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Spatial accuracy of orthorectified IKONOS imagery and historical aerial photographs across five sites in China

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High-resolution ($\leqslant 1$ m) satellite imagery and archival World War II era (WW2) aerial photographs are currently available to support high-resolution long-term change measurements at sites across China. A major limitation to these measurements is the spatial accuracy with which this imagery can be orthorectified and co-registered. We orthorectified IKONOS 1 m resolution GEO-format imagery and WW2 aerial photographs across five 100 km^2 rural sites in China with terrain ranging from flat to hilly to mountainous. Ground control points (GCPs) were collected uniformly across 100 km^2 IKONOS scenes using a differential Global Positioning Systems (GPS) field campaign. WW2 aerial photos were co-registered to orthorectified IKONOS imagery using bundle block adjustment and rational function models. GCP precision, terrain relief and the number and distribution of GCPs significantly influenced image orthorectification accuracy. Root mean square errors (RMSEs) at GCPs for IKONOS imagery were <2.0 m (0.9–2.0 m) for all sites except the most heterogeneous site (Sichuan Province, 2.6 m), meeting 1:12 000 to 1:4800 US National Map Accuracy Standards and equalling IKONOS Precision and Pro format accuracy standards. RMSEs for WW2 aerial photos ranged from 0.2 to 3.5 m at GCPs and from 4.4 to 6.2 m at independent checkpoints (ICPs), meeting minimum requirements for high-resolution change detection.

1. Introduction

The IKONOS 2 satellite, launched on 24 September 1999 by Space Imaging Inc., is the world's first commercial satellite offering high-spatial resolution (1 m) multispectral imagery (e.g. Toutin and Cheng 2000). Large-scale historical aerial photographs are the only source of high-spatial resolution imagery prior to the 1960s (e.g. Kadmon and Harari-Kremer 1999, Cousins 2001), and more and more of this historical imagery is being made available to the public by governments. Combined use of IKONOS imagery and historical aerial photographs make possible the detection and mapping of long-term changes in fine-scale landscape features, including small crop fields, houses, ponds, field borders, ditches, local roads and transitional areas between forests and agricultural fields that are commonplace in the densely populated rural landscapes that cover much of China and other developing agricultural nations (Ellis *et al.* 2000). These fine-scale features are

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usually too small to be detected even in 10 m resolution remotely sensed data. The broad availability of IKONOS imagery and historical aerial photographs therefore offers a unique opportunity for high-resolution mapping and change detection across densely populated landscapes in developing countries where imagery of this quality has been very difficult to acquire in the past (Kadmon and Harari-Kremer 1999, Cousins 2001, Kayitakire *et al.* 2002, Davis and Wang 2003, Di *et al.* 2003).

IKONOS image products are offered with differing levels of planimetric positional accuracy including Geo, Reference, Pro, Precision and Precision Plus with corresponding positional accuracies in root mean square error (RMSE) of 25, 11.8, 4.8, 1.9 and 0.9 m, respectively (Di *et al.* 2003, Space Imaging Inc., http://www.spaceimaging.com/products/imagery.htm). The IKONOS Geo product is the most affordable but offers the lowest positioning accuracy (25 m with 90% level of confidence) and is not corrected for terrain distortion (Toutin and Cheng 2000).

The positional accuracy of remotely sensed data limits its effective application to measurements of environmental change. For example, positional errors cause uncertainties in feature area calculation in land use and land cover change detection that can have serious consequences when estimating ecological changes or evaluating resources (Hunter and Goodchild 1995, Ellis *et al.* 2000, Davis and Wang 2003). The positional accuracy of IKONOS Geo imagery should be especially poor in mountainous areas, with errors in the 300 to 1000 m range for images acquired with 15–30° off-nadir viewing angles (Toutin 2003). IKONOS Geo imagery therefore requires orthorectification before application in high-resolution change mapping. Fortunately, IKONOS Geo images can be orthorectified using accurate ground control points (GCPs) and appropriate models to meet high-resolution ecological and environmental mapping standards at a scale of 1:10 000 and larger (Toutin 2001, Kayitakire *et al.* 2002, Davis and Wang 2003, Toutin 2004).

Most applications of IKONOS imagery have focused on urban or forest environments in developed nations (e.g. Toutin and Cheng 2000, McCarthy *et al.* 2001, Ganas *et al.* 2002, Davis and Wang 2003). There are very few published applications of this imagery to the highly heterogeneous rural landscapes of developing countries where geodetic ground control systems suitable for image orthorectification are rarely available. These densely populated rural areas cover as much as 8×10^6 km^2 globally, with almost 3×10^6 km^2 in China alone (Ellis *et al.* 2000). Given the limited availability of current high-resolution aerial photography in China and other developing countries, IKONOS imagery provides an unprecedented resource for high-resolution mapping and change detection in China's densely populated and highly heterogeneous rural landscapes. By co-registering large-scale World War II era (WW2) aerial photographs to orthorectified IKONOS imagery, for the first time, it should be possible to make precision measurements of land use change from the 1940s to the current time (2001–2002) at sites within China's rural landscapes.

It is especially critical to evaluate the spatial accuracy of all imagery used for change measurements in terms of positional co-registration errors before attempting to map and measure change based on these images (Townshend *et al.* 1992, Verbyla and Boles 2000). Previous studies indicate that planar accuracies of 3 to 5 m circular error at 90% confidence (CE90) are required for 1 m resolution spatial data (Davis and Wang 2003). This paper describes the orthorectification of IKONOS imagery and historical aerial photographs (circa 1945) across five densely populated rural sites selected across environmentally distinct regions of China. To test the suitability of these methods for high-resolution long-term change measurement, we compare IKONOS orthorectification and co-registration accuracy with historical aerial photos across five different landscapes and determine the factors most important to this accuracy, with a focus on terrain, image and GCP characteristics.

2. Materials and methods

2.1 *Orthorectification of IKONOS imagery*

Five 100 km^2 IKONOS Geo image scene acquisitions were purchased from Space Imaging Inc. (www.spaceimaging.com) across five rural sites distributed across China based on anticipated differences in terrain (table 1, figure 1).

The Gaoyi (Hebei Province), Yixing (Jiangsu Province), Jintang (Sichuan Province), Yiyang (Hunan Province) and Dianbai County (Guangdong Province) sites represent the North China Plain, Yangtze Plain, Sichuan Hilly Area, subtropical hilly area and tropical hilly and mountainous areas of China, respectively (Ellis 2004). IKONOS products were delivered in 1 m resolution pan-sharpened 4-band Geo format at UTM projection, WGS84 datum and with a nominal accuracy (90% confidence in circular error, CE90) of approximately 8–27 m on the ground. Table 1 shows the characteristics of IKONOS imagery at the five sites, some of which were acquired in two or more parts.

Orthorectification corrects imagery into a planar, map-like form by accurately removing all sensor-, camera- and terrain-related distortions based on camera/sensor models, terrain models and GCPs. Prior to locating GCPs in the field, ArcMap software (ArcInfo 8.1 Geographic Information System (GIS), Environmental Systems Research Institute, Redlands, CA, USA) was used to uniformly distribute a set of 25 to 28 'ideal' GCP locations, depending on image shape, across each IKONOS scene, and to buffer these points at 0.5 km, creating 'ideal GCP area' circles within which features to be used as GCPs in the field were selected. Figure 2 illustrates IKONOS imagery and historical (WW2) aerial photos as well as the GCPs for orthorectifying IKONOS and WW2 aerial photos for Gaoyi site as an example for flat areas and Yiyang site as an example for hilly areas.

Features selected as GCP locations fulfilled the following requirements:

- close to the ideal GCP location and within the ideal area circle;
- easy to identify the specific pixel for the GCP in the image;
- easy to identify on the ground visually (e.g. crossroads, field borders);
- no complicated elevations (bridges over rivers, buildings, cliffs);
- easily navigable (located on or near main roads, along with other GCPs).

To assist with GCP collection in the field, large-format maps were printed of entire IKONOS scenes overlaid with ideal GCP circles and GCP feature points, along with single-page maps for each GCP at 1:1200 scale, to aid in field identification of features at a pixel level. The distribution of field GCPs for the Gaoyi and Yiyang sites can be seen in figure 2.

A differential GPS (DGPS) for GCP collection was made possible by establishing a GPS base reference station either within the coverage of each IKONOS scene (Jintang, Dianbai, Gaoyi sites), or within 5 km of the scene (Yiyang) at each field site prior to GCP collection, except for the Yixing site, where DGPS correction for GCP fieldwork was provided by a real-time coastal DGPS beacon located ~200 km

Table 1. Characteristics of IKONOS Geo imagery acquired at five different sites in China.

Site	Region	Elevation (m)†	Width (km)	Length (km)	Acquisition Date	Number of images	Projection	Positional error (m)
Gaoyi, Hebei	Yellow River Plain	25–45	9	11.1	29 Nov. 2001	2	UTM 50N	8
Yixing, Jiangsu	Middle and Lower Yangtze Plain	3–15	7	14.25	26 Sept. 2002	3	UTM 50N	11
Jintang, Sichuan	Sichuan hilly area	380–570	7	14.25	22 Dec. 2001	1	UTM 48N	25
Yiyang, Hunan	Subtropical hilly area	40–260	7	14.25	1 Jan. 2002	1	UTM 49N	16
Dianbai, Guangdong	Tropical hilly and mountainous area	5–450	7	14.25	27 Oct. 2001 23 Nov. 2001	2	UTM 49N	27

†Gaoyi and Yixing elevations from GPS in height above ellipsoid (HAE); other sites from DEM above sea level (ASL) based on EGM96 (Pathfinder Office 2.6 software).

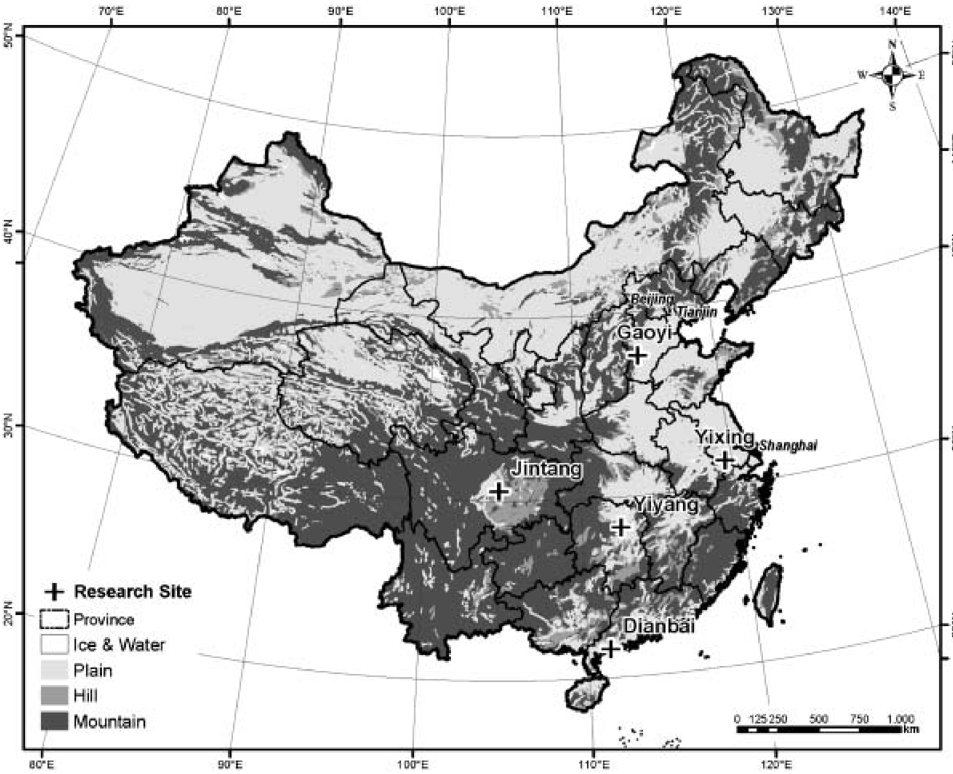

Figure 1. Locations of the five study sites in China, Albers equal area projection.

from the site (Haozhigang station). Base reference stations were located at high points protected from theft, with a clear view of the sky, either at the top of a building with a painted mark point (Dianbai, Gaoyi, Yiyang), or as a permanently placed stone marker (Jintang site). The precise location of each GPS base was established by at least 12 h of 5 s positions collected using a ProXRS GPS receiver (Trimble Navigation, Ltd., Sunnyvale, CA, USA) and post-processed using Pathfinder Office 2.6 software (Trimble Navigation, Ltd., Sunnyvale, CA, USA) against base data from permanent geodetic base stations of the International GPS Service (IGS; igscb.jpl.nasa.gov/index.html) for the Gaoyi site (BJFS station, Beijing, Hebei, ~240 km from site) and Yiyang site (WUHN station, Wuhan, Hubei, ~300 km from site), by real-time DGPS positions at the Dianbai site based on a coastal beacon ~110 km distant (Naozhoudao station), or as the median of 19 000 5 s high-quality uncorrected GPS positions (positional dilution of precision <3) collected over three different days at the Jintang site, where the nearest IGS base station was >600 km from the site.

GCP locations were collected in the field during April to June 2002 using two Trimble ProXRS GPS receivers, one set as a base and one set for simultaneous use as a rover. GCPs were visited and identified on the ground using 1:1200 maps in the field. At each GCP location, >60 5 s positions were taken with the ProXRS. These were then post-processed against site base station data using Pathfinder Office (except the Yixing site, see above), yielding horizontal, vertical and total field GCP precisions of <0.4 m, <0.75 m and <1 m, respectively, except for the Jintang site

(*a*)

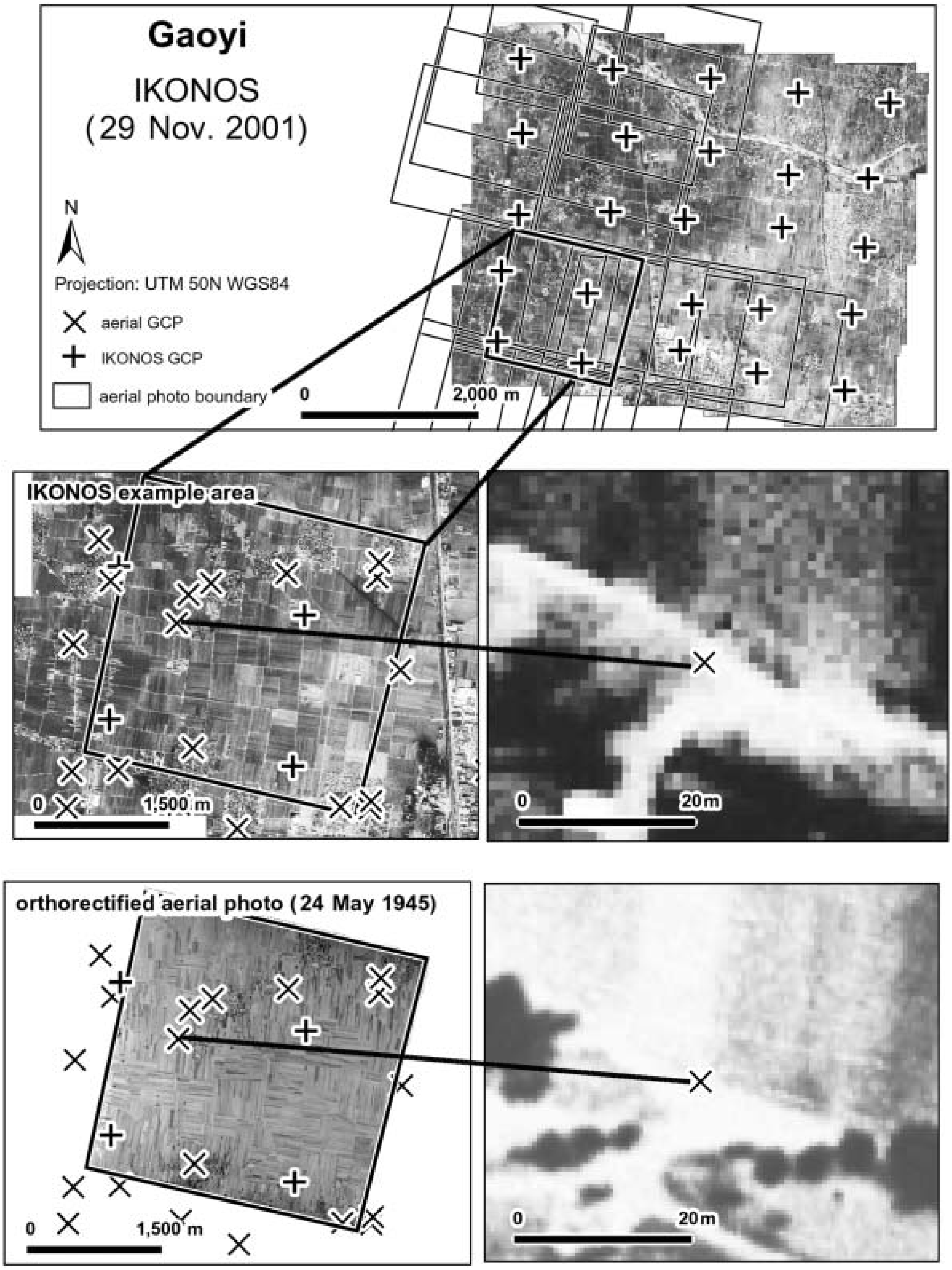

Figure 2. Maps showing orthorectified IKONOS imagery, 1945 aerial photos, photo boundaries and GCPs at (a) a nearly flat site, Gaoyi and (b) a hilly site, Yiyang. The warped photo edges at the Yiyang site are caused by removing terrain distortion. Positional error of GCPs for orthorectifying the historical (1945) aerial photos was <3 m for the example point in Gaoyi (intersection of local roads) and <2 m in Yiyang (intersection of field border).

(*b*)

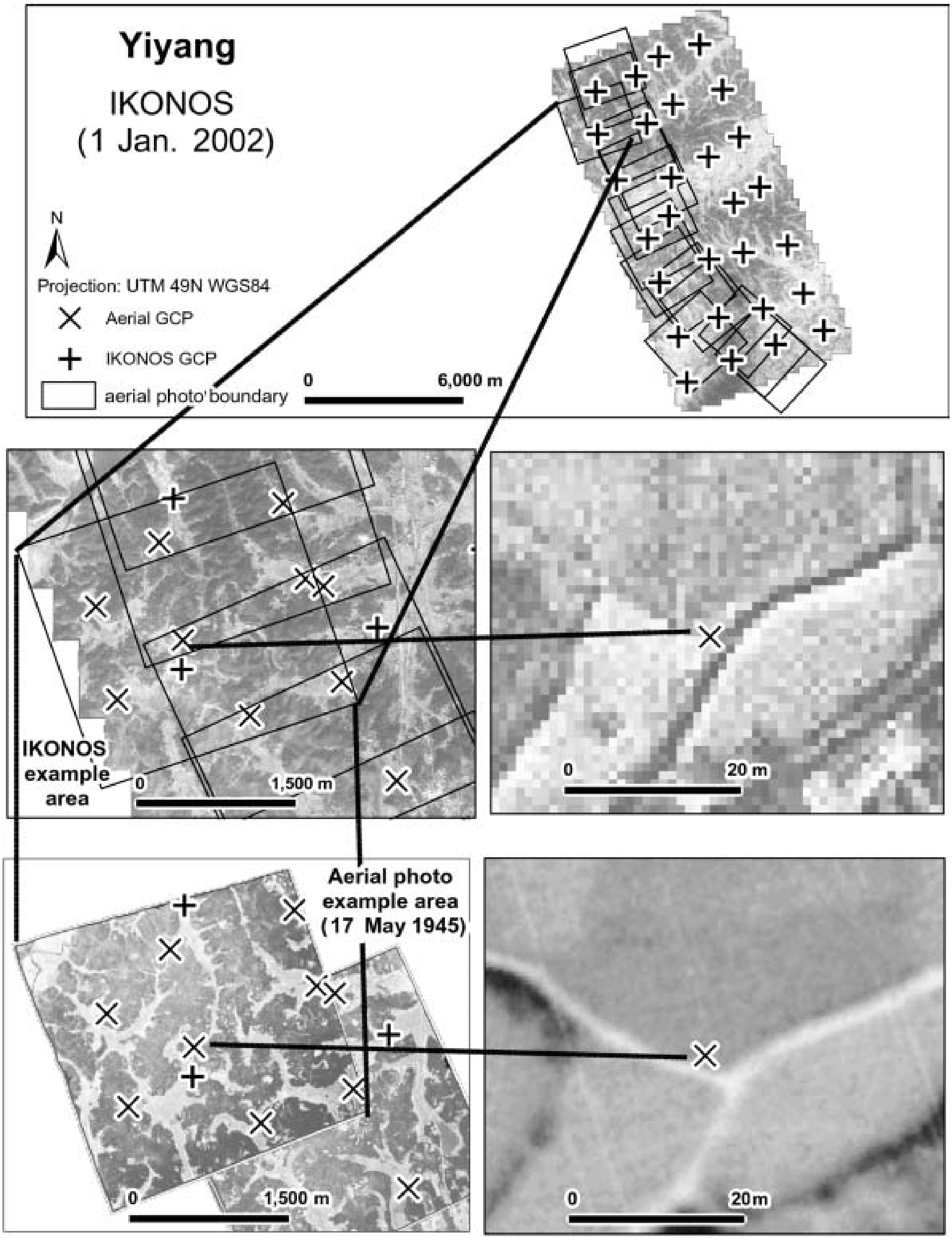

Figure 2. (*Continued.*)

(table 2). GPS elevations were converted to mean sea level elevations (MSL) using the EGM96 model in Pathfinder Office.

Digital elevation models (DEMs) were prepared for orthorectification of imagery at hilly and mountainous sites (i.e. Jintang, Yiyang and Dianbai) using the ArcInfo TOPPGRIDTOOL to create a 2 m resolution DEM based on 10 m interval elevation

Table 2. Field GCP precision (in m) at five sites in China.

Site	Horizontal	Vertical	Total
Gaoyi, Hebei	0.36	0.62	0.72
Yixing, Jiangsu	0.39	0.66	0.76
Jintang, Sichuan	0.9	1.44	1.69
Yiyang, Hunan	0.37	0.73	0.82
Dianbai, Guangdong	0.33	0.68	0.76

contours digitised from 1 : 50 000 Chinese maps (Beijing 1954 Datum). Map elevations, in the 1956 Yellow Sea System, were assumed equivalent to MSL.

IKONOS imagery was orthorectified using field GCPs and DEMs (for hilly sites only; flat site elevations were set to 0 m) using the High Resolution Satellite Model (i.e. rigorous model) of PCI Geomatics OrthoEngine Version 8.2 (PCI Geomatics, Richmond Hill, Ontario, Canada; Toutin 1995, Toutin and Cheng 2000). The RMSE of images was computed using:

$$\mathrm{RMSE}=\sqrt{\frac{\sum_{i=1}^{N}\left(P_{\mathrm{cp}}-P_{\mathrm{image}}\right)^{2}}{N}} \tag{1}$$

where P_{cp} and P_{image} are the x, or y, or horizontal position (xy) for GCPs or independent checkpoints (ICPs) and the image locations, respectively. Errors at GCPs are a proxy for errors within the geocorrection model while errors at ICPs are an approximate measure of overall planimetric accuracy across the image. CE90 indicates that feature positions are located in imagery within the stated accuracy 90% of the time and is estimated by rank ordering the radial errors from smallest to largest and selecting the radial error corresponding to the 90th percentile as detailed by Davis and Wang (2003).

2.2 *Orthorectification of WW2 aerial photos*

WW2 aerial photographs were obtained from the Records of the Defense Intelligence Agency (DIA) Record Group (RG) No. 373 at the US National Archives and Records Administration (NARA, www.archives.gov). Diapositive transparency reproductions of the NARA photos (most in 9 × 9 inch format, some in 9 × 18 inch) obtained from King Visual Technology, Inc. (www.kvt.com) were scanned at 1200 dpi with 14-bit greyscale using an Epson 1640XL scanner with transparency adapter (Epson, Long Beach, CA, USA).

Camera focal length, scale, altitude and photo date were obtained for each photograph from existing archival information (table 3). Before orthorectifying WW2 aerial photographs, we first roughly registered scanned aerial photos to orthorectified IKONOS imagery using visible features in imagery and the ArcMap Georeferencing tool. GCPs were obtained by identifying features visible in both WW2 photographs and current IKONOS imagery, so that WW2 photographs could be co-registered to current imagery. Figure 2 presents examples of GCPs from orthorectified IKONOS imagery at the Gaoyi and Yiyang sites. In sites with major land use changes such as Gaoyi, it was often very difficult to locate ground features that were unchanged from the 1940s to 2002 directly from imagery. In such cases, we first selected point locations of potentially unchanged features (e.g. corners of old

Table 3. Historical aerial photograph and camera data at five sites in China.

Site	Region	Acquisition date	Number of photos	Format (inch)	Scale†	Altitude (feet)	Focal length (inch)	Visual quality
Gaoyi, Hebei								
Group 21728	North China Plain	24 May 1945	14	9×9	1 : 13 750	27 500	24	Good
Group 52923	North China Plain	1 Apr. 1945	8	9×18	1 : 13 000	26 000	24	Good
Yixing, Jiangsu	Yangtze Plain	24 Sept. 1942	14	9×9	1 : 15 000	9900	8	Good
Jintang, Sichuan	Sichuan Hilly Area	25 June 1944	5	9×9	1 : 40 800	20 400	6	Poor
Yiyang, Hunan	Subtropical Hilly Area	17 May 1945	15	9×9	1 : 10 500	21 000	24	Excellent
Dianbai, Guangdong	Tropical Hilly Area	14 May 1944	26	9×9	1 : 10 000	20 000	24	Excellent

†Scale refers to image quality rating by intelligence expert at original photo acquisition time.

houses, road intersections, field borders, etc.), and then visited these locations in the field to verify with local elders of suitable age that the same features were indeed present at both times (WW2 photography and IKONOS image acquisition). If the feature was verified as present at both times, a commercial-grade GPS was used to obtain point locations of the four corners of old buildings or other unchanged local features visible on the ground, and these were used to aid in finding the exact feature location in both the IKONOS and WW2 imagery. The orthorectified IKONOS image coordinates of these features were used as GCPs in correcting WW2 images. We used the same DEMs for orthorectifying both WW2 aerial photos and IKONOS imagery (above).

The PCI OrthoEngine Bundle Block Adjustment method was used to orthorectify multiple photos in the standard 9×9 inch format based on camera focal length, distances between fiducial marks and the calculated radial lens distortion coefficient. Photos in 9×18 inch format (e.g. photos of Group 52923 in Gaoyi site) required copying and scanning in two parts, so that there were no suitable camera models available. For these photos we used the OrthoEngine Rational Function (RF) model (a single frame model), which does not require camera information, but requires at least 6 GCPs per photo and a DEM.

2.3 *Terrain relief index*

Variation in terrain relief is an important factor affecting the orthorectification accuracy of remotely sensed imagery (e.g. Toutin 2001, Davis and Wang 2003). In landscapes with more complex terrain relief, orthorectification accuracy is generally lower than in landscapes with less variable terrain relief due to terrain distortion of uncorrected imagery. We used the standard deviation of the heights of 25 or 28 GCPs at each site as the index of terrain relief to examine the effects of terrain variability on orthorectification accuracy using terrain relief index from five sites. We excluded the Jintang site from our statistical analysis of the relationship between terrain relief and orthorectification accuracy because of the more than twofold difference in GCP precision between Jintang and the other sites, most likely caused by a lower precision GPS base at this site (table 2).

2.4 *Experiments on number and distribution of GCPs on orthorectification accuracy of IKONOS imagery*

To examine the accuracy of IKONOS image orthorectification at each site, we varied the number of GCPs and ICPs across images by selecting an optimum uniform distribution of points across the image at each number of GCPs and ICPs. There were insufficient GCPs per image in the Yixing site to determine GCP number effects on accuracy because the IKONOS image for this site was acquired in three separate parts. We also experimented with asymmetric positioning of GCPs in the Dianbai (mountainous) and Gaoyi (flat) IKONOS images to examine the effects of GCP distribution on orthorectification accuracy. We split the 21 GCPs in the larger component IKONOS image in Dianbai into GCP/ICP=11/10 and the 25 GCPs in the larger component IKONOS image in Gaoyi into GCP/ICP=15/10 into two halves, either north/south or east/west, with all of the GCPs in one half, and all of the ICPs in the other, to observe the impacts of this asymmetric azimuthal GCP distribution on orthorectification accuracy.

3. Results and discussion

3.1 *Accuracy of IKONOS image orthorectification*

Root mean square errors at GCPs of the five orthorectified IKONOS images are summarized in table 4. For all but the Jintang site, the total horizontal RMSEs were less than 2 m and CE90s were less than 3 m (table 4). RMSEs of all but the Jintang site were therefore equivalent to IKONOS Precision and Pro format standards (spaceimaging.com) and met the requirement for mapping at 1:12 000 to 1:4800 or larger of the US National Map Accuracy Standards (NMASs) (http://www.spaceimaging.com/whitepapers_pdfs/IKONOS_Product_Guide.pdf). The accuracies of the orthorectified IKONOS imagery at the Jintang site were 2.6 m RMSE and 4.0 m CE90, equivalent to the accuracy of IKONOS Pro imagery and meeting NMAP requirements for mapping at scales between 1:12 000 and 1:4800.

The planar accuracies (1–2.5 m RMSE and 2–4m CE90) of orthorectified IKONOS imagery at the five sites are likely the best that can be achieved based on available DEM data and the GPS technology used for GCP acquisition and meet the accuracy requirement of 3–5 m CE90 for 1 m resolution spatial data (Davis and Wang 2003). The lower accuracy for the Jintang site relative to the other sites (table 2) most likely resulted from the low precision of field GCPs at this site caused by imprecision in determining the GPS base location.

3.2 *Accuracy of WW2 aerial photograph orthorectification*

The accuracy of orthorectified WW2 aerial photographs is presented in table 5. RMSEs at GCPs ranged from 0.24 to 3.5 m with CE90s from 0.34 to 5.3 m, while RMSEs at ICPs ranged from 4.4 to 6.2 m with CE90s from 6.5 to 9.3 m (table 5). Aerial photos at all sites but Jintang were of sufficient resolution to identify small features (⩾1 m), and also met requirements for high-resolution ecological mapping and change detection. Though the Jintang site had the lowest visual quality (scale=1:40,800), it also had the lowest CE90 (6.5 m) because it was much easier to identify unchanged features for GCPs at this site due the small amount of land use change at this site relative to the other sites.

Overall, for the five sites, positional errors for WW2 image co-registration to IKONOS imagery are <10 m CE90 (table 5). The accuracy of WW2 image co-registration depends, to a large degree, on the accuracy of the GCPs obtained from IKONOS imagery. The most accurate possible GCPs for orthorectifying WW2 aerial photos would be high-precision GCPs obtained for 1940s-era features located using GPS and elders in the field, but this would require an extreme and impractical amount of fieldwork of the order of one to four GCPs per day. On the other hand, it

Table 4. Accuracy of the orthorectification of IKONOS imagery at five sites in China.

Site	Number of GCPs	Accuracy (m)			
		$RMSE_x$	$RMSE_y$	$RMSE_{xy}$	CE90
Gaoyi, Hebei	25	0.96	0.99	1.38	2.02
Yixing, Jiangsu	28	0.48	0.76	0.90	1.26
Jintang, Sichuan	28	2.48	0.74	2.59	4.03
Yiyang, Hunan	28	1.70	1.03	1.99	2.46
Dianbai, Guangdong	28	1.51	1.01	1.82	2.91

Table 5. Planimetric accuracy of orthophotos for five sites in China.

Site	Number of photos	Number of GCPs†	Number of ICPs†	RMSE at GCP (m)	RMSE at ICP (m)	CE90 at GCP (m)	CE90 at ICP (m)	Visual quality
Gaoyi, Hebei								
Group 52923‡	8	36	29	0.24	5.15	0.34	7.92	Good
Group 21728	14	52	20	3.38	6.21	5.31	9.31	Good
Yixing, Jiangsu	14	35	30	2.31	4.42	3.38	7.23	Good
Jintang, Sichuan	5	29	25	2.61	4.9	3.79	6.48	Poor
Yiyang, Hunan	15	33	30	2.98	5.46	4.31	9.05	Excellent
Dianbai, Guangdong	26	65	40	3.48	6.22	4.96	8.77	Excellent

†Numbers of GCPs and ICPs did not include stereo GCPs and ICPs.
‡Using rational function (RF) model, other photos using bundle block adjustment method.

is unlikely that this error would be smaller if ideal GCP collection methods were used because the purpose of WW2 photo orthorectification is their co-registration to current IKONOS imagery for change measurement, so that overall accuracy is less important than the precision of co-registration with IKONOS imagery. Nevertheless, the ~10 m CE90 positional error in image co-registration will certainly limit the precision of change detection using WW2 and IKONOS imagery. The impact of this limitation to ecological change detection is a valuable subject for future study.

3.3 *Factors affecting accuracy of image orthorectification*

We examined the basic factors that impact the accuracy of orthorectification of IKONOS imagery and WW2 aerial photographs, including orthorectification models, DEMs, GCP precision, landscape characteristics and the number and distribution of GCPs.

3.3.1 Orthorectification model. We found that orthorectification accuracy of WW2 aerial photographs using rational function (RF) models was greater than when rigorous models were applied. RMSEs and CE90s at ICPs for RF orthorectified photos (Group 52923) were 5.2 and 7.9 m, respectively, 17% and 15% lower than that for rigorous model orthorectified photos (Group 21728) although the landscapes covered by these two sets of photos were similar and the photos were similar in quality and camera data (table 5).

The RF model is generally best suited to small areas with gentle terrain and a large number of GCPs, because a large number of coefficients and GCPs are required in mountainous areas (Davis and Wang 2003). Though the RF model tends to produce greater orthorectification accuracy than the rigorous model given the same GCPs and DEM, Davis and Wang (2003) demonstrated that the RF method tended to require about 0.4 GCPs km^{-2} to produce no noticeable linear distortions in the orthorectified image, rendering this technique impractical for most applications. The rigorous model is both stable and robust and requires a limited number of GCPs—often ten are enough to obtain accurate orthorectification (e.g. Toutin and Cheng 2000, Toutin 2001, Davis and Wang 2003). We therefore used the rigorous model to orthorectify IKONOS Geo imagery and limited our use of the RF model to historical aerial photos in 9×18 format (Gaoyi site) for which no camera model was available, rendering the rigorous model unusable.

3.3.2 DEM. Previous research indicates that DEMs do not significantly improve the accuracy of image orthorectification in flat areas (Toutin and Cheng 2000). For hilly and mountainous areas, DEM use significantly improves orthorectification accuracy, with more accurate and precise DEMs tending to enhance orthorectification accuracy (Davis and Wang 2003). Though we did not test the effects of DEM quality on orthorectification accuracy due to the limited availability of terrain data at our five sites in China, it is likely that IKONOS orthorectification accuracy would be improved by more accurate DEMs if they became available.

3.3.3 Field GCP precision. Though field GCP precisions differed among the five sites, horizontal accuracy was less than 0.4 m and vertical accuracy less than 0.8 m for all sites except Jintang (0.9 m horizontal and 1.44 m vertical accuracy), and total GCP accuracy was less than 1 m for all sites but Jintang (1.69 m) (table 2).

There was a weak linear relation between orthorectification RMSE and field GCP precision ($n=5$, $R^2=0.60$, $p=0.12$): lower GCP precision was associated with higher RMSE (figure 3). On the other hand, the Yixing and Dianbai sites had about the same total field GCP precision (0.8 m), but Yixing had a higher accuracy than Dianbai (RMSE 0.9 m vs. 1.8 m), most likely because the Yixing site is flat while Dianbai is mountainous. Overall, these results indicate that IKONOS orthoimagery with planar accuracies ~4 m CE90, equivalent to the IKONOS Precision product, can be obtained using much lower cost IKONOS Geo imagery whenever field GCP precision is less than 1 m.

GPS accuracy varies substantially by type of GPS equipment, correction technique, number and geometry of satellites, duration of observation, distance from rover to base station, and the number of base stations (Bobbe 1992). We used the same GPS equipment and duration of observation (>60 5 s positions) at all five sites, with post-processed DGPS correction using a local base station at all sites except Yixing, where real-time DGPS was used. Therefore, the most likely reason for the lower field GCP accuracy of the Jintang site is that the base station location

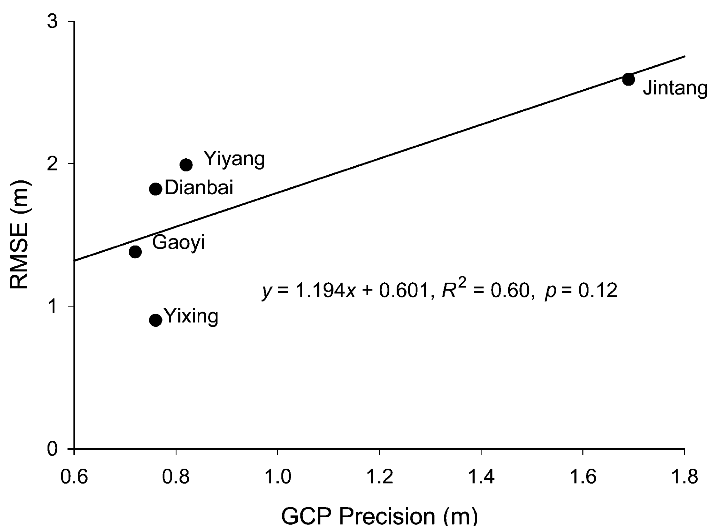

Figure 3. The relationship between field GCP precision and RMSE of IKONOS orthorectification at GCPs across five sites in China.

was not measured as precisely as at the other sites because it was not possible to use DGPS based on a precision reference at this site.

Previous research has demonstrated horizontal RMSE at GCPs and ICPs ranged from 0.3 to 0.5 m in flat terrain to 1.1 to 2.9 m in hilly areas, using field GCPs with precision of 0.03 to 0.05 m with the rigorous model and DEM accuracy around 2 m (Davis and Wang 2003). This agrees with our observation that orthorectification RMSE at our two flat sites (Gaoyi and Yixing) was lower than at the hilly and mountainous sites.

3.3.4 Terrain relief index. A terrain relief index was calculated as the standard deviation field GCP height at each site, with values of 28.8, 19.6, 14.9, 4.3 and 1.8 m for the Dianbai, Yiyang, Jintang, Gaoyi and Yixing sites, respectively, demonstrating that Dianbai had the most variable terrain relief followed by Yiyang, Jintang, Gaoyi and Yixing. However, due most likely to the small sample size of our analysis, there was no statistically significant linear relationship between orthorectification RMSE and the terrain relief index either with or without the Jintang site included in the analysis ($n=5$: $R^2=0.364$, $p=0.282$, figure 4(*a*); $n=4$: $R^2=0.728$, $p=0.147$, figure 4(*b*)). Still, the trend suggests that, as expected, more heterogeneous landscapes have lower orthorectification accuracy.

When GCP precision, number and distribution are held constant along with DEM accuracy and orthorectification model, the accuracy of orthorectified IKONOS imagery should depend largely on landscape and terrain characteristics. Toutin (2003) found that the image RMSE at GCPs for hilly areas on the central coast of Venezuela with GCP precision ~1 m and DEM accuracy ~5 m was ~7.5 m. RMSEs at GCPs for hilly areas in our study were 1.8–2.6 m (table 4), probably because the our field GCP precision was less than 0.5 m except for the Jintang site (table 2). Positional accuracies of orthorectified IKONOS imagery at our flat sites (RMSE 0.9–1.4 m in Gaoyi and Yixing) were also comparable with previous work on Fredericton, Canada (1.3–2.3 m, McCarthy *et al.* 2001).

3.3.5 Number and distribution of GCPs. Orthorectification accuracy is usually impacted by the number and distribution of GCPs used, and more than six uniformly distributed GCPs are recommended for orthorectification of IKONOS Geo products (Toutin and Cheng 2000, Ganas *et al.* 2002, www.pcigeomatics.com). We observed significant polynomial relationships between the number of GCPs and RMSEs at GCPs and ICPs selected in optimum distributions across different sites – R^2 for GCPs=0.24, 0.60, 0.87 and 0.97 for Gaoyi, Dianbai, Jintang and Yiyang, respectively, and $P<0.01$ for Dianbai, Jintang and Yiyang; Gaoyi $P=0.13$ (figure 5(*a*)–(*d*)); Yixing excluded because the image was acquired in three parts. As expected, with a minimum number of GCPs (seven) the RMSE of ICPs was highest, demonstrating that the error at checkpoints is greater when fewer GCPs are used for orthorectification. As the number of GCPs increased, RMSE at ICPs decreased, while RMSE at GCPs increased up to a certain level after which neither ICP nor GCP RMSE changed. This means that for a given landscape, GCP precision and rigorous modelling approach, there is a limit to the image positional accuracy that can be reached, no matter how many GCPs are used. At the mountainous Dianbai site for example, RMSE at ICPs was reduced up to 15 GCP, but more than this number had no significant effect on accuracy (figure 5(*d*)). In flat Gaoyi, increasing the number of GCPs from 7 to 25 had virtually no effect on accuracy, and the maximum RMSE was about 50% lower than at Dianbai (figure 5(*a*)).

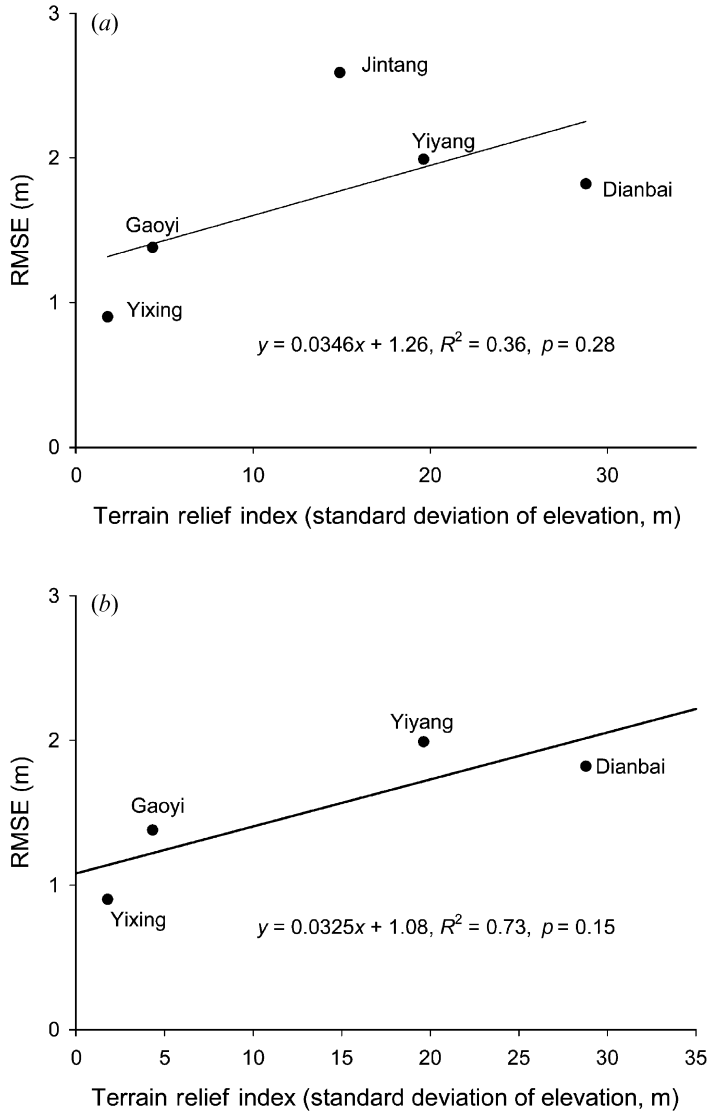

Figure 4. The relationship between RMSE of IKONOS orthorectification and terrain relief index as measured by the standard deviation of field GCP elevations at five sites in China.

Increasing the number of GCPs from 7 to 15 improved accuracy at ICPs significantly in landscapes with greater relief: from 11.5 to 4.2 m RMSE in mountainous Dianbai; from 4.5 to 3 m for hilly Yiyang and Jintang; but only 2.5 to 1.8 m in the flat landscapes of Gaoyi and Yixing (analysis using only one of three IKONOS component images). This indicates that for flatter areas, less GCPs are needed than in mountainous landscapes to reach the highest orthorectification accuracies.

Toutin (2001) investigated orthorectification accuracy of IKONOS Geo imagery using GCPs and DEMs with different precision in regions differing in environment and relief across North America and Europe. He found that when GCP accuracy was <1 m, ten GCPs over a$\approx$100 km^2 IKONOS image were adequate to obtain 2–3 m accuracy, but when GCP accuracy was 1–3 m, 20 GCPs were needed to obtain

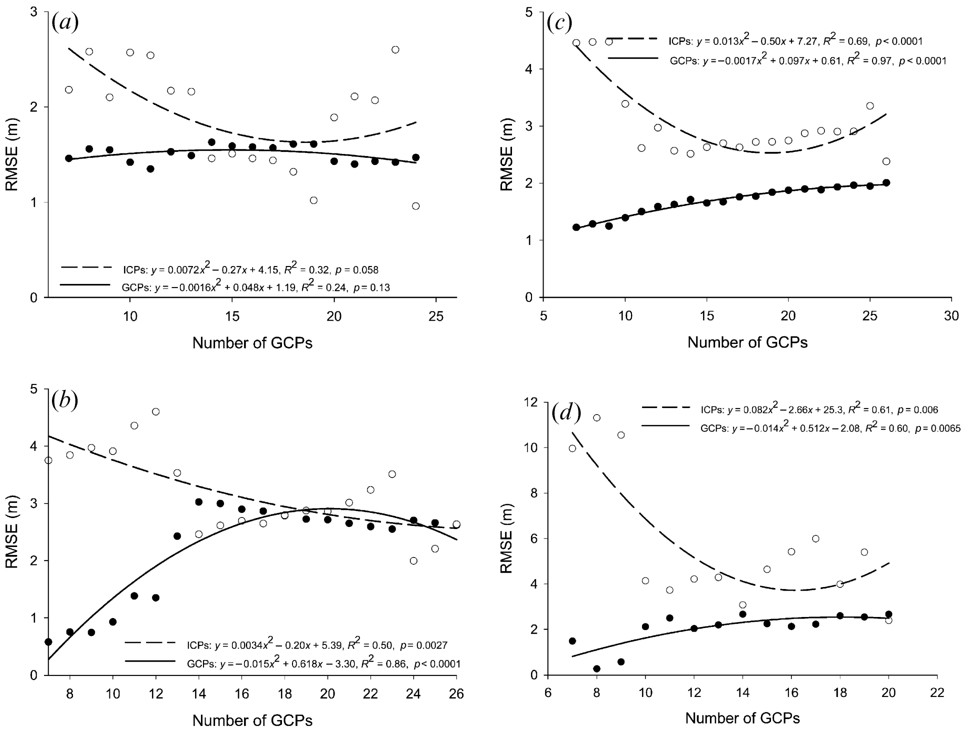

Figure 5. Relationships between number of GCPs and RMSE of IKONOS orthorectification at ICPs (○) and GCPs (•) for (*a*) Gaoyi (*b*) Jintang, (*c*) Yiyang and (*d*) Dianbai.

3–4 m image accuracy. In some flat areas, even four good GCPs were adequate to achieve 2–3 m image accuracy (Zhou and Li 2000). Our study demonstrates that ten well-distributed GCPs are enough to obtain 2–3 m accuracy with GCPs accurate to <1 m in flat areas, while 15–20 GCPs are needed to obtain 2–3 m accuracy in hilly and mountainous regions (figure 5).

IKONOS orthorectification accuracy should be influenced by the distribution of GCPs across the image. We tested this by asymmetrically rearranging the locations of GCPs vs. ICPs across the Dianbai (mountainous) versus Gaoyi (flat) sites using approximately equal numbers of each type of CP, and measuring ICP RMSE to determine whether these azimuthal GCP distributions influenced orthorectification accuracy (table 6). Though GCP RMSEs were virtually unaffected by azimuthal placement in imagery, the Dianbai ICP $RMSE_X$ varied from 9.99 to 31.15 m depending on whether GCPs were placed in the north or the east of the IKONOS image (table 6). This probably resulted because the north of the image was flatter and less complex than the rest of the image area, while the western area of the image contained a more varied sample of the complex mountainous terrain of the entire image. Though positional errors caused by azimuthal GCP placement in flat Gaoyi were much lower than in Dianbai, Gaoyi RMSE at ICPs varied from 4.2 m with GCPs in the south to 1.8 m with GCPs in the north (table 6), which is likely explained by the observation that the greatest terrain variation across the Gaoyi site is present in a dry riverbed in the north.

Based on these results, orthorectification accuracy of IKONOS imagery may be improved in hilly to mountainous areas by placing field GCPs not only in a uniform

Table 6. The influence of azimuthal positioning of GCPs on the quality of orthorectification for Dianbai (11 GCPs and 10 ICPs) and Gaoyi (15 GCPs and 10 ICPs) sites in China.

Site	Points	GCP RMSE$_x$ (m)	GCP RMSE$_y$ (m)	ICP RMSE$_x$ (m)	ICP RMSE$_y$ (m)
Dianbai	North	1.06	0.7	31.15	3.79
	South	1.8	0.42	17.37	2.46
	East	1.57	0.83	11.94	3.44
	West	1.47	0.47	9.99	2.13
Gaoyi	North	0.83	0.91	1.79	2.42
	South	1.14	0.84	4.23	2.88
	East	1.1	0.83	2.46	2.08
	West	0.71	0.9	3.27	2.19

horizontal distribution, but also in a distribution across the full range of the variation in terrain. However, areas with the most variable terrain or extremes of terrain tend to be more difficult to access and also tend to be areas, such as remote forests, where it is more difficult to identify ground features for use as GCPs, so that it may not be practical to manage GCP fieldwork based on this sampling design.

3.4 *Lessons learned*

Positional errors in the co-registration of two images for land use change detection are inherent in all image orthorectification strategies. It is therefore critical to measure positional errors in orthorectified imagery to aid in assessing the impacts of this error on change detection (Wang and Ellis, in press). Though some degree of positional error is unavoidable, the orthorectification accuracy of high-resolution images (and therefore the accuracy of image co-registration) can be improved by:

- increasing field GCP precision;
- arranging field GCPs to uniformly cover entire images;
- emphasising GCP collection in areas with the greatest terrain and landscape variation with more GCPs in hilly to mountainous areas than in flat areas;
- using more than the minimal number of field GCPs (if possible double the planned number) and using them as independent checkpoints for accuracy assessment;
- obtaining DEMs with the highest accuracy available.

4. Conclusions

Our results demonstrate that even though the same methodology for orthorectifying IKONOS imagery was applied at five sites in China, the accuracy achieved differed between sites due primarily to differences in GCP precision and terrain, with hilly and mountainous sites tending toward lower accuracy than flat areas and greater GCP precision giving greater orthorectification accuracy. The influence of GCP number and distribution on IKONOS orthorectification accuracy differed between sites, with the use of more than ten GCPs increasing accuracy only at hilly and mountainous sites.

Historical aerial photo orthorectification accuracy depended mostly on the accuracy of GCPs selected from IKONOS imagery, the accuracy of orthorectified

IKONOS imagery and the image quality of the aerial photos. It was often difficult to find unchanged features to serve as GCPs for historical photo orthorectification in sites with major landscape changes, and this may have reduced orthorectification accuracy at least in some sites.

RMSEs at GCPs obtained for IKONOS imagery were less than 2.0 m for all sites except Jintang (2.6 m), meeting 1:12 000 to 1:4800 high-resolution US National Map Accuracy Standards and equal to IKONOS Precision accuracy standards. RMSEs at GCPs and ICPs for historical aerial photos were 0.24–3.5 m and 4.4–6.2 m, respectively, meeting the minimum requirements for high-resolution environmental mapping and change detection. Nevertheless, the remaining positional errors in imagery following orthorectification and co-registration are significant (>4 m), ultimately limiting the precision and resolution of long-term environmental change measurements.

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References

Bobbe, T., 1992, Real-time differential GPS for aerial surveying and remote sensing. *GPS World*, **3**, pp. 18–22.

Cousins, S.A.O., 2001, Analysis of land-cover transitions based on 17th and 18th century cadastral maps and aerial photographs. *Landscape Ecology*, **16**, pp. 41–54.

Davis, C.H. and Wang, X., 2003, Planimetric accuracy of Ikonos 1 m panchromatic orthoimage products and their utility for local government GIS basemap applications. *International Journal of Remote Sensing*, **24**, pp. 4267–4288.

Di, K., Ma, R. and Li, R., 2003, Geometric processing of Ikonos stereo imagery for coastal mapping applications. *Photogrammetric Engineering and Remote Sensing*, **69**, pp. 873–879.

Ellis, E.C., 2004, Long-term ecological changes in the densely populated rural landscapes of China. In *Ecosystem Interactions with Land Use Change*, G.P. Asner, R.S. DeFries and R.A. Houghton (Eds) (Washington, DC: American Geophysical Union), pp. 303–320.

Ellis, E.C., Li, R.G., Yang, L.Z. and Cheng, X., 2000, Long-term change in village-scale ecosystems in China using landscape and statistical methods. *Ecological Applications*, **10**, pp. 1057–1073.

GANAS, A., LAGIOS, E. and TZANNETOS, N., 2002, An investigation into the spatial accuracy of the IKONOS 2 orthoimagery within an urban environment. *International Journal of Remote Sensing*, **23**, pp. 3513–3519.

HUNTER, G.J. and GOODCHILD, M.J., 1995, Dealing with error in spatial databases: a simple case study. *Photogrammetric Engineering & Remote Sensing*, **61**, pp. 529–537.

KADMON, R. and HARARI-KREMER, R., 1999, Studying long-term vegetation dynamics using digital processing of historical aerial photographs. *Remote Sensing of Environment*, **68**, pp. 164–176.

KAYITAKIRE, F., FARCY, C. and DEFOURNY, P., 2002, IKONOS-2 imagery potential for forest stands mapping. In *Proceedings of ForestSAT Symposium*, 5–9 August 2002, Heriot Watt University, Edinburgh (Scotland: ForestSAT), pp. 1–11 (CD-ROM).

MCCARTHY, F., CHENG, P. and TOUTIN, T., 2001, Case study of using IKONOS imagery in small municipalities. *Earth Observation Magazine*, **10**, pp. 1–5.

TOUTIN, T., 1995, Multi-source data fusion with an integrated and unified geometric modeling. *EARSeL Journal on Advances in Remote Sensing*, **4**, pp. 118–129.

TOUTIN, T., 2001, Geometric processing of IKONOS Geo images with DEM. In *ISPRS Joint Workshop High Resolution from Space*, 19–21 September 2001, Hannover, Germany (Hannover: University of Hannover), pp. 1–9 (CD-ROM).

TOUTIN, T., 2003, Block bundle adjustment of IKONOS in-track images. *International Journal of Remote Sensing*, **24**, pp. 851–857.

TOUTIN, T., 2004, Review article: geometric processing of remote sensing images: models, algorithms and methods. *International Journal of Remote Sensing*, **25**, pp. 1893–1924.

TOUTIN, T. and CHENG, P., 2000, Demystification of IKONOS. *Earth Observation Magazine*, **9**, pp. 17–21.

TOWNSHEND, J.R.G., JUSTICE, C.O., GURNEY, C. and MCMANUS, J., 1992, The impact of misregistration on change detection. *IEEE Transactions on Geoscience and Remote Sensing*, **30**, pp. 1054–1060.

VERBYLA, D.L. and BOLES, S.H., 2000, Bias in land cover change estimates due to misregistration. *International Journal of Remote Sensing*, **21**, pp. 3553–3560.

WANG, H. and ELLIS, E.C., in press, The effect of image misregistration on feature-based change measurements. *Photogrammetric Engineering & Remote Sensing*, submitted for publication.

ZHOU, G. and LI, R., 2000, Accuracy evaluation of ground points from IKONOS high-resolution satellite imagery. *Photogrammetric Engineering and Remote Sensing*, **66**, pp. 1103–1112.