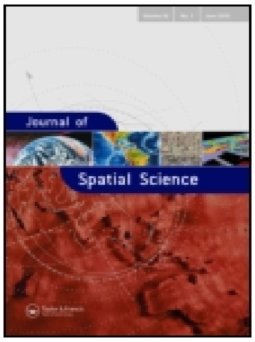

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Geometric correction and accuracy assessment of Landsat-7 ETM+ and Landsat-5 TM imagery used for vegetation cover monitoring in Queensland, Australia from 1988 to 2007

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A range of programs exist globally that use satellite imagery to derive estimates of vegetation-cover for developing vegetation-management policy, monitoring policy compliance and making natural-resource assessments. Consequently, the satellite imagery must have a high degree of geometric accuracy. It is common for the accuracy assessment to be performed using the root mean square error (RMSE) only. However the RMSE is a non-spatial measure and more rigorous accuracy assessment methods are required. Currently there is a lack of spatially explicit accuracy assessment methods reported in the literature that have been demonstrated to work within operational monitoring programs. This paper reports on the method used by the Statewide Landcover and Trees Study (SLATS) to georegister and assess the registration accuracy of Landsat-5 Thematic Mapper (TM) and Landsat-7 Enhanced Thematic Mapper (ETM+) imagery in Queensland, Australia. A geometric baseline with high accuracy (a statewide mean RMSE of 4.53 m) was derived by registering Landsat-7 ETM+ panchromatic imagery acquired in 2002 to a database of over 1600 control points, collected on the ground using a differential global positioning system. Landsat-5 TM and Landsat-7 ETM+ imagery for 12 selected years from 1988 to 2007 was registered to the baseline in an automated procedure that used linear geometric correction models. The reliability of the geometric correction for each image was determined using the RMSE, calculated using independent check points, as an indicator of model fit; by analysing the spatial trends in the model residuals; and through visual assessment of the corrected imagery. The mean RMSE of the statewide coverage of images for all years was less than 12.5 m (0.5 pixels). Less than 1 percent of images had non-linear spatial trends in the model residuals and some image misregistration after applying a linear correction-model; in those cases a quadratic model was deemed necessary for correction. Further research in the development of automated spatially explicit accuracy assessment methods is required.

Keywords: Landsat-5 TM; Landsat-7 ETM+; geometric correction; large area monitoring

1. Introduction

Governments globally are developing policies and implementing monitoring programs to control the loss of the world's natural resources. Broad-scale monitoring programs use satellite imagery as a means

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to extract information about the state of the environment over multiple years to detect change and monitor trends. Landsat imagery is used in Australia by state and federal government agencies for carbon accounting, state of environment reporting and monitoring land cover change (Phinn *et al.* 2008). Calculation of accurate change statistics and integration of field measurements require precise positioning of the satellite imagery. The Landsat products used in these studies are path-oriented images and have had some systematic geometric corrections applied based on Landsat orbital data. These systematic corrections minimise image distortions from a range of sources including sensor co-alignment, scan skew, mirror scan velocity, panoramic distortion, platform velocity and Earth rotation (Lee *et al.* 2004; Jensen 1996). The remaining systematic and non-systematic errors need to be corrected by the data users to produce consistent geometrically registered images.

Within Australia, the Queensland Department of Environment and Resource Management (DERM), the Department of Climate Change and Geosciences Australia have all reported on the geometric correction methods applied to Landsat imagery and their accuracies (Armston *et al.* 2002; Furby 2002; Wang and Smith 2003). A standard method, which involves developing an accurately registered baseline image to which all subsequent images are registered (Figure 1), was used in these studies. The accuracy of the corrected imagery was reported using the root mean square error (RMSE). The RMSE does not provide a complete indication of the quality of geometric correction. The RMSE is an aspatial measure, and as such no information about the trends in accuracy across an image can be retrieved (Phinn and Rowland 2001). Therefore the RMSE needs to be combined with other assessment methods for the rigorous correction of satellite image data. However, there is a lack of studies in the literature that demonstrate the use of other accuracy assessment procedures within an operational monitoring program.

Since the reporting of the geometric correction methods in the Australian studies (Armston *et al.* 2002; Furby 2002; Wang and Smith 2003) there have been developments in the Landsat program that require refining the geometric correction processes used. There was a major update to the sensor-alignment parameters in response to a realignment of the Celestial Sensor Assembly of Landsat-7 on 18 July 2000, and further corrections applied to account for biases in the direction of platform travel (along-track) in 2002 (Lee *et al.* 2004). As a result, the baseline imagery needs to be updated so that images collected after the sensor realignment are used. For Landsat-5 TM, degradation of mechanical components on the sensor has required additional systematic corrections to be applied in the software processing (Storey and Chaote 2004). The consequence of these developments for monitoring agencies is that their archives of image data have had different levels of processing applied to them. What is required is a rigorous geometric correction and quality assessment process to ensure the accurate registration of image data to a fixed datum.

There are two aims of this paper. First, to describe the processes used by the Statewide Landcover and Trees Study (SLATS) in Queensland, Australia, to manage the challenges presented by the recent developments in the Landsat program. The method used to generate a geometric baseline for the year 2002 and the automated methods used to efficiently register an archive of Landsat-5 TM and Landsat-7 ETM+ multispectral imagery, dating from 1988 to 2007, to the baseline are outlined. The second aim is to report on the methods used to incorporate spatially dependent measures of registration accuracy in

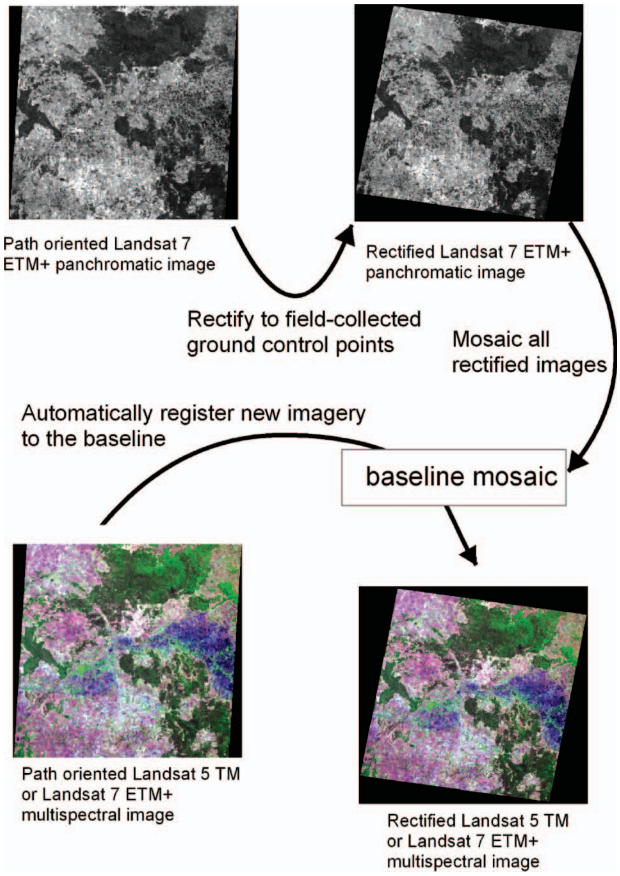

Figure 1. The two main stages of the geometric correction process. First, create a geometric baseline by rectifying path oriented, Landsat-7 ETM+ panchromatic images to field-collected ground-control points. Second, automatically register newly acquired path-oriented images to the geometric baseline.

addition to the RMSE, thereby addressing a gap in the literature. The results of the accuracy assessment are reported. Trends evident in the results from the accuracy and quality assessments are discussed, along with implications for long-term monitoring of woody-vegetation change, and the need for further development of the geometric correction procedures.

2. Methods

Generation of the geometric baseline

The geometric baseline was created from Landsat-7 ETM+ panchromatic imagery acquired in 2002, taking advantage of the high accuracy of the systematic geometric corrections (within 50–100 m) and 15 m spatial resolution of the ETM+ panchromatic band (Masek *et al*. 2001). Year 2002 imagery was chosen as the systematic geometric corrections were of a higher quality compared to the previous years. The higher quality was due to a major update in the sensor-alignment parameters in response to a realignment of the Celestial Sensor Assembly on July 18 2000, and to correct for along-track biases in 2002 (Lee *et al*. 2004). Year 2002 imagery was also chosen because Queensland received lower than average rainfall across the state that year, resulting in less green vegetation cover and therefore high contrast between features in the imagery that assist with geometric correction. A total of 87 Landsat-7 ETM+ scenes were required for complete spatial coverage of Queensland.

A property of baseline imagery used for image registration is that it must be accurately registered to ground control. Removal of geometric errors in the baseline images required rectifying the imagery to accurately located ground control points (GCPs). A database of over 1600 GCPs was created from field measurements conducted throughout Queensland from 1995 to 1997 using a real-time differential global positioning system (DGPS) mounted in a 4WD vehicle. The system for collecting the GCPs consisted of a Fugro Omnistar demodulator that received a differential signal from the Optus AUSSAT satellite, and was linked to a Garmin 12XL hand-held GPS fixed inside the vehicle. At each GCP location 200 DGPS measurements were used to determine the GCP coordinate with a standard deviation of less than 5 m. A digital photograph, site description and field diagram were produced on site showing the exact GCP position with respect to the surrounding ground features, and Landsat imagery of the field site was displayed on a laptop computer to facilitate identification of the GCP within the Landsat imagery. Each scene was gridded into nine zones (three rows and three columns) of equal areas, with the objective to collect a minimum of 18 GCPs per scene, with at least two in each of the nine zones to ensure an even spatial distribution of points. However, in some remote areas, and on coastal scenes, this was not always possible, and the GPS-measured GCPs were supplemented with points identified using high-resolution topographic maps.

Each scene was orthorectified using the ERDAS Imagine 8.6 Landsat Geometric Model (ERDAS Inc 1997). This Landsat-dependent model was chosen as sensor-dependent models, such as this, generally produce high-accuracy corrections (Bannari *et al.* 1995; Novak 1992; Palà and Pons 1995; Toutin 1995), and it has also been shown to give reliable results compared to other models (Armston *et al.* 2002). The model is specific to Landsat-5 TM and Landsat-7 ETM+, which are whiskbroom sensors that use a scanning mirror to scan perpendicular (across-track) to the satellite's direction of travel (along-track). The 15° field of view of the sensor equates to an image swath width of approximately 185 km, and 16 multispectral detectors with a ground instantaneous field of view of 30 m results in 480 m of the Earth's surface being scanned in the along-track direction on each rotation of the scan-mirror (NASA 1998). The model transforms the image coordinates to ground coordinates using the GCPs and a digital elevation model (DEM). The 3-second Shuttle Radar Topography Mission (SRTM) DEM was used (Farr *et al.* 2007). Two equations, one for the x-direction and one for the y-direction, are obtained for each GCP. The resulting set of equations is solved to derive the parameters of the model.

Three criteria were used to determine an acceptable transformation model for each image. First, the total root mean square error (RMSE) of the model had to be less than 7.5 m (0.5 pixels of the panchromatic image). The RMSE was computed as

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left[\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2\right]}{n}} \tag{1}$$

where x_i and y_i are the easting and northing coordinates of the transformed point, x_j and y_j are the easting and northing coordinates of the corresponding GCP, and n is the number of points used in the transformation. Second, a uniform distribution of GCPs across the scene with a minimum of two GCPS for each of the nine zones was required. Third, no individual GCP had a root squared error (RSE) of greater than 12 m (0.8 pixels), calculated as

$$RSE = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \qquad (2)$$

The transformation was used to register the panchromatic image to MGA94 coordinates. The same model was then applied to the corresponding Landsat-7 ETM+ multispectral and thermal images. A cubic convolution kernel was used to resample the panchromatic, multispectral and thermal imagery to 12.5 m, 25 m and 50 m, respectively. These pixel sizes were chosen to match imagery previously acquired by the SLATS program.

Image to baseline registration

Once the geometric baseline was established, all other Landsat imagery acquired by SLATS was registered to it. The years in which landcover monitoring were performed by SLATS and the corresponding Landsat multispectral imagery used are shown in Table 1. Landsat-5 TM imagery was used for monitoring prior to the launch of Landsat-7 in April 1999. Landsat-7 ETM+ imagery was used from 1999 until 2002 in preference to Landsat-5 TM due to the higher geometric and radiometric quality of the data. Landsat-5 TM imagery has been used for monitoring since 2003 due to failure in the scan-line corrector of the Landsat-7 ETM+ sensor on 31 May 2003 (Maxwell *et al.* 2007). In the image registration process, the image coordinates were mapped to ground coordinates (MGA 1994), via coregistration to the panchromatic (ETM+ imagery) and multispectral (TM imagery) baseline as described below.

The transformation model between image and baseline relies on a set of tie points, which are those that can be identified in both the baseline and the unregistered images. They are high in spectral contrast to their surrounding pixels, with the potential to be spectrally invariant through time. A database of over 24,000 points across Queensland was created, consisting of both the field-collected GCPs and points

Table 1. Mean RMSE statistics for the geometric corrections applied to all scenes across Queensland for each change year when registered to the 2002 baseline image. The final column shows the average number of control points used per scene to parameterise the geometric-correction model. The italic rows are used to indicate Landsat 7 ETM+.

Year	Sensor	Across-track RMSE (m)	Along-track RMSE (m)	Total RMSE (m)	Mean # of control points per scene
1988	L5 TM	7.68	5.43	9.52	260
1991	L5 TM	7.22	5.51	9.20	258
1995	L5 TM	5.59	4.68	7.37	281
1997	L5 TM	5.63	4.60	7.40	319
1999	*L7 ETM+*	*4.23*	*4.06*	*5.96*	*352*
2000	*L7 ETM+*	*5.38*	*4.61*	*7.33*	*346*
2001	*L7 ETM+*	*4.57*	*4.42*	*6.49*	*355*
2003	L5 TM	5.30	4.04	6.84	319
2004	L5 TM	5.09	4.20	6.76	351
2005	L5 TM	4.48	3.82	6.00	391
2006	L5 TM	4.98	4.09	6.56	370
2007	L5 TM	4.21	3.95	5.87	357

identified by manual interpretation of the baseline image. For any given image registration, the subset of all points located within the boundaries of the image and the baseline image were candidate tie points. The consistency of the Landsat orbit and view-angle means that an image corresponds to a well-defined location with a nominal latitude and longitude for the image centre (NASA 2009). These correspond to Landsat scenes where the footprints (scene extents) are approximately the same for each complete cycle of the Landsat orbit (which takes 16 days). Therefore, for a given Landsat scene approximately the same number of points from the database were candidate tie points regardless of the year.

Model initialisation

The initial selection of tie points from the database was determined using custom developed chip-matching software that uses a fast Fourier transform (FFT) based technique to compute the local translation of points within the newly acquired image to be registered back to the baseline image. The algorithm searches in a regular grid across the baseline image and uses the Fourier phase correlation to locate the matching point on the image to be registered (Reddy and Chatterji 1996). The algorithm searches within a 1771-pixel-wide window around each point using a 241-pixel-wide window. The window sizes were chosen as the resulting 2011-pixel-wide images are an optimal size to use in a two-dimensional Fourier transform, reducing processing time. In addition, the match window is large enough to be relatively insensitive to minor land-use changes, such as vegetation clearing or cropping, and the baseline window is large enough to allow for initial misregistration between the two images. Landsat TM and ETM+ band 5 (shortwave infrared - SWIR) was used as it provided the highest contrast between features. The initial transformation for each scene was computed from the set of matched tie points.

Model refinement

The geometric model for each scene was refined using the ERDAS Imagine 8.6 Geocorrection tool. The initial tie points and SRTM DEM were used to compute a transformation based on the ERDAS Imagine 8.6 Landsat Geometric Model. A linear model was the preferred order of transformation, with non-linear models being used when the linear models result in an unsatisfactory transformation. The criteria used to determine a satisfactory transformation were the same as those used for creating the geometric baseline and additional quantitative and qualitative assessment described in the subsection on quality assessment below. After the transformation was applied the tie points were matched using chip-matching, searching within a 21 $\times$ 21 pixel window centred on each tie point using a 15-pixel-wide window, with the aim of obtaining the maximum spectral correlation between the images around each tie point. Any points where the correlation coefficient was less than 0.5 were removed. The tie point with the maximum RSE was also removed. A new transformation model was computed from the remaining tie points and the entire process repeated until there were no points with a RSE of greater than 0.8 pixels remaining, there were at least 50 tie points evenly distribution across the image, and the total RMSE of the model was less than 0.5 pixels. The resulting model was used with a cubic-convolution kernel to resample the image. While cubic convolution will result in some smoothing of the image data, it was deemed appropriate as it produced more natural-looking images than nearest-neighbour or bilinear sampling kernels, which were available with the software, and tended to result in blocky images or over-smoothed images respectively. Natural-looking images are important for visual interpretation used both in quality assessment and when validating areas of detected tree clearing as performed by the SLATS program. The image-registration process was automated by using the Autohotkey software (Autohotkey 2008) to simulate the sequence of mouse and key strokes that an analyst performs manually within the ERDAS Imagine software.

Quality assessment

The United States Federal Geographic Data Committee recommends the use of the RMSE as a measure of map quality, and that the method used to compute the RMSE be reported (FGDC 1998). The RMSE for each scene in a statewide mosaic of Landsat imagery for each year was computed from an independent set of points (defined as check points), that is, those not used to generate the transformation models. However, the RMSE is a non-spatial statistic and therefore unable to provide information about the spatial trends in misregistration and the distribution of control points across a scene. As such, an analysis of the spatial trends in the geometric-model residuals and visual inspection of all transformed images were also conducted to provide a complete quality assessment. The analysis of spatial trends and visual inspection of the images was performed on all images acquired by the SLATS program.

Trends in the model residuals, computed at the tie points, were plotted against the across-track and along-track distances to investigate the spatial properties of the correction. A non-linear trend suggested that a non-linear geometric transformation model may have been necessary. The distribution of control points across a scene was also visually inspected, as an uneven distribution may result in a poor transformation model and be a cause of misregistration or non-linear trends in the residuals. Regression models with quadratic and cubic terms were fitted to the residuals and nonlinearity was flagged if a t-test showed that the higher-order terms were deemed to be statistically significant in the model fit ($p < 0.001$). However, a quadratic or higher-order model was only applied if it provided a noticeable improvement. An improvement was determined through careful visual inspection of the linear and non-linear orthorectified products and assessment of residual trends.

Visual inspection of the transformed images was performed to confirm that the final correction was acceptable. The visual assessment involved overlaying the newly registered image on the geometric baseline, and rapidly switching between the two images to check for misregistration. Misregistration was evident as misalignment between pixels in one or more regions of the image. If the misalignment was consistently greater than one pixel in any one or more of the image quadrants, the scene was manually refined by locating more control points, further chip matching or the application of a higher-order transformation. In rare cases imagery was re-purchased after re-processing by The Australian Centre for Remote Sensing (ACRES) with updated calibration parameter files.

3. Results

The mean and standard deviation of the RMSEs for the geometric baseline, computed using the field-collected GCPs, in the across-track, along-track and combined directions for all Queensland scenes were 3.21 m and 0.77 m, 3.15 m and 0.80 m, and 4.53 m and 0.97 m, respectively. The total RMSE of 4.53 m is less than one-third the 15 m pixel size of the Landsat-7 ETM+ panchromatic imagery used to create the baseline. The maximum and minimum RMSEs in the across-track, along-track and combined directions respectively were 4.89 m and 0.69 m, 5.61 m and 1.40 m, and 7.21 m and 1.56 m. The maximum total RMSE of 7.21 m is less than half a pixel, indicating all scenes are accurately registered to the ground control data.

Table 1 shows the mean RMSEs, calculated using the check points, for all multispectral Landsat TM and ETM+ scenes across Queensland registered to the baseline using both linear and quadratic models, and Figure 2 shows the range of the RMSE values for all scenes across Queensland. Of the 1044 scenes 939 (89.9 percent) had a total RMSE of less than 12.5 m (or 0.5 pixels), with all RMSEs being less than 30 m (Figure 2).

Of the 1044 images rectified to the geometric baseline, there were 172 cases where a significant nonlinear trend ($p < 0.001$) was identified, and 373 scenes where some misregistration was evident (Table 2). These non-linear errors are most likely explained by the polynomial models used to characterise the scan-mirror's motion in the forward and reverse scans in the along and across track direction over time (NASA 1998). Of the images where a nonlinear trend in the residuals was identified, a quadratic model was only required for 10 percent of those cases (corresponding to less than 1 percent of all images) to significantly improve the registration. As an example of the analysis of residual trends, Figure 3a and 3c shows two scenes where a non-linear trend in the residuals was evident after a linear correction model was applied. Figure 3b and 3d shows the residuals after a quadratic model was applied to each of the images. In the case of the image shown in Figure 3c, a linear model was deemed appropriate as there was only a small improvement in the RMSE; however, a quadratic model was required to adequately account for the relatively large non-linear residuals shown in Figure 3a.

4. Discussion

The results show that the geometric baseline is accurately registered to ground control information facilitating accurate image registration. The main trends in the results, their implication for monitoring woody-vegetation cover change, and potential improvements to the geometric-correction process are discussed.

Trends in accuracy

The mean Queensland-wide total RMSE error for image-to-baseline registration, as computed using the check points, of between 6 m and 10 m is an improvement on those reported previously, which were found to be between 15 m and 20 m (Armston *et al.* 2002). The image-to-baseline registration is also an improvement on the previously used baseline image. The mean total RMSE of the 2002 statewide baseline, computed using the field-collected GCPs, was found to be 4.53 m, compared with the 1999 baseline which was reported at 17.26 m (Armston *et al.* 2002).

There were 105 out of a 1044 images (or approximately 10 percent) that were found to have a total RMSE, calculated using check points, of greater than 12.5 m (or 0.5 pixels; Figure 2). Sixty-two (or 60 percent) of those images corresponded to only eight scenes. Five of those were coastal scenes where water covered more than 75 percent of the area of the scene. The other three scenes were located in the Simpson Desert. Registration in these areas was difficult because of the lack of control points that could be derived due to the low number of contrasting features in the scene.

While visual checks found there was some misregistration error, the low RMSEs indicate that the error is consistently small.

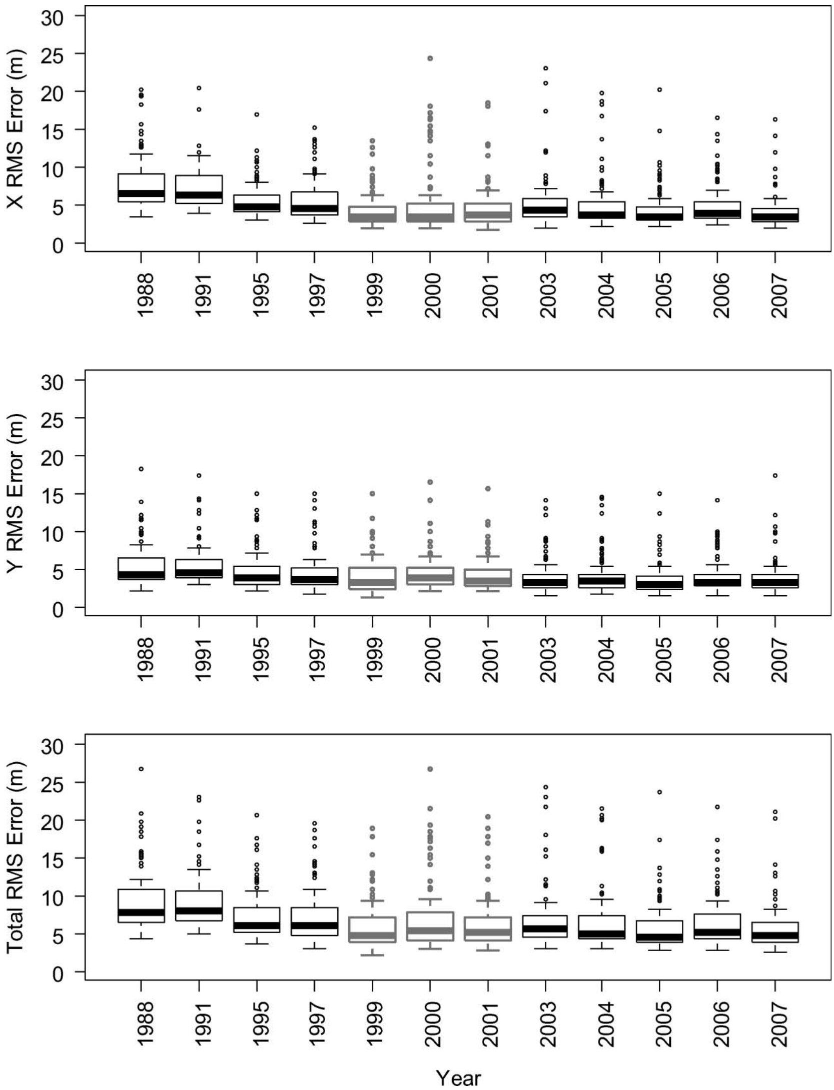

Figure 2. Box and whisker plots of the across-track (X), along-track (Y), and total root-mean square (RMS) errors for the Queensland coverage of Landsat multispectral imagery registered to the 2002 baseline. The boxes represent the second and third quantiles and the whiskers represent the first and fourth quantiles. The black and grey plots correspond to Landsat-5 TM and Landsat-7 ETM+ respectively. The length of the whiskers is 75 percent of the length of the interquartile range (height of the box).

There were a relatively higher number of scenes where misregistration was visually identified for Landsat-5 TM in 1988, 1991 and 2003–2007 compared to the other years. The large differences in the earlier years may be due to the large time difference to the 2002 baseline imagery, in which ground features may have changed. Alternatively, there has been an improvement in the geometric processing procedures of the USGS over time. Since 2002 the increase in observed misalignment may be

Table 2. Summary of the quality assessment performed for all scenes across Queensland. The non-italic rows show the results for Landsat 5 TM, and the italic rows show the results for Landsat 7 ETM+.

Year	Number of scenes with non-linear trends in the residuals	Number of scenes where some misregistration was evident	Total number of scenes analysed
1988	18	35	89
1991	14	33	111
1995	10	16	88
1997	13	16	95
1999	*6*	*17*	*110*
2000	*32*	*18*	*79*
2001	*58*	*30*	*117*
2003	16	55	125
2004	22	54	157
2005	29	31	119
2006	23	27	101
2007	35	41	162
Total	172	373	1353

due to poor synchronisation between the calibration shutter and scanning mirror on Landsat-5 TM, due to the degradation of the bumpers used to change the direction of the mirrors (Storey and Chaote 2004). This poor synchronisation caused a shift in the across-track direction and apparent shifting of blocks of pixels between scans as shown in Figure 4. For the multispectral bands, the shifting occurs in blocks as each scan-sweep captures 16 lines of data. While the system was switched to bumper mode in April 2002 to reestablish synchronisation, the visual observations here would suggest that images processed using bumper mode are likely to contain small misregistration errors. Interestingly, the RMSE, as calculated using the check points, for the Landsat 5 TM scenes for the same period is consistently low. The result highlights the importance of using a combination of image quality assessment methods, in addition to the RMSE.

Implications for detecting and mapping woody-vegetation change in Queensland

One of the applications of the Landsat imagery is to derive woody foliage projective cover (FPC) estimates (Armston *et al.* 2009). These FPC estimates are used to derive maps and land cover change reports to support the implementation of Queensland Government policies (Department of Natural Resources and Water 2008). The Landsat products are suitable for producing maps at the 1:50 000 scale (Walls *et al.* 1998). At this scale, the National Mapping Council of Australia (NMCA) recommends a tolerance of 25 m (NMCA 1975). The RMSE statistics for image to baseline registration show that the geometric accuracy of the SLATS products is within this tolerance and therefore suited to 1:50 000 scale mapping.

The analysis of the spatial variation of the residuals was able to detect low-frequency variation. However, detection of high-frequency variation in the residuals required visual assessment of the imagery. The visual assessment of the imagery revealed that there were small misregistration errors in the image data, indicating the RMSE alone is not a sufficient indicator of the quality of the geometric correction. Where these misregistrations were deemed to be unacceptable, the geometric

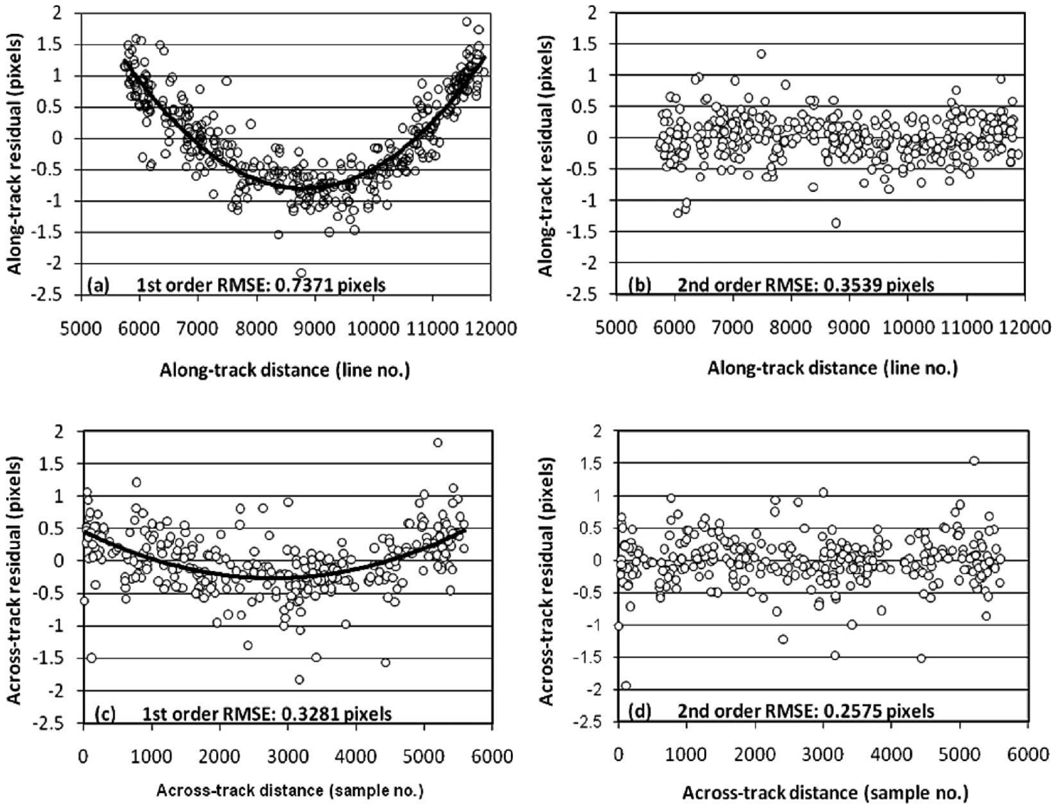

Figure 3. Panels (a) and (c) show two images that exhibited statistically significant ($p < 0.001$) non-linear trends in the residuals after a linear (first-order) geometric-correction model was applied. Panels (b) and (d) show that there is no spatial trend in the residuals after a quadratic (second-order) model was applied to the same images. In the case of the first image (top row) a quadratic model was deemed necessary as it reduced the RMSE of the geometric correction to less than 0.5 pixels. However, it was not deemed necessary to apply the quadratic model in the case of the second image (bottom row) as the RMSE for the linear model was less than 0.5 pixels and the improvement in RMSE when using the quadratic model was small.

transformation model was improved using quadratic models. Checking variation in the residuals and performing a visual assessment of the corrected imagery are therefore important steps in the geometric-correction process as they ensure the geometric correction is of a high quality.

Woody-vegetation change maps are created by SLATS with the automated differencing of the woody FPC products (Scarth *et al.* 2008). As false change events can result from the differencing process due to small image-misregistration errors during the differencing process, a RMSE of 0.2 of a pixel or less is required to achieve a change detection error of less than 10 percent (Dai and Khorram 1998). A consequence of not achieving a geometric correction with such low RMSE errors is that tree clearing and regrowth rates may be overestimated. Post-processing with the SLATS woody-vegetation change products is therefore necessary to eliminate falsely detected changes. For example, a raster filter is

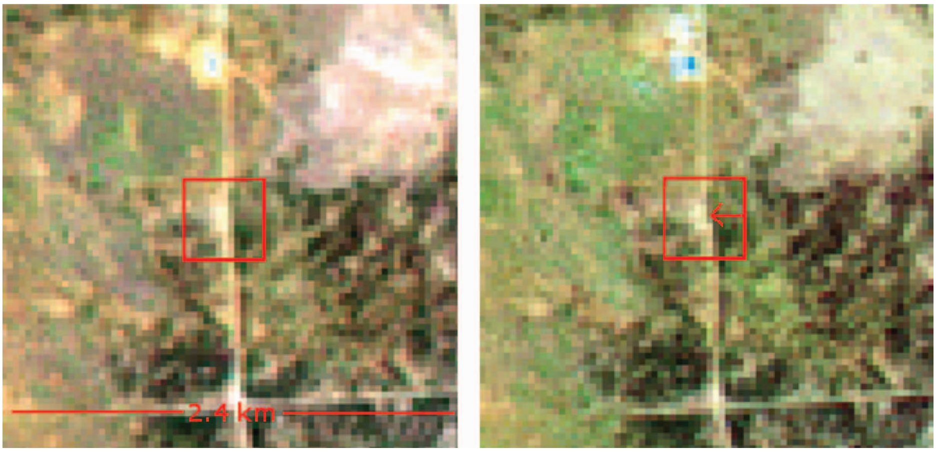

Figure 4. ACRES Level 5 Landsat-5 TM imagery acquired near Winton in Queensland, Australia, acquired on 13 August 2002 (left) and 10 August 2004 (right). The vertically oriented road in the image clearly shows the shift of pixels in the along-track direction due to bumper-mode processing (highlighted by the arrow).

applied to woody-vegetation change maps to remove clumps of change smaller than 3 pixels (1875 m^2 in size) that may have been caused by small misregistration errors in the original imagery (Wedderburn-Bisshop *et al*. 2002). Minimising the use of post-processing requires the use of more accurate image-registration methods. Recent research highlights new methods that may be able to give image-registration accuracy of 1/50th of an image pixel (Leprince *et al*. 2007). Future development of the georegistration procedure may use new methods to improve the image-registration accuracy.

Geometric correction and large archives of image data

There has been a large increase in the number of government agencies and private companies developing and deploying multi-spectral (3–10 bands) moderate spatial-resolution (10–30 m) satellite sensors. Such sensors include the French SPOT-4 HRVIR and SPOT-5 HRG, the Japanese ALOS AVNIR-2, the Chinese and Brazilian CBERS-2 high-resolution camera and the Indian IRS LISS-III. In addition, the United States Geological Survey has made the Landsat archive freely available (Woodcock *et al*. 2008). The Landsat archive consists of global coverage of the Earth's surface at moderate spatial resolution since 1972. This unprecedented level of access to satellite imagery will enable new understanding of the variability of Earth's environments and the processes that maintain them. However, these large amounts of data present storage and processing challenges to monitoring agencies.

The current image-registration procedure used by SLATS is automated and suited to large data archives. However, it is based on proprietary software and therefore at risk to changes and discontinued development or support. A new geometric-correction system that is based on open-source software, which will handle data from a range of multi-spectral moderate spatial-resolution sensors, is currently being developed.

While the current image-registration procedure used by SLATS is automated, accuracy assessment requires user intervention.

The current check of the spatial variation of model residuals can be automated with problem imagery being flagged. Performing visual checks of the imagery is not feasible for processing large archives of image data. Therefore automated methods that can reliably identify images with poor registration are required. These methods need to go beyond the use of the RMSE as an indicator of image-registration quality, towards spatially explicit measures (Phinn and Rowland 2001).

5. Conclusions

The Landsat-7 ETM+ panchromatic imagery, acquired in 2002, registered to field-collected ground-control points had a mean RMSE of 4.54 m (0.3 pixels) for all scenes across Queensland, making it a suitable geometric baseline. The Landsat-7 ETM+ and Landsat-5 TM multispectral imagery acquired for selected years between 1988 and 2007 and registered to the geometric baseline had a mean total RMSE of less than 15 m (0.5 pixels) for all scenes across Queensland, indicating a high geometric-correction accuracy. However, RMSE statistics do not provide a thorough assessment of the quality of the geometric correction. Therefore, visual assessment of each scene and an analysis of the spatial trends in residuals were found to be necessary to confirm that there was minimal misregistration and to identify where further refinement was required. These visual assessment procedures need to be replaced with more accurate image-registration methods and combined with automated, spatially explicit accuracy-assessment techniques to manage the processing of the large archives of image data that are now available.

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The use of trade names in this manuscript was to communicate the methodology and was not intended to be an endorsement of a company or its products.

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