid spacing is required in addition to well-defined GCPs benchmarked on the ground.

1. INTRODUCTION

IKONOS, launched September 24 1999, orbits the Earth once every 98 minutes at an altitude of approximately 680 kilometres in a sun-synchronous path. The sensor is capable of viewing up-to-60º in any azimuth (in-track and cross-track pointing). The satellite's sensor generates 1-m panchromatic (Pan) and 4-m multi-band (XS) images if they are acquired with a viewing angle between 0º and 26º. Over 26º viewing angles Space Imaging insures 2-m resolution for the panchromatic images (Space Imaging, 2001). Only map georeferenced and a range of orthorectified products with applied geometric correction and oriented to the North are delivered by Space Imaging. The Geo product, which is the most affordable but offers the lowest positioning accuracy, is not corrected for terrain distortions. It has an accuracy of 50m with 90% level of confidence. Accuracy becomes worse in mountainous areas if the images are acquired with off-nadir viewing, which commonly occur for the IKONOS data. Hence, the product will only meet the geometric requirements of mapping scale at 1:250,000 in flat area or less in mountainous areas.

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Preliminary accuracy tests with real images using a parametric geometric correction model were performed with few precise GCPs (Toutin and Cheng, 2000; Kersten *et al.*, 2000; Davies and Wang, 2001). Their results demonstrated accuracy in planimetry of around 2-3 m and then confirmed that IKONOS images have a high potential for mapping.

The objectives of this paper are to expand on these preliminary results with a larger data set of IKONOS images: 1-m Pan and 4-m XS, acquired with 10º-30º viewing angles at different azimuth angles. The study sites span low-to-high relief in urban, semi-rural and rural areas of North America and Europe with different topographic data and accuracy. Using a multi-sensor geometric model developed at the Canada Centre for Remote Sensing (CCRS) (Toutin, 1995) and adapted to IKONOS images (Toutin and Cheng, 2000), the paper will track the error propagation from the input data to the final ortho-image. Different cartographic parameters affecting the accuracy are also evaluated.

2. STUDY SITES and DATA SET

Seven study sites with different environments and relief are used in this research. IKONOS Geo-product data (some acquired by international collaborators), covering an area of approximately 10 km by 10 km, have been acquired either in Pan mode and/or XS (Table 1):

1. Toronto, Ontario, Canada is a sub-urban environment and a flat topography with 60-m elevation range. Pan image was acquired April 23, 2000 with collection and azimuth angles of 51º and 21º, respectively. 30 GCPs were collected and their map coordinates were obtained from 20-cm pixel ortho-photos with 0.5-m accuracy and 2-m grid spacing DEM with 5-m accuracy;
2. Beauport, Quebec, Canada is a residential and semi-rural environment and a hilly topography with 500-m elevation range. Two Pan images were acquired January 3, 2001 with collection and azimuth angles for each image of 63º and 322º, 63º and 252º, respectively. 56 GCPs were collected and their map coordinates were obtained from six 1-m pixel ortho-photos with 3-m accuracy and 5-m grid spacing DEM with 5-m accuracy. However, a mean positioning error of 5-7 m in the X direction was found between the different ortho-photos; this error is mainly due to 5-m DEM error during the ortho-photo generation;
3. Toulouse, France is an sub-urban environment and a flat topography with 100-m elevation range. Pan and XS images simultaneously were acquired May 14, 2000 with collection and azimuth angles of 70º and 138º, respectively. 33 GCPs were collected and their map coordinates were obtained from 0.5-m pixel ortho-photo mosaic with 1-m accuracy and 10-m grid spacing DEM with 5-m accuracy;
4. Trier, Germany is an urban and semi-rural environment and a rolling topography with 300-m elevation range. XS image was acquired June 13, 2000 with collection and azimuth angles of 65º and 177º, respectively. 23 GCPs were collected and their map coordinates were obtained from differential GPS with 0.5-m accuracy and 20-m grid spacing DEM with 5-m accuracy;
5. Dresden, Germany is a rural environment and a rolling topography with 300-m elevation range (Meinel *et al.*, 2001). Pan and XS co-registred images were simultaneously acquired August 1, 2000 with collection and azimuth angles of 71º and 335º, respectively. 112 GCPs were collected and their map coordinates were obtained from 1:10,000 topographic maps

with 4-m accuracy and 1-m grid spacing laserscanning DEM with 1-m accuracy. In addition, a second set of map coordinates (118 GCPs) were obtained from 0.4-m pixel ortho-photo mosaic with 1-m accuracy;

6. Caracas, Venezuela is a urban and rural environment and a mountainous topography with 2200-m elevation range (Arismendi *et al.*, 2000). Four Pan in-track images were acquired from the same orbit December 30, 1999 with collection and azimuth angles for each image of 59º and 12º, 65º and 46º, 73º and 71º, 76º and 122º, respectively. Around 30 GCPs were collected for each image and their map coordinates were obtained from 2.5-m pixel ortho-photos with 5-m accuracy and 5-m grid spacing DEM with 5-m accuracy; and
7. Luzern, Switzerland is an urban and rural environment and a mountainous topography with 2000-m elevation range. Pan image was acquired April 22, 2000 with collection and azimuth angles of 68º and 256º, respectively. 70 GCPs were collected and their map coordinates were obtained from 1.25-m pixel images of scanned 1:25,000 topographic maps with 5-m accuracy in the three axes.

Table 1: Description of study sites with environment types, relief and elevation variation (Δelevation), of IKONOS images with mode, collection (Coll.) and azimuth (Az.) angles and of cartographic data with number of GCPs, accuracy of the planimetry (Plani.) and DEM. For Dresden study site, different GCPs were collected twice with different cartographic accuracies.

Study Site	Environment Type	Relief Δelevation	IKONOS Image			Cartographic Data		
			Mode	Coll.	Az.	GCP	Plani.	DEM
Toronto Canada	Sub-urban	Flat 60 m	Pan	51º	21º	30	0.5 m	5 m
Beauport Canada	Residential Semi-rural	Hilly 500 m	Pan Pan	63º 63º	322º 252º	56	3-7 m	5 m
Toulouse France	Sub-urban Rural	Flat 100 m	Pan XS	70º	138º	33	1 m	5 m
Trier Germany	Urban Semi-rural	Rolling 300 m	XS	65º	177º	23	0.5 m	5 m
Dresden Germany	Rural	Rolling 300 m	Pan XS	71º	335º	115	1) 4 m 2) 1 m	1 m
Caracas Venezuela	Urban Rural	Mountains 2200 m	4 Pan	59º to 76º	12º to 122º	30	5 m	5 m
Luzern Switzerland	Urban Rural	Mountains 1800 m	Pan	68º	256º	35	5 m	

Since the processing is performed on the full image area, GCPs cover the total surface (100 km^2) with also points at the lowest and highest elevation to avoid extrapolations, both in planimetry and altimetry. In general, the plotting accuracy for Pan images is about 1-2 pixels in the urban and sub-urban areas and 2-3 pixels in the rural and mountainous areas due to the difficulty to find and locate 1-m precise ground elements. For XS images, the plotting accuracy depends of the method used to evaluate different possibilities and the environment:

- in the Trier site, GCPs have been plotted on the XS image, most of them in the urban environment with an accuracy of half-pixel (about 2 m);
- in the Dresden site, GCP coordinates have been imported and computed by dividing by four

from Pan image coordinates with the same accuracy, 2-3 m in rural environment; and

- in the Toulouse site, GCPs collected on the Pan image have been re-plotted on the XS image with an accuracy better than one pixel. However, these points are not necessarily the best defined in the XS image.

3. RESULTS AND DISCUSSIONS

The error propagation can be tracked along the geometric processing steps with bundle adjustment results on independent check points (ICPs) as a function of GCP numbers, location and accuracies and with the ortho-images as a function of DEM accuracy and spacing. It should be noted that the processing is performed on the full image size (about 100 km^2) and not only on small sub-area.

Bundle Adjustment Results

The first test is performed using different GCPs/ICPs configurations using the Dresden site, which has the most complete data set, were thus evaluated to find the optimal number of GCPs in relation with the error of the cartographic co-ordinates. With Dresden_Pan1 data set, the number of GCPs varies from 112 to 6 and the results (Figure 1, left) are evaluated on the 118 1-m accurate ICPs from the second set of coordinates (Dresden_Pan2). With Dresden_Pan2 data set, the number of GCPs varies from 70 to 6 and the results (Figure 1, right) are evaluated on the remaining ICPs (from 48 to 112, respectively).

In Figure 1 (left), the RMS error on ICPs is always more than 3 m whatever the number of GCPs (even 112), and 15-20 GCPs are a good compromise to keep 3-4 m accuracy. The combination of cartographic and plotting errors (4 m and 2-3 m, respectively) avoid a better accuracy to be obtained, even with a large degree of freedom in the least square adjustment. On the other hand (Figure 1, right), the RMS error consistently decreases to 2-3 m when using the 1-m accurate second set of GCP coordinates (Dresden_Pan2), with slightly better results in the Y-coordinate. Ten precisely located GCPs are then a good compromise to achieve this 2-3 m accuracy. For this test, the RMS error reflects the major source of error, which is the plotting error (2-3 m).

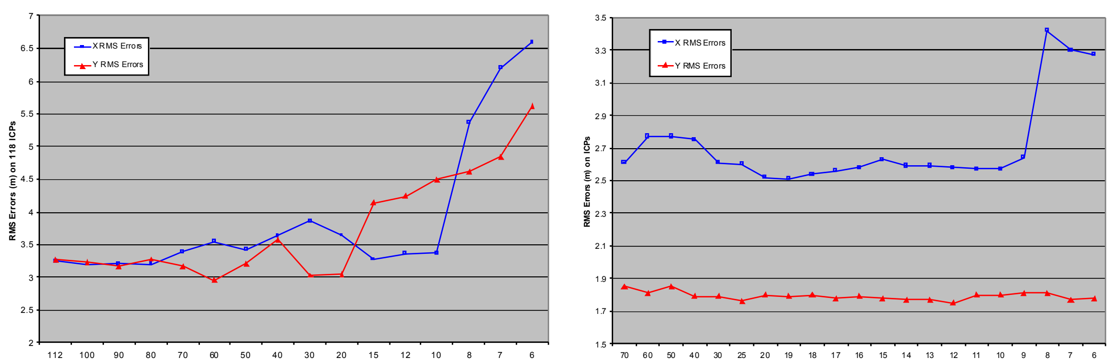

Figure 1.Left: Root mean square (RMS) errors (in metres) on 118 1-m accurate ICPs from the least-square bundle adjustment computed with GCPs varying from 112 to 6 for the Dresden study site. Right: RMS errors (in metres) on 1-m accurate ICPs from the least-square bundle adjustment computed with GCPs varying from 70 to 6 for the Dresden study site.

By applying these values (25 GCPs for 5-m accurate coordinates and 10 GCPs for 1-m accurate coordinates) on the other data set, Table 2 shows statistical results of the bundle adjustment: number of GCPs/ICPs and the RMS and minimum/maximum errors on the ICPs. For some data sets (Toronto, Caracas), a smaller number of GCPs is used to keep enough ICPs for the statistical evaluation. When the cartographic coordinates are 1-m precise (Toronto, Toulouse, Trier, Dresden_2), RMS errors are always around 2-3 m with slightly worse results for Toulouse. The accuracies for these data sets are due to the plotting errors for each image depending of the environment. When the cartographic coordinates are 5-m precise (Beauport, Dresden_1, Caracas, Luzern), the RMS errors are a little worse than 3-5 m with slightly worse results for Beauport in the X-direction due to the ortho-photo X-error. The slightly worse results for Caracas are partly related to the reduced number of GCPs in the least square adjustment: 12 instead of 20 reducing the advantages of least square adjustment. Consequently, the errors for these data sets result from the map coordinate errors for each study site. These results then confirm the first results on Dresden. Finally, the RMS errors on ICPs are 10-15% higher than the RMS residuals on GCPs, and are in the order of magnitude of the input data errors. Consequently, the results of the bundle adjustment reflect the cartographic error and this cartographic error does not propagate through the modelling but through the residuals.

Table 2: Bundle adjustment results for all study sites with the number of GCPs and ICPs, the root mean square (RMS) and min./max errors (in metres) on the ICPs. For Dresden study site, there are two sets of results as a function of different GCP numbers and accuracies. For Beauport and Caracas study sites, results are given for the different Pan images (A, B, C, D).

Study Site	GCP Number	ICP Number	RMS Errors		Min./Max Errors	
			X	Y	X	Y
Toronto	7	23	1.3	1.3	-3/3	-3/2
Beauport_A	20	36	7.5	2.7	-16/6	-2/6
Beauport_B	20	36	7.6	2.6	-16/11	-4/7
Toulouse_Pan	10	23	3.9	1.8	-8/3	-3/5
Toulouse_XS	10	23	4.9	3.3	-5/11	-6/5
Trier	10	12	2.3	1.8	-3/5	-2/4
Dresden_Pan1	20	118	4.1	2.7	-8/4	-5/8
Dresden_XS1	20	118	4.1	2.7	-8/4	-5/8
Dresden_Pan2	10	108	2.9	1.7	-7/7	-4/5
Dresden_XS2	10	108	2.9	1.7	-7/7	-4/5
Caracas_A	12	15	2.9	3.9	-6/4	-6/7
Caracas_B	12	23	6.4	4.4	-11/12	-9/14
Caracas_C	12	26	6.9	4.4	-13/8	-4/4
Caracas_D	12	12	3.4	4.4	-5/5	-9/7
Luzern	20	56	5.8	3.0	-10/11	-8/9

Refining this analysis demonstrates that the RMS errors are slightly larger than the ICP planimetric error when the input coordinates are 1-m or less precise (Toronto, Toulouse, Trier, Dresden_2). It is the reverse when the input coordinates are 5-m precise (Beauport, Dresden_1, Caracas, Luzern). In fact, the plotting error is the major source of error in the first case (2-3 m versus 1 m) while the map coordinate error is the major source in the second case (5 m versus 2-

3 m). When the plotting error is the major source of error, it thus explains that:

- the RMS error differences between Pan and XS images (Toulouse) are not proportional to pixel spacing because the plotting accuracy is about the same (2-3 m);
- the RMS errors in urban environment (Toronto, Trier) are better than the RMS errors in rural environment (Toulouse, Dresden_2) because the GCP definition and plotting are more accurate in urban environment; and
- The RMS errors for XS images are correlated with the plotting error: the best results for Trier (RMS and plotting error of 1.4 m and 2 m, respectively) and the worse for Toulouse (RMS and plotting error of 3 m and 4 m, respectively). In Toulouse the GCPs firstly collected from the Pan image were not necessarily the best-defined points in the XS image.

The last test on bundle adjustment is related to the location of GCPs. It is well known that extrapolation in planimetry outside of the GCP boundary is not recommended. However, it is not well recognized that large extrapolation should also not be applied in the elevation direction. To test the impact of elevation extrapolation, Caracas and Luzern study sites are used because they have more than 2000-m elevation difference. When the highest GCP used in the bundle adjustment is 1000-m lower than the mountain summit (generating 1000-m extrapolation) the largest planimetric errors on the highest ICPs are around 20-30 m. This error reduced to 10 m when the elevation extrapolation is reduced to 500 m.

These tests demonstrate that the CCRS-developed model and method are both stable and robust for IKONOS Geo-product images without generating local errors, and filter random or systematic errors. The input GCP error does not propagate through the rigorous model, but is reflected in the residual. It then gives a good level of confidence of the applicability and robustness of the CCRS parametric model applied to IKONOS Geo-product data in operational environments.

Ortho-images Results

Evaluations of ortho-images of three study sites are performed (Beauport_A, Trier and Dresden). These sites were chosen because digital vector files with 1-3 m accuracy were available. Figure 2 shows the ortho images with vector lines overlaid: Trier (top left), Dresden (top right) and Beauport (top right) compared to otho-photo (bottom right). For Beauport_A, a first quantitative comparison of the panchromatic ortho-image (1-m pixel) was realized with 31 ICPs extracted both from 3-m accurate vector lines. RMS errors of 5 m and 3 m with 1.5-m and –0.5-m bias for X and Y, respectively were computed with no errors larger than 10 m when compared to the vector lines. In a second step, qualitative analysis is performed on the ortho-image (Figure 2, top right) and the ortho-photo (Figure 2, bottom right). The road vector lines are always inside the IKONOS roads: considering 10-m width for the main road, 4-m error can be estimated. These two estimated errors from checkpoints and vector lines are better than a circular error of 8 m directly computed from the ICP errors (Table 2) (the 5-m elevation error has only 2.5-m error impact in the error budget). However, the 5-7 m X-error of the ortho-photos is included in the 8-m circular error, which then biased the predicted error. Furthermore, when comparing the same roads overlaid on the 1-m ortho-photo the same deviations can be noticed: it could mean that part of errors comes from the 3-m error vector lines. Evaluation on other features, such as secondary roads, rivers and even private houses confirms the 4-m error.

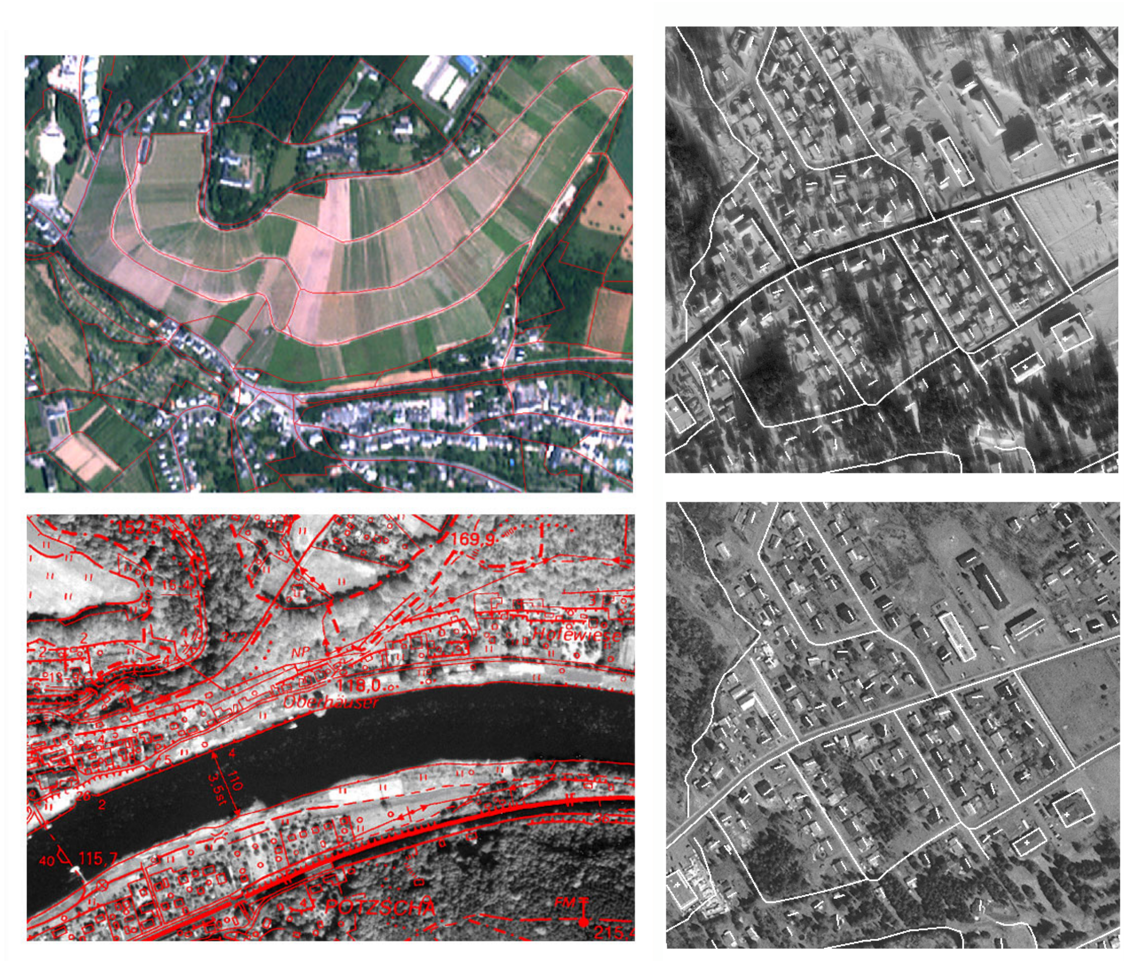

Figure 2. Top-left: sub-area of the Trier ortho-image (2-m pixel spacing, 640 pixels by 440 lines) with 2-m accurate vector lines overlaid. Bottom-right: Dresden ortho-image (1-m pixel spacing, 940 pixels by 660 lines) with 2-m accurate vector lines overlaid. Top-right: sub-area of the Beauport_A ortho-image (1-m pixel spacing, 512 pixels by 512 lines). Bottom-right: Beauport ortho-photo (1-m pixel spacing, 512 pixels by 512 lines) with 1:25,000 3-m accurate vector lines overlaid.

For Dresden, the quantitative comparison of the Pan ortho-image (1-m pixel) was independently realized at Dresden using 31 independent check points extracted from the 0.4-m pixel ortho-photo mosaic with 1-m accuracy. RMS errors of 2 m with 0.5-m bias in both axes were computed with no errors larger than 5 m. It is consistent with a circular error of 3 m directly computed from the ICP errors (Table 2) because the 1-m elevation error has a minor impact in the ortho-rectification process and in the error budget.

Trier and Dresden images with the vector files were evaluated both in Canada and Germany: there is in general a good superposition between the vectors on the appropriate image features. The Trier sub-area (640 pixels by 440 lines) is the most pronounced relief area of the full image with 150-m elevation variation along a steep vineyard. The cartographic lines along the slope, such as in the villages appear to exactly conform to ortho-image geometry with one pixel error

(2 m). It is more evident in 3-m wide vineyard tracks. This approximate error evaluation is consistent and even better than the predicted error of 4 m, previously computed. For Dresden sub-area (940 pixels by 660 lines), the coastlines of the river show errors no more than 2-3 pixels (2-3 m). Other well-defined features, such as roads or city streets visually show the same accurate superposition with the ortho-image in accordance with the check point accuracy evaluation previously done. More results on the other study sites will be given at the Workshop.

4. CONCLUSIONS

To expand on the applicability of CCRS-developed geometric model for IKONOS Geo-product images, 13 Pan or XS images from five international collaborators over seven study sites with various environments and terrain were tested. Cartographic data (maps, ortho-photos, GCPs, DEM, digital vector files) were acquired from different sources, methods and accuracy. The objective of the paper was to track the error propagation during the full geometric correction process (bundle adjustment and ortho-rectification).

When GCPs are less than 3-m accurate, 20 GCPs is a good compromise to obtain 3-4 m accuracy in the bundle adjustment. When they are better than 1-m, 10 GCPs are then enough to achieve 2-3 m accuracy. In the first result, map coordinates is the major source of error while it is the GCP definition and plotting error in the second result. With good GCPs (1-2 pixel accurate for the definition and plotting; 1-m accurate for the map coordinates), 2-m accuracy can be achieved in the bundle adjustment of both Pan and XS images (Toronto and Trier, respectively). Since definition and plotting error of GCPs becomes a key aspect with IKONOS images to increase the final accuracy (to 1-2 m), future research at CCRS will address this point with benchmark on the ground for defining 1-m precise GCP, as done in photogrammetry.

To track the error during the ortho-rectification, quantitative and qualitative evaluations of relative and absolute errors in the ortho-images were performed with either independent check points or digital vector files overlaid. Generally, the measured errors confirm the predicted errors or even were slightly better: 2-m accuracy was achieved for some ortho-images when the cartographic data was of good quality and 4-m accuracy for the others. To achieve a better positioning accuracy, such as 1 m, 1-2 m accurate DEM with fine grid spacing is required in addition to precise GCPs (definition, plotting and map).

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