Evaluation and Improvement of Geopositioning Accuracy of IKONOS Stereo Imagery

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Abstract: IKONOS imagery has been used in many commercial, government, and research applications ranging from environment monitoring, to coastal change detection, and to national security. The high costs of IKONOS high end products (Pro and Precision products) make it extremely attractive to find practical methods that use lower-cost IKONOS Geo products to produce highly accurate mapping products. This paper presents four different models defined in both object space and image space to refine the rational function derived ground coordinates. The models are the translation, scale and translation, affine, and second-order polynomial models. Different configurations of ground control points (GCPs) are carefully examined to evaluate the impact on accuracy improvement. The models are tested based on two IKONOS stereo pairs acquired in the Lake Erie coastal area. It is demonstrated that if an appropriate model and GCPs are used, ground point errors can be reduced from 5–6 to 1.5 m in horizontal and from 7 to 2 m in vertical directions.

DOI: 10.1061/(ASCE)0733-9453(2005)131:2(35)

CE Database subject headings: Imaging techniques; Coastal environment; Mapping; Oceanographic surveys.

Introduction

The newly available submeter resolution satellite imaging systems, such as IKONOS and QuickBird, usher in a new era for mapping using space-borne sensors. For example, the IKONOS imaging system simultaneously collects 0.8 m resolution stereo panchromatic and 4 m multispectral images. An overview of the IKONOS mapping accuracy is given in Grodecki and Dial (2001). IKONOS image products including Geo, Reference, Pro, Precision, and Precision Plus, provide different processing levels and corresponding positioning accuracies (Table 1). Highly accurate products such as Precision or Precision Plus cost much more than the less accurate Geo product. It is sometimes very desirable and important to use the lower-cost IKONOS Geo product and still achieve outcomes comparable to the more expensive products. A number of investigations on the accuracy attainable by various methods for photogrammetric processing of IKONOS imagery have been reported. Li (1998) discussed the potential accuracy of IKONOS imagery using basic photogrammetric principles. In addition, Zhou and Li (2000) demonstrated the potential accuracy (2–3 m) of ground points achieved using simulated 1 m IKONOS stereo images and the pushbroom imaging principle. Tao and Hu (2001) derived a least-squares solution to the rational function (RF) and comprehensively evaluated and analyzed the results of numerous tests with different data sets. Also, using one ground control point (GCP) for bias compensation in IKONOS RFs achieved submeter accuracy (Fraser and Hanley 2003). Toutin (2003) used a parametric model for panchromatic and multispectral IKONOS image geometric processing.

The IKONOS stereo images are supplied with RF that is an alternative to a physical camera model that describes the transformation between the image and object spaces. Although they do not describe sensor parameters explicitly, RFs are simple to implement and fast to perform the transformations. They are effectively used for feature extraction, terrain model generation, and orthorectification. Generally, RF coefficients are estimated without the aid of ground control (Di et al. 2001; Tao and Hu 2001). Thus, some biases may not be corrected and inherent in RFs, which are reflected in the achieved geopositioning accuracy. A systematic error of 6 m was found between the RF-derived coordinates and the ground truth (Li et al. 2003). A similar result was reported in Fraser and Hanley (2003). It is desirable that such errors in the image products be reduced or eliminated using relatively simple methods by users, so that they can be used for many applications that require higher mapping accuracy.

There are two methods that can be used to improve the ground accuracy from the IKONOS RFs (Di et al. 2003b; Li et al. 2003). The first method is to refine the RF coefficients based on a large number of GCPs (more than 39 GCPs required for third-order RF). This method is theoretically applicable, but not practical where a large number of GCPs is not available. The second approach refines the ground coordinates calculated from the RFs using a polynomial correction in either image space or object space. This method has the advantage of simplicity and efficiency. It requires significantly fewer GCPs than the first approach. A number of publications reported results of this approach with some variations. Grodecki and Dial (2003) proved that a RF-based block adjustment model is mathematically simpler and numerically more stable than the traditional adjustment using a physical camera model with exterior and interior orientation pa-

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Note. Discussion open until October 1, 2005. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on December 3, 2003; approved on June 22, 2004. This paper is part of the ***Journal of Surveying Engineering***, Vol. 131, No. 2, May 1, 2005. ©ASCE, ISSN 0733-9453/2005/2-35–42/$25.00.

Table 1. Accuracy of 1 m Resolution IKONOS Products

Product	Geo	Reference	Pro	Precision	Precision plus
Accuracy	25 m	11.8 m	4.8 m	1.9 m	0.9 m

rameters. Also, its result is as accurate as an adjustment using a physical camera model. Di et al. (2003a) used first-, second-, and third-order polynomials defined in the object space to improve ground coordinates computed from the RFs. The first-order polynomials using a three-dimensional affine transformation were found to be most efficient. The accuracy reached about 1.5 m in planimetry and 2 m in height.

This paper expands on the above-mentioned investigations, to conduct a systematic study on numerical patterns and results using the second method that improves the accuracy of ground coordinates derived from the vendor-provided RFs. Four transformation models are used in both object space and image space, including translation, scale and translation, affine, and second-order polynomials. They are tested using two IKONOS stereo pairs acquired in the Lake Erie coastal area. Different configurations of GCPs are carefully examined to evaluate effects of GCPs on the accuracy. Additional effects of variations in the number, location, and accuracy of GCPs on the accuracy are also analyzed. The least-squares adjustment technique is applied to compute the transformation parameters.

Rational Functions

Rational functions are described in detail in Tao and Hu (2001) and Grodecki and Dial (2003). A brief summary is presented here.

A RF performs a transformation between an image point (i,j) and its point in the object space (X,Y,Z) through a ratio of two polynomials in the following equation:

$$i = P_1(X,Y,Z)/P_2(X,Y,Z)$$

$$j = P_3(X,Y,Z)/P_4(X,Y,Z) \quad (1)$$

where the polynomial P_i (i=1, 2, 3, and 4) has the following general form:

$$\begin{aligned}P(X,Y,Z) = {} & a_1 + a_2X + a_3Y + a_4Z + a_5XY + a_6XZ + a_7YZ + a_8X^2 \\ & + a_9Y^2 + a_{10}Z^2 + a_{11}XYZ + a_{12}X^3 + a_{13}XY^2 + a_{14}XZ^2 \\ & + a_{15}X^2Y + a_{16}Y^3 + a_{17}YZ^2 + a_{18}X^2Z + a_{19}Y^2Z + a_{20}Z^3\end{aligned} \quad (2)$$

This is a third-order RF with a 20-term polynomial that transforms a point from the object space to the image space.

Substituting P_is in Eq. (1) by the polynomials in Eq. (2) and eliminating the first coefficient in the denominator, we have 39 RF coefficients (RFCs) in each equation, including 20 in the numerator and 19 in the denominator. Since each GCP produces two equations for image coordinate i and j separately in Eq. (1), at least 39 GCPs are required to solve for the 78 coefficients.

The RFCs are usually computed by satellite image providers without using GCPs. Instead, the object space is sliced in the vertical direction to generate virtual control points for calculating the RFCs (Tao and Hu 2001; Di et al. 2003b). The ground coordinates derived from such RFCs typically have an accuracy of Geo products (about 25 m). If quality GCPs are available, there is a potential to use the GCPs for enhancing the ground accuracy.

Data

The IKONOS images used in this experiment were taken in May 2002 in the Lake Erie coastal area. They are two stereo pairs. RFCs of each image were supplied by Space Imaging Corp. They also provided the four geographic corner coordinates of each image, nominal collection azimuth, and nominal collection elevation of the satellite. With these parameters (shown in Table 2), the convergence angles of the two stereo pairs were calculated. The convergence angle is calculated by an intersection of two lines: a line from the first position of the satellite to the observer (the center of the image) and another line from the second position of the satellite to the observer. The GCPs and check points (CKPs) used in this experiment were obtained from high quality aerial photogrammetric triangulations of 12 aerial images in the same area. In total 52 points in the first pair and 57 points in the second pair were used. These points were used as GCPs and CKPs for different configurations. The accuracy of these points was estimated as 0.5 m. Fig. 1 gives a distribution of GCPs and CKPs in the two stereo pairs.

Accuracy Improvement

The experiment uses four improvement models (translation, scale and translation, affine, and a second-order polynomial) in both object space and image space (Table 3). In the object space, Model 1 adds a translation (a_0,b_0,c_0) to the ground coordinates (X,Y,Z) computed from the RFCs to achieve the improved ground coordinates (X',Y',Z'). This can be carried out by using at least one GCP. Model 2 uses three additional scale factors (a_1,b_1,c_1) to correct nonhomogeneous scale distortions. An affine transformation and a second-order polynomial are applied in Models 3 and 4, respectively. In implementation, for each GCP, we measure the image coordinates (i,j) of the point. The RF-based triangulation (Di et al. 2001, 2003b) is applied to calculate the ground coordinates (X,Y,Z). Since we know the correct coordinates (X',Y',Z') of the GCP, three equations can be established according to the models in Table 3. Using all available GCPs that are usually more than the minimum number required, overdetermined equation systems can be set up to compute the optimal estimates of the transformation parameters by a least-

Table 2. Image Parameters of Data Used in Experiment

	Pair 1	Pair 2
Image size	8,796 pixels × 7,900 pixels	8,708 pixels × 7,480 pixels
Nominal collection azimuth	328.862800°	237.974000°
Nominal collection elevation	69.235570°	68.016880°
Convergence angle	30.183908°	30.183890°

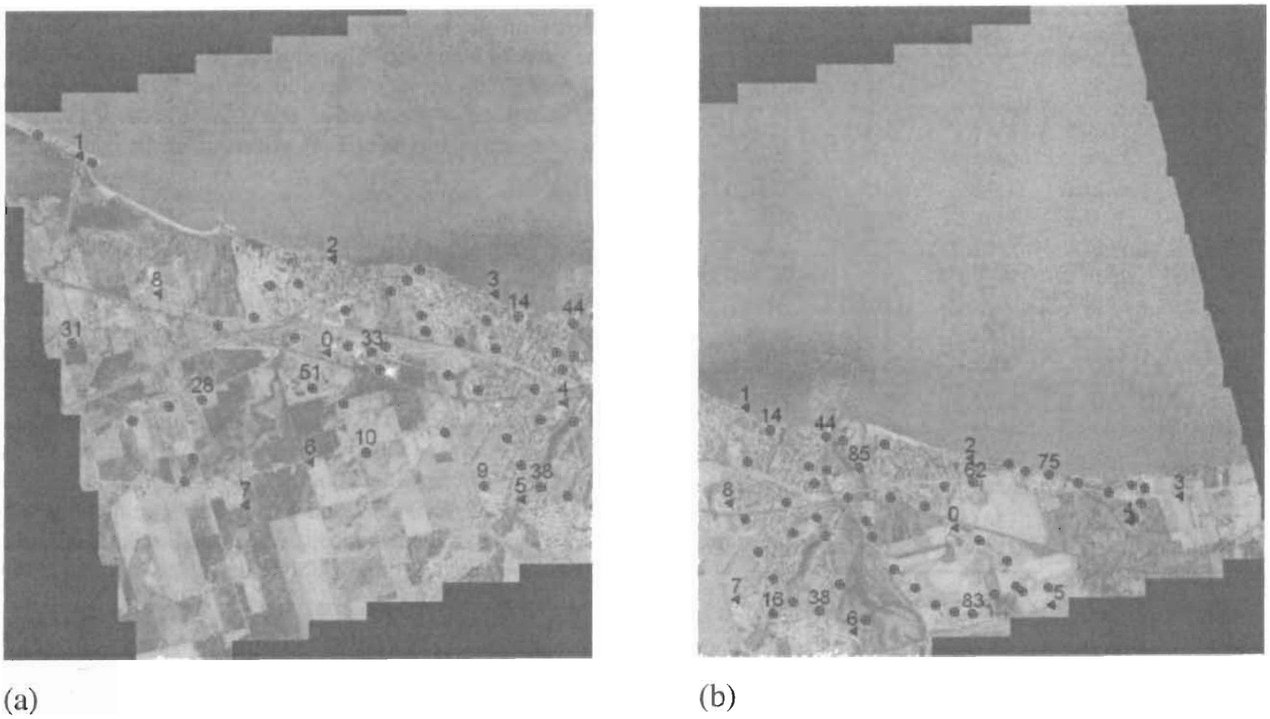

Fig. 1. Ground control points (triangles) and check points (crossed circles) used in 1 m resolution IKONOS stereo images: (a) first image of pair 1 and (b) first image of pair 2

squares adjustment. The transformation parameters can then be used to compute the improved coordinates of other points. In order to assess the appropriateness of the models, CKPs are used, which are not used for estimating the transformation parameters in the adjustment. Differences between calculated and known coordinates of the CKPs are the basis for the root mean square error (RMSE) of each model.

Similarly, in the image space, image coordinates (i, j) are improved by four similar models to compute the corrected image coordinates (i', j'). However, the models are simplified by dropping the parameters associated with the third dimension. The implementation and assessment processes are not different from those of the models in the object space.

To study the importance of different configurations of GCPs,

Table 3. Improvement Models in Both Object Space and Image Space

	Model ID		Model	Minimum number of ground control points
Object space	1	Translation	$X' = a_0 + X, Y' = b_0 + Y, Z' = c_0 + Z$	1
	2	Scale and translation	$X' = a_0 + a_1 X$ $Y' = b_0 + b_1 Z$ $Z' = c_0 + c_1 Z$	2
	3	Affine	$X' = a_0 + a_1 X + a_2 Y + a_3 Z$ $Y' = b_0 + b_1 X + b_2 Y + b_3 Z$ $Z' = c_0 + c_1 X + c_2 Y + c_3 Z$	4
	4	Second-order polynomial	$X' = a_0 + a_1 X + a_2 Y + a_3 Z + a_4 XY + a_5 XZ$ $+ a_6 YZ + a_7 X^2 + a_8 Y^2 + a_9 Z^2$ $Y' = b_0 + b_1 X + b_2 Y + b_3 Z + b_4 XY + b_5 XZ$ $+ b_6 YZ + b_7 X^2 + b_8 Y^2 + b_9 Z^2$ $Z' = c_0 + c_1 X + c_2 Y + c_3 Z + c_4 XY + c_5 XZ$ $+ c_6 YZ + c_7 X^2 + c_8 Y^2 + c_9 Z^2$	10
Image space	1	Translation	$i' = a_0 + a_0 + i, j' = b_0 + j$	1
	2	Scale and translation	$i' = a_0 + a_1 i$ $j' = b_0 + b_1 j$	2
	3	Affine	$i' = a_0 + a_1 i + a_2 j$ $j' = b_0 + b_1 i + b_2 j$	3
	4	Second-order Polynomial	$i' = a_0 + a_1 i + a_2 j + a_3 ij + a_4 i^2 + a_5 j^2$ $j' = b_0 + b_1 i + b_2 j + b_3 ij + b_4 i^2 + b_5 j^2$	6

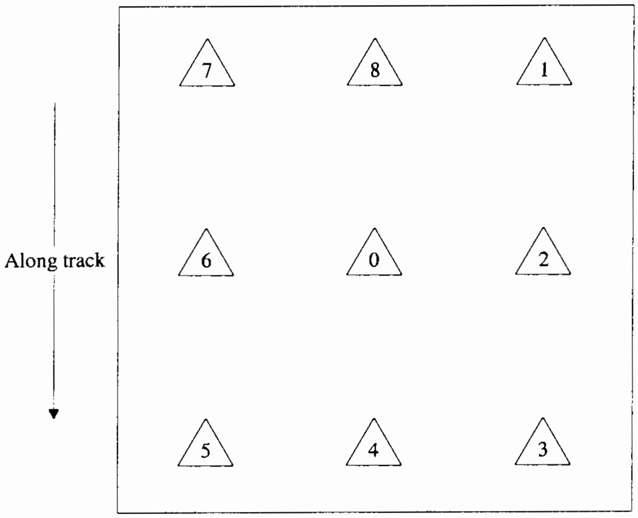

Fig. 2. Distribution of ground control points and position ID

we assume nine typical GCP positions in Fig. 2. The satellite track is in the north–south direction. The experiment starts with each model using the minimum number of GCPs (Table 3). Additional GCPs are then added to achieve better accuracy. Various combinations of the number and distributions of GCPs are also tested to find patterns and effectiveness of the configurations.

Experimental Results and Discussion

Tables 4 and 5 summarize the results of accuracy improvement by the four methods performed in the object space. For the two stereo pairs, various numbers and distributions of GCPs were used according to the methods applied. Once the transformation parameters of a method were estimated through a least-squares adjustment using the GCPs, they were along with the RFCs available for transformation from the image space to the object space. All CKPs, 52 for Pair 1 and 57 for Pair 2 minus the number of GCPs used in the adjustments, were measured in the image space. Their computed ground coordinates were compared with the

Table 4. Accuracy of Ground Points Improved by Four Methods in Object Space (Pair 1)

Method	Number of ground control points (GCPs)	GCP distribution	Redundancy	Root mean square error (m)			Maximum difference (m)		
				X	Y	Z	X	Y	Z
Translation	1	0	0	0.9779	1.1102	2.6760	3.6313	2.5313	5.3889
		1		1.4672	1.0114	2.3281	4.7185	2.4082	5.8635
		2		1.0119	0.7148	2.6434	3.3775	2.0389	6.5666
		3		0.9832	0.6919	2.8272	3.5349	1.9828	6.8749
		4		1.2835	0.6727	2.2424	4.4587	1.8319	4.7133
		5		1.0008	0.7337	2.2648	3.4245	2.0795	4.6060
		6		1.3185	1.0197	2.3778	4.5112	2.4189	4.7696
		7		1.0701	0.6559	3.3871	4.0657	1.7653	7.6685
		8		1.0695	0.8431	2.7904	4.0643	2.2691	5.5807
Scale and translation	2	Along track 0-51	0	2.5362	1.8610	1.8810	5.6730	6.8645	4.2728
		0-2		1.5686	2.0993	2.0015	3.9375	5.2759	5.6761
		10-33		2.1214	1.1988	3.9411	4.8702	4.4710	6.7542
		3-9		1.1179	0.6931	2.1868	3.8588	1.8156	5.5241
		5-14		4.7895	0.6249	2.9226	10.660	1.5225	8.8231
		38-44		2.1004	1.4276	2.5185	5.0710	2.8034	7.9822
		Cross track 5-7	0	2.6147	0.6156	2.3959	6.8279	1.5289	7.5161
		4-31		1.1454	0.7341	2.7168	4.2638	2.2986	8.8149
		3-8		1.0317	0.8217	2.2205	3.6729	2.8669	5.9843
		4-28		1.1022	1.8570	1.8882	4.1329	4.3173	4.1255
	4	1-3-5-7	2	1.1926	0.6265	2.0089	3.8243	1.6509	4.9435
		8-4-5-7		1.0706	0.7004	2.8344	4.0049	2.0937	8.8988
		1-3-4-8		1.1553	0.6219	2.0946	4.1047	1.5920	4.8074
		1-2-6-7		1.1678	0.7367	1.9591	3.7512	1.9622	4.7737
		2-3-5-6		1.1713	0.6944	1.8521	3.6185	2.1180	3.8913
	6	0-2-3-4-6-8	4	1.0733	0.9587	1.9613	3.9426	2.9195	4.6719
		0-2-4-5-6-8		1.0679	0.7121	1.9413	3.9257	2.0343	4.6392
		1-3-4-5-7-8		1.1342	0.6321	1.8919	3.9603	1.5724	4.1129
		1-2-3-5-6-7		1.1964	0.6316	1.9208	3.7241	1.5039	4.4032
Affine	4	1-3-5-7	0	1.5249	0.6446	3.2167	4.8705	1.4884	5.8502
		8-4-5-7		1.2428	0.9314	3.2945	4.6870	2.2343	10.813
	6	0-2-3-4-6-8	2	1.2081	0.9425	2.3563	3.7706	3.30391	6.3570
		0-2-4-5-6-8		1.2052	0.9081	2.2449	4.1694	3.2073	6.2545
		1-3-4-5-7-8		1.1787	0.7364	1.6778	4.4984	2.0978	4.1948
		1-2-3-5-6-7		1.3249	0.7021	2.7653	4.1076	1.5012	4.6707
Second-order	10	evenly	0	The computation is not converged					
polynomial	12	evenly	2	The computation is not converged					

Table 5. Accuracy of Ground Points Improved by Four Methods in Object Space (Pair 2)

Method	Number of ground control points (GCPs)	GCP distribution	Redundancy	Root mean square error (m)			Maximum difference (m)		
				X	*Y*	*Z*	*X*	*Y*	*Z*
Translation	1	0	0	1.3036	0.7093	1.7875	2.9660	2.2534	6.3705
		1		1.1102	0.7112	2.4360	2.9887	2.2592	7.4788
		2		0.8437	1.0214	2.0411	2.1470	2.7919	6.8894
		3		0.8338	1.4809	2.0137	2.1197	3.3813	6.8421
		4		0.9654	0.6731	1.8363	2.7501	2.1014	5.3820
		5		0.9228	1.3142	2.0383	2.3775	3.1491	6.8846
		6		1.8776	0.7032	2.1849	3.9230	2.2335	6.0107
		7		1.3470	0.7293	1.6925	3.3071	2.3533	5.3772
		8		0.8465	0.6727	1.9660	2.1595	2.0876	6.7565
Scale and translation	2	Along track 1-7	0	1.0445	0.7717	1.6221	2.6922	2.4314	6.0191
		14-16		6.5801	0.7149	2.7353	13.992	2.2909	7.2546
		38-44		5.6119	1.0109	4.2684	12.581	2.7587	11.577
		6-85		8.2184	0.8933	3.6936	19.042	2.1496	10.959
		62-83		2.6659	0.6846	2.1917	4.5000	2.1367	5.8086
		5-75		1.6143	0.8074	3.0251	3.3945	1.9849	7.0553
		Cross track 3-8	0	0.8496	1.4134	1.9925	2.1178	3.4908	6.7857
		7-83		1.1633	0.9727	2.5777	2.7206	2.1956	7.0308
		5-38		0.9253	0.8291	2.8084	2.3949	2.2800	7.9066
		16-83		1.0954	1.1922	1.7853	3.1629	2.8161	6.1197
	4	1-3-5-7	2	0.9793	0.6429	1.8227	2.0327	2.1040	6.4097
		8-4-5-7		0.8669	0.7066	1.6705	2.2994	1.9374	6.0849
		1-3-4-8		0.8747	0.9103	1.6794	2.4446	2.7202	6.1302
		1-2-6-7		1.1005	0.7361	1.5997	2.2148	2.2580	5.7927
		2-3-5-6		1.2717	0.6477	2.8034	2.5266	2.1434	7.7530
	6	0-2-3-4-6-8	4	0.8401	0.7716	2.2615	2.2228	2.2572	6.5461
		0-2-4-5-6-8		0.8322	0.7613	2.2837	2.1041	2.3133	6.4949
		1-3-4-5-7-8		0.9032	0.6550	1.7542	2.2479	2.0928	6.2333
		1-2-3-5-6-7		1.0721	0.6649	1.7554	2.1844	2.1532	6.2196
Affine	4	1-3-5-7	0	1.2006	1.7426	1.9205	2.6684	5.1707	6.2010
		8-4-5-7		3.0124	2.2732	4.7157	8.9045	5.9241	13.602
	6	0-2-3-4-6-8	2	1.0112	1.1934	1.7792	2.8186	2.6805	6.2549
		0-2-4-5-6-8		0.9521	0.7950	2.0745	2.2843	2.2715	6.4089
		1-3-4-5-7-8		0.9542	1.0633	1.8091	2.3626	2.8776	5.8245
		1-2-3-5-6-7		1.0396	0.6697	1.9085	2.0801	2.1447	7.3882
Second-order polynomial	10	evenly	0	The computation is not converged					
	12	evenly	2	The computation is not converged					

known coordinates to compute the coordinate differences in three dimensions, which were in turn applied to estimate RMSE of coordinates and to list the maximum coordinate differences in the tables. In the GCP distribution column, each number (from 0 to 8) in a digit represents a location close to that indicated in Fig. 2. For instance, 0 represents a single point around the center, and 1-3-5-7 stand for four points at four corners. Additional GCPs along and cross track were needed to study special configurations. They were chosen from the CKP set and with identifications (IDs) greater than 8 (Tables 4 and 5). Since the two stereo pairs cover a large portion of water, the actual GCP distributions are not exact as in Fig. 2. The results of the four improvement methods performed in the image space are summarized in Tables 6 and 7. Discussions about the results regarding each method are given below.

Translation Model

The translation model offers a simple way to improve accuracy by a translation in either object or image space (Tables 4–7). No other transformation parameters are included. Using one GCP, one can achieve a reasonable accuracy (RMSE generally less than 2 m in horizontal and 3 m in vertical directions). The accuracy has no apparent relationship with the location of the GCP used. Since only one GCP is used, the quality of the GCP is critical to the final result. Obviously, more than one GCP is recommended.

Scale and Translation Model

The scale and translation model has additional scaling factors in the coordinate axis directions. Two GCPs are necessary for this model. In the object space, if two GCPs used are distributed in the cross-track direction, the computed RMSEs of ground points are slightly smaller than those in the along-track direction in stereo Pair 1 (Table 4). This trend is particularly obvious in stereo Pair 2 (Table 5) and is consistent with the results achieved using simulated IKONOS images (Zhou and Li 2000). The RMSEs calculated by using the method in the image space with two GCPs do not seem to show any significant variations associated with the GCP distribution. In order to increase the redundancy, more GCPs should be used. With four GCPs distributed evenly, a more consistent and improved result (less than 1.5 m in horizontal and 3 m

Table 6. Accuracy of Ground Points Improved by Four Methods in Image Space (Pair 1)

Method	Number of ground control points (GCPs)	GCP distribution	Redundancy	Root mean square error (m)			Maximum difference (m)		
				X	Y	Z	X	Y	Z
Translation	1	0	0	1.2781	1.0281	2.1239	3.7634	2.1197	4.4990
		1		1.8427	0.6776	1.3678	4.9989	1.4826	3.3098
		2		1.3368	0.8356	1.8443	3.4476	2.0308	4.7784
		3		1.4193	0.7594	1.7591	3.4461	1.8193	4.5292
		4		1.4329	0.7303	1.4623	4.3702	1.6332	3.1882
		5		1.3650	0.6312	1.3558	3.7027	1.5303	3.2194
		6		1.6057	1.0962	2.0778	4.7357	2.2196	4.6034
		7		1.6402	0.7957	1.6640	4.0738	1.6893	5.0388
		8		1.0696	0.8430	2.7904	5.7285	1.8747	4.3199
Scale and translation	2	7-3	0	3.9693	1.8927	6.0180	8.5488	4.5457	14.864
		5-1		1.3179	0.6529	1.2719	4.0985	1.3856	2.8216
		7-1		1.5905	1.0561	1.9923	4.0267	2.3791	5.7127
		6-2		10.9551	1.4869	1.4063	22.773	3.4549	4.2722
		5-3		5.5535	0.5591	1.3719	13.076	1.3106	3.1004
		7-5		2.0615	0.5413	1.5747	4.9550	1.1998	3.6730
		8-4		2.1155	0.8312	1.9862	7.1179	2.3818	5.5209
		1-3		1.2017	1.2139	2.8553	3.8556	2.5768	7.7864
	4	1-3-5-7	2	1.3610	0.6779	1.4029	3.9825	1.5070	3.3656
		8-4-5-7		1.4078	0.6337	1.1661	4.8146	1.4423	2.5801
		1-3-4-8		1.3658	0.6336	1.2206	4.4329	1.4393	2.9530
		1-2-6-7		1.6083	0.7129	1.3715	4.1036	1.7116	3.1162
		2-3-5-6		1.3666	0.6584	1.1636	4.0172	1.5311	2.7570
	6	0-2-3-4-6-8	4	1.5536	0.8968	1.5138	4.8329	2.6044	3.8660
		0-2-4-5-6-8		1.4854	0.6759	1.3188	4.8767	1.7945	3.1142
		1-3-4-5-7-8		1.3507	0.6514	1.2334	4.2259	1.4482	2.8728
		1-2-3-5-6-7		1.4316	0.6285	1.2182	3.9728	1.2728	2.9197
Affine	3	1-4-7	0	7.5001	3.5210	10.781	17.564	8.5119	25.823
		3-5-8		1.5812	0.6180	1.3307	5.6502	1.6242	3.0365
		2-5-7		2.9574	1.8723	3.8407	6.3367	4.2013	7.4969
		1-3-6		1.4759	0.6244	1.4452	3.9169	1.3704	3.6280
		1-5-7		1.5377	0.5369	1.4470	4.1883	1.2187	3.2957
		1-3-7		2.7913	1.1555	3.2716	6.6153	2.5799	8.4072
		3-5-7		2.4087	0.9789	3.1195	5.7514	2.0717	8.8494
		1-3-5		1.3684	0.5016	1.2244	3.8870	1.1319	2.9921
	4	1-3-5-7	1	1.3738	0.5002	1.2884	3.8883	1.1709	3.0068
		8-4-5-7		1.5530	0.8009	1.1658	4.6627	2.0503	3.1227
		1-2-6-7		1.5371	0.6533	1.5240	4.0722	1.4898	3.1290
	6	0-2-3-4-6-8	3	1.5084	0.8379	1.2859	4.1255	2.5081	2.7483
		0-2-4-5-6-8		1.4287	0.5790	1.2915	4.5437	1.6856	3.1005
		1-3-4-5-7-8		1.4318	0.5978	1.1378	4.2303	1.5020	2.7870
		1-2-3-5-6-7		1.4658	0.5709	1.5002	3.7362	1.2959	3.3026
Second-order polynomial	6	0-2-3-4-6-8	0	1.5246	1.2878	1.5373	5.9154	5.1674	4.5052
		0-2-4-5-6-8		1.6241	1.5276	1.6496	4.7217	6.9614	4.5135
		1-3-4-5-7-8		2.0656	1.6138	1.8842	6.0130	5.0983	5.0090
		1-2-3-5-6-7		2.3551	1.4619	2.7251	6.4048	5.2789	8.2834
	7	evenly	1	1.5804	1.3800	1.4758	4.0907	4.9347	4.0168
	10	evenly	4	1.3668	0.5572	1.3623	3.6816	1.5315	3.8603

Table 7. Accuracy of Ground Points Improved by Four Methods in Image Space (Pair 2)

Method	Number of ground control points (GCPs)	GCP distribution	Redundancy	Root mean square error (m)			Maximum difference (m)		
				X	*Y*	*Z*	*X*	*Y*	*Z*
Translation	1	0	0	1.5441	0.5157	1.1662	6.9378	1.4245	3.9226
		1		1.4766	0.8527	1.7280	4.9741	1.9130	4.1771
		2		1.2206	0.9737	1.5688	6.2516	2.1291	3.9958
		3		2.2691	1.1142	1.8397	5.1552	1.9644	6.8298
		4		1.4388	0.5278	1.3157	6.2672	1.2796	5.2159
		5		1.2714	0.9590	1.5516	6.5008	2.0700	3.9749
		6		1.8343	0.5702	1.4957	6.1391	1.4661	5.9713
		7		1.5830	0.4892	1.2604	5.6655	1.1262	4.6303
		8		1.3030	0.5852	1.2089	6.0796	1.4855	3.4836
Scale and translation	2	7-3	0	1.9856	1.0469	1.6161	5.2229	2.7599	6.9732
		5-1		1.2983	0.9059	1.6211	6.2053	2.0248	4.3651
		7-1		1.7706	0.7055	1.2005	6.7395	1.5903	3.5938
		6-2		10.108	1.4663	1.0906	20.546	3.1664	3.4637
		5-3		2.5500	1.1250	1.8079	5.0942	2.7881	6.8180
		7-5		1.3584	1.4406	1.6987	4.6895	2.8181	3.9752
		8-4		1.8440	13.803	19.592	4.3734	28.333	39.911
		1-3		2.4713	2.1452	1.6568	5.0475	4.2641	6.6939
	4	1-3-5-7	2	1.4947	0.5124	1.1442	5.3685	1.3937	3.2619
		8-4-5-7		1.3238	0.5708	1.1682	6.1532	1.4746	4.4243
		1-3-4-8		1.4960	0.8666	1.1382	5.4039	1.9416	3.6025
		1-2-6-7		1.4546	0.6671	1.1579	6.2471	1.5848	3.6193
		2-3-5-6		1.3554	0.5428	1.0342	5.4980	1.5546	3.3012
	6	0-2-3-4-6-8	4	1.3343	0.5178	1.0721	5.6531	1.3028	3.4426
		0-2-4-5-6-8		1.2989	0.6394	1.0528	6.1583	1.5932	3.6569
		1-3-4-5-7-8		1.4327	0.5100	1.1218	5.5714	1.3201	3.5634
		1-2-3-5-6-7		1.4313	0.5485	1.0802	5.5762	1.4293	3.3596
Affine	3	1-4-7	0	1.5062	0.5490	1.1662	5.8739	1.2607	4.4690
		3-5-8		1.5942	0.9708	1.8820	5.1540	2.3036	6.8214
		2-5-7		1.3341	0.8767	1.4450	6.3959	2.3516	4.7306
		1-3-6		1.8613	0.6283	1.4450	5.0791	1.7732	6.7792
		1-5-7		1.2781	1.0430	1.7993	5.8962	2.6990	5.6933
		1-3-7		1.8839	0.7287	1.4702	5.0730	1.9392	6.7597
		3-5-7		2.4456	1.6402	1.9501	5.4686	4.6019	6.5480
		1-3-5		1.5931	1.3546	2.0177	5.1012	3.5602	6.8200
	4	1-3-5-7	1	1.5794	0.5475	1.2287	4.9481	1.6358	4.7006
		8-4-5-7		1.3221	0.5777	1.1917	6.3592	1.3504	4.5997
		1-2-6-7		1.4670	0.8232	1.1409	6.4897	2.1039	3.7787
	6	0-2-3-4-6-8	3	1.4257	0.6069	1.2114	5.8983	1.6376	4.2019
		0-2-4-5-6-8		1.3116	0.6344	1.0893	6.4362	1.5251	3.7384
		1-3-4-5-7-8		1.4772	0.5219	1.1524	5.3147	1.5447	4.0976
		1-2-3-5-6-7		1.5089	0.5898	1.0836	5.3659	1.6707	3.5788
Second-order polynomial	6	0-2-3-4-6-8	0	2.8608	1.7467	3.4292	8.5164	6.0669	10.119
		0-2-4-5-6-8		1.3972	0.8497	1.5809	6.3116	2.3622	4.4147
		1-3-4-5-7-8		3.9788	1.6533	6.1030	9.7068	2.9794	14.877
		1-2-3-5-6-7		1.4577	1.1442	2.0874	6.0925	2.4375	5.2906
	7	evenly	1	1.5027	0.6258	1.3888	6.0899	1.5345	5.8144
	10	evenly	4	1.5322	0.6283	1.3832	6.1736	1.4379	5.6946

in vertical directions) is demonstrated using the method in both object and image spaces. No significant improvement is achieved with six GCPs.

Affine Model

The affine model offers the capability to consider affinity in addition to translation and rotational corrections. From Tables 4–7, we can observe that the affine model with six GCPs generates about the same or slightly better results than that of the scale and translation model with four GCPs. Overall, the additional affine parameters and GCPs do not generate a very significant improvement over the result of the scale and translation model in both object and image spaces. It appears that the geopositioning errors from the original RFCs contain mostly a translation and a small scale change.

Second-Order Polynomial

The addition of the second-order parameters requires more GCPs. But it does not provide results comparable to other methods in the object space (Tables 4 and 5). In the image space, the model uses six GCPs and obtains the comparable results. However, the accuracy degrades if the GCP distribution is not even. Note that the model gives the best results (about 1.5 m in all three coordinates) if seven or ten GCPs are used. High-order polynomials are generally sensitive and require a large number of GCPs and a good GCP distribution. They do not exhibit convincing advantages over other methods.

Conclusions

This paper presents experimental results of a study on accuracy improvement of ground points determined by IKONOS images using GCPs and different transformation models in both object and image spaces. Two stereo pairs of IKONOS images acquired in the Lake Erie area and highly accurate GCPs are used in the experiment. Different methods and GCP distribution patterns are tested. Complete tables of computational results are given for drawing conclusions and discussions, as well as supplying the reader for his own analysis. Although the stereo pairs are from one area, based on the above experimental results, we can draw the following conclusions:

1. In general, there are no significant differences in the results of the models in object or image space, although the affine and higher-order polynomial models in the image space require fewer GCPs (Table 3). However, the models in the object space are generally more stable, considering the maximum differences listed (particularly in Table 7).
2. The quality of IKONOS images is very high. Using a simple translation model and one GCP we can correct the majority of errors and reach RMSEs of 2 m horizontal and 3 m vertical.
3. It is recommended that a scale and translation model or an affine model with four to six well-distributed GCPs be used to achieve a better accuracy (about 1.5 m horizontal and 2 m vertical). These methods seem to be most practical in applications.
4. The second-order polynomial model in image space with seven to ten GCPs provides the highest accuracy (1.5 m in both horizontal and vertical). However, higher-order polynomial models generally require more GCPs and are sensitive to GCP distribution and other factors. Its application in mountainous areas should be explored in the future.

This experiment is not focused on high precision subpixel object identification using IKONOS images, in which special image features, for example circles, sharp corners of large structures, and symmetric man-made objects, can be mathematically modeled and determined. The objects chosen in this study are general image features, such as road intersections, building corners, and other distinguished objects in the coastal area. The precision of the image point measurement is about a half pixel to one pixel. The achieved accuracy can be repeated without any additional unreasonable requirements.

Acknowledgments

This research is a part of a study supported by the National Science Foundation (NSF) Digital Government Program. Collaboration with the National Geodetic Survey/NOAA and the Ohio Department of Natural Resources (ODNR) is greatly appreciated. The writers also thank Ruijin Ma for assistance in GCPs data collection and processing.

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