GEOMETRIC DISTORTIONS IN OPTICAL REMOTELY SENSED SATELLITE DATA – THEIR REMOVAL AND RESULTING PRODUCT ACCURACY

by
Paul Wise
Director Operations, ACRES

Introduction

The very act of remotely sensed data acquisition, by satellite, imparts geometric distortions to the data. Geometric distortions can be attributed to the satellite, its sensor and the earth individually, and the relative motions of the satellite and the earth. In addition, the raw data acquired by the sensor is transmitted and recorded as a sequential stream of pixels with no image structure. The geometric correction process restores this data to a two dimensional image using sets of corrections to enable it to be interpreted as a spatial representation of the Earth's surface.

While ACRES is able to supply corrected optical raster data many users may still wish to carry out this task themselves. However, ACRES is able to facilitate this task by providing data with many systematic errors already removed which reduces the need for numerous Ground Control Points (GCP).

This paper looks at the causes of geometric errors in satellite remotely sensed data, their traditional removal using GCPs and mathematical polynomials and the ACRES Geocoded Image Correction System and use of GCPs.

Geometric Distortion

Geometric distortions can be attributed to the satellite, its sensor and the earth individually, and the relative motions of the satellite and the earth. They include:

• satellite related	- orbit and attitude variations
• sensor related	- mirror scan nonlinearity (LANDSAT only) - band to band alignment
• earth related	- panoramic distortion - earth curvature
• satellite and earth related	- earth rotation - relief displacement.

These distortions can also be described as systematic and nonsystematic. The nature and magnitude of systematic distortions can be modelled and used to establish correction formulae. Residual and nonsystematic distortion is removed by establishing mathematical relationships (functions or polynomials) between the *addresses* of pixels in an image and the corresponding coordinates of those points on the ground, generally via a map. Historically, however, mathematical functions were most commonly used as they did not require the analyst to have any knowledge of the source and type of distortion.

At this stage is worthwhile to look at the effects of relief on information in an image.

Relief Displacement

Relief displacement or relief distortion is a shift in the position of the optical image of an object caused by the height of the object above or depth below a datum plane. In an optical image the tops of hills are generally imaged away from the optical centre of the image and their orthogonal (true) position. Table 1 - Relief Displacement, shows the relief displacement (r (metres)) that could be expected for both SPOT and LANDSAT for points of increasing elevation (h (metres)). In a LANDSAT image a point at the edge of the image with an elevation of some 110metres above the datum would be displaced by half a pixel (15metres). Similarly, a point at the edge of a SPOT Panchromatic image with an elevation of some 142metres above the datum would be displaced by half a pixel (5metres).

It will be noted later that when GCPs are selected that they should be selected to have the same height. If this is not possible then, if the relief distortion is over half a pixel then the coordinates should be adjusted before inclusion in the polynomial otherwise relief errors may be introduced and reduce the accuracy of the fit.

TABLE 1

RELIEF DISPLACEMENT

Relief displacement = Height of terrain * (Distance from nadir /Height of satellite)
r (metres) = h (metres) * (R (kilometres) / H (kilometres))

LANDSAT				**SPOT**			
H (km)	700			H (km)	850		
R (km)	95			R (km)	30		
h (m)	1.0	r (m)	0.1	h (m)	1.0	r (m)	0.0
	50.0		6.8		100.0		3.5
	100.0		13.6		142.0		5.0
	110.5		15.0		200.0		7.1
	147.0		20.0		284.0		10.0
	184.0		25.0		425.0		15.0
	221.0		30.0		568.0		20.0

Historically Correcting for Geometric Distortions

This process initially involves selecting image features that have matching ground coordinates in the desired coordinate system. The ground coordinate being scaled from a map or derived by field survey methods.

The probable error in the coordinates of the ground control points should be an order of magnitude less than the spatial resolution of the original data and where possible all points should be at the same elevation so that the amount of relief distortion is similar. Refer Table 1 - Relief Displacement.

The next stage of the process is the development of a mathematical function or polynomial using the set of coordinates from the uncorrected data and the coordinates of the output or corrected data. The polynomial model chosen should be appropriate for the errors in the original data and more importantly for the distribution of the control points throughout the uncorrected data set.

The degree (order) of the polynomial is selected to account for the remaining distortions in the satellite data. Second or higher order polynomial functions should only be implemented when the distortions in the data can only be modelled by such higher order functions and the behaviour of the polynomial can be well controlled by a good distribution of control points. This approach ensures that unwanted local distortions are not introduced during the geocoding process.

The polynomial is then used to map each pixel coordinate in the satellite projection into the geographic coordinate system. This mapping usually yields noninteger positions in the new projection, so the desired pixel intensity for each position is usually calculated using an algorithm selected to maintain radiometric resolution. During the transformation process the data are also resampled to a specified output pixel size.

GCP Distribution and Quantity

To ensure that unwanted local distortions are not introduced during the geocoding process the behaviour of the polynomial must be controlled. This can be achieved through the selection of well distributed GCPs; generally around the edges of the image to be corrected with a scattering of points internally.

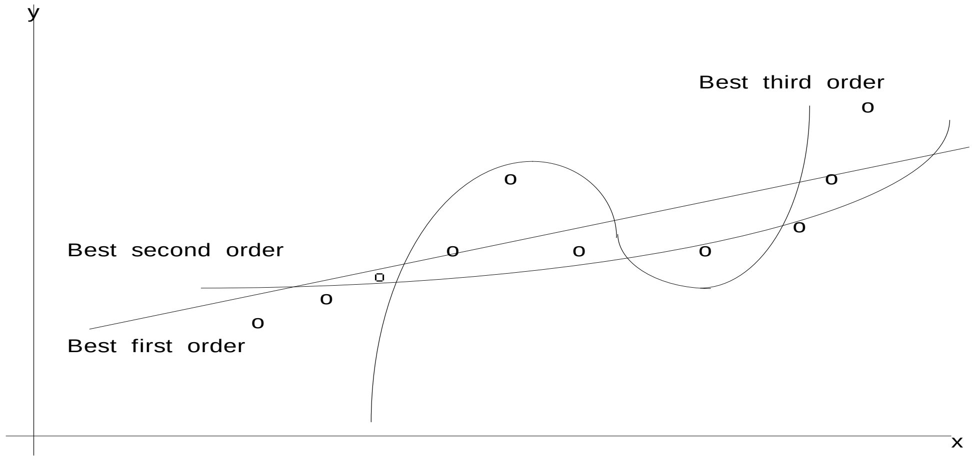

Figure 1 : Curve fitting illustrating the potentially poor behaviour of mathematical functions when used for extrapolation (after Richards, 1996)

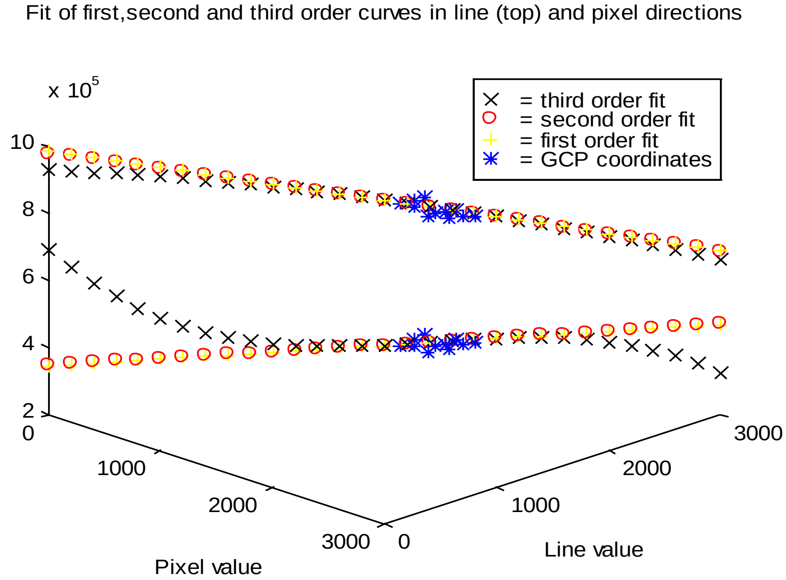

Figure 2 : An example of using third order polynomials without GCPs around the edge of the image.

This concept can be illustrated by considering an example from curve fitting. While the nature of the problem is different the undesirable effects that can be generated are similar (Richards, 1986). Figure 1 above shows a set of data points in a graph through which first order, second order and third order curves are fitted. Note that as the order (degree) of the curve is increased the curves pass closer to the points. However, if it is presumed that the data would have continued for larger values of x with much the same trend as apparent in the points plotted then clearly the linear fit will extrapolate moderately acceptably. In contrast, the cubic curve can deviate markedly from the trend when used as an extrapolator. This is essentially true in geometric correction of image data. Although higher order polynomials will be accurate in the vicinity of the control points themselves, leading to small residuals, they can lead to significant image distortions for regions of images outside the range of the control points. Figure 3 above graphically depicts such a situation.

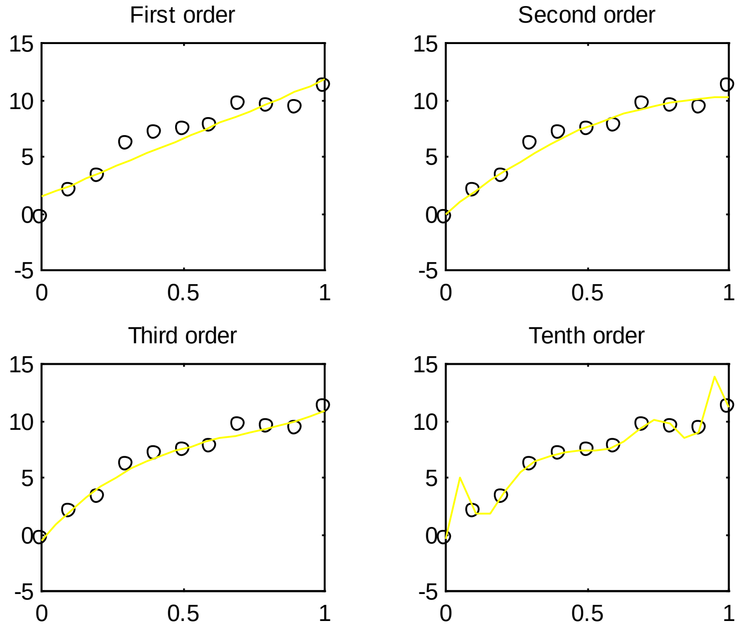

Figure 3: An extreme example of fitting first, second, third and tenth order curves through the same set of points. While the tenth order curve fits the points best note the extreme departure away from the points.

Selecting well defined and distributed GCPs modelled in a first, but no higher than second, order polynomial will generally remove the geometric distortions present as is indicated in the literature a summary of which is given below.

Source	**Data set**	**Conclusion**
Manual of Remote Sensing, 1983	MSS	Between 10 and 20 GCPs and a first degree polynomial would give corrected data to pixel accuracy. For guaranteed subpixel accuracy more than 20 GCPs and a second degree polynomial needed to be employed. More GCPs and/or a third, or higher order polynomial would NOT improve the results.
Welch & Usery, 1984	MSS	In excess of 20 GCPs and a first order polynomial gave an RMSE in excess of one pixel. Second and third order polynomials and (at least) 20 control points yielded RMSEs at the subpixel level.
Welch & Usery, 1984	TM	Pixel sized residuals are achieved with first and second order polynomials and less than 10 GCPs.
Labovitz and Marvin, 1986	TM	Between 7 and 11 GCPs are all the control points needed in geometric rectification and the distribution or evenness of control points is not crucial to the ability to perform geodetic rectification. As long as the control points are not all clustered at the beginning (or end) of the scene, many control point spatial arrangements will yield approximately the same results.
Forster et al, 1988	SPOT	With a first order polynomial and 9 optimally selected GCPs subpixel residuals were generated.

Table 2: A summary, from the literature, of analyses relating numbers of GCPs, polynomial order and resultant RMSE.

In summary then, high order polynomials may give small residuals but may also introduce unwanted and even worse unnoticeable distortions between points.

Cross-Validation
In a his1996 paper McGwire points out the standard RMSE (Root Mean Square Error), as calculated from residuals, is a diagnostic, and a weak diagnostic at that, which has been confused as an accuracy statistic. McGwire strongly suggests that the *cross-validated RMSE* be used rather than *the traditional RMSE*.

The cross-validation method has a number of strengths in that it only needs to use the reliable GCPs, as few as there may be, to create a pool of pseudo check points which are independent from a corresponding pool of polynomial coefficients. The mean error for predicting these pseudo check points more effectively represent the actual error of a single geometric rectification calculated from all control points. In addition, the traditional RMSE is an overly optimistic statement of accuracy and, as mentioned above, not necessarily an indicator that a different order polynomial will improve the result.

Rather than taking the residuals of a single transformation the cross-validation RMSE (written as RMSE*) is calculated by removing the first point from the pool and calculating the transformation parameters which are then applied to the first point. The difference from the true X, Y values is then determined. Each point in the data set is treated similarly and the resulting X, Y residuals used in the traditional RMSE equation to determine RMSE*.

To ensure that the RMSE* is not biased McGwire recommends that the number of GCPs used should exceed five degrees of freedom for a given order of polynomial. The following table demonstrates this concept.

Polynomial Order	GCPs required to solve polynomial	Further GCPs for 5 degrees of freedom plus one	Total number of GCPs recommended
1st order	3	6	9
2nd order	6	6	12
3rd order	10	6	16

Table 3: The recommended number of GCPs for cross-validation for first, second and third order polynomials.

Bearing in mind that these American studies used 1: 24 000 scale maps TM data could be geometrically corrected using around 10 GCPs and a first degree polynomial. As such large scale mapping is not common in Australia, the 1: 100 000 being the largest common scale for the most part, 15 GCPs may be required from which at least 10 to 12 would be finally used in a first and not more than a second order polynomial after rejecting any poorly identified points.

Geocoded Image Correction System
The Geocoded Image Correction System (GICS) was developed by MacDonald Dettwiler of Canada and has the capability to produce different levels of geometric processing (Sharpe, 1989).

The basis of the GICS process is the removal of systematic distortion, through modelling the sensor, earth, satellite orbit and attitude. The models are developed from manufacturer's data, prelaunch measurements, an understanding of the physical processes involved and *a priori* knowledge. Those model parameters that are not known *a priori* are determined from telemetry data and GCP measurements.

In GICS the models that are determined without using ground truth are called systematic models. They typically have errors on the order of 1kilometre due to uncertainties in absolute orbit position. However, they have a fairly high internal accuracy. Models that are determined with the use of ground control are called precision models.

Precision models are determined by using GCPs to refine the systematic orbit and attitude models. This approach provides maximum accuracy with minimum GCPs and differs from the correction polynomial approach, described above, which uses *best-fit* curves and generally requires significantly more GCPs to achieve comparable accuracy.

The input of GCPs into GICS is from State and Commonwealth printed topographic maps or map compilations at scales of 1: 25 000, 1: 50 000 and 1: 100 000. The procedure is controlled by GICS and requires points be selected in the centre, opposite corners and around the edge. This procedure has the effect of sequentially reducing the major errors. GICS also requires that the height of each GCP is entered so relief distortion can be removed as a source of error.

The GICS process requires that 7 GCPs be entered. Where this is not possible 3 or more GCPs are selected and at worst one point is selected to reduce the major positional error. Two GCPs are not used as they may introduce rotational errors. This systematic approach ensures that the modelling process works only with reliable data. Unlike the *best-fit* technique where the results of including more but less reliable GCPs into the process help to average out the result the best result is gained from the input of only the best information even if that is limited.

GICS Error Analysis

GICS provides an output of the residual errors in metres at each of the GCPs used and determines the Root Mean Square Error (RMSE) which is printed on the GICS report. Please refer to Attachment A for details about RMSE.

For simplicity the along track or North/South GICS residual is known as Y and the across track or East/West GICS residual is known as X. Then the RMSE, as used in GICS, is given by :

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(X_i^2 + Y_i^2\right)}$$

where *n* is the number of GCPs used.

As shown in Attachment A, GICS avoids taking the square root and uses the RMSE squared as the value for determining confidence.

However, while ACRES has only the RMSE value upon which to judge its geocoding, ACRES is aware of its limitations for this purpose, as stated by McGwire above. ACRES therefore also assess its geocoding on consideration of the following:

- the RMSE is significantly dependent on image resolution and its value should be around a pixel or better;
- the magnitude of the X and Y residuals should be of the same order; and
- any residual should generally not exceed twice the RMSE (95% confidence level is 1.96 times RMSE, (say) 2).

In general terms then the first check is that the RMSE value for a set of measurements given by GICS is around the pixel value of the data set. Secondly that the magnitude of the X and Y values are within twice (2 times) the GICS RMSE value. If any X or Y value does exceed twice the GICS RMSE value then it is possibly suspect and should be checked. After checking a judgement is made as to whether the GCP is included or excluded.

Product Errors

The residual error in a product is the combined error from all the sources used to generate the product.

From the law of propagation of Root Mean Square Errors (RMSE), the combined RMSE of a number of independent variables is the square root of the sum of the individual RMSEs squared.

In the case of ACRES products, the stages where errors occur or exist are:

⇒ map used for GCP selection; call σ_{map} see further discussion below;
⇒ GCP digitising from the map; call σ_{gcp}, estimated at ±0.2mm at map scale;
⇒ GCP selection in the image; call σ_{img} estimated at ±0.5 pixel;
⇒ GICS model error; call σ_{mod} estimated at ±0.5 pixel;

then the combined error ($\sigma_{combined}$) from all these sources is expected to be:

$$\sigma_{combined} = \pm\sqrt{[(\sigma_{map})^2 + (\sigma_{gcp})^2 + (\sigma_{img})^2 + (\sigma_{mod})^2]}$$

The National Mapping Council specifications for map accuracy states that *90% of well-defined points shall be within 0.5mm of their true position at map scale*. What does this mean in terms of RMSE?

Statistically the 90% confidence limit equates to 1.645 times RMSE and that at a standard Australian map scale of 1: 100 000, half a millimetre equates to 50metres, giving:

$$1.645(\sigma_{map}) = \pm 50\text{m} \quad \text{or} \quad \sigma_{map} = \pm 30.5\text{m}$$

Similarly, for 1: 50 000 scale mapping $\sigma_{map} = \pm 15.2$m

Tabulating the above errors for both LANDSAT TM and SPOT XS and PA sensors theoretically using GCPs from both 1: 100 000 and 1: 50 000 scale maps yields the results for the combined error as set out in Table 4 below.

The table indicates that using l: 100 00 scale maps the positional error in a product is around ±40m irrespective of the image data set. The use, where possible, of 1: 50 000 scale mapping in conjunction with SPOT data halves the combined error from around ±40m to around ±20m.

Satellite & Sensor / Error Source	LANDSAT TM	SPOT XS	SPOT PA
σ_{map} (100k)	±30.5	±30.5	±30.5
σ_{map} (50k}	±15.2	±15.2	±15.2
σ_{gcp} (100k)	±20	±20	±20
σ_{gcp} (50k)	±10	±10	±10
σ_{img}	±15	±10	±5
σ_{mod}	±15	±10	±5
$\sigma_{combined}$ (100k)	±42.2	±39.1	±37.1
$\sigma_{combined}$ (50k)	±28.0	±23.1	±19.6
$\sigma_{combined}$ as integer Pixels (100k)	±2	±2	±4
$\sigma_{combined}$ as integer Pixels (50k)	±1	±2	±2

Table 4: An estimation of the combined errors for both LANDSAT TM and SPOT XS and PA sensors theoretically using GCPs from both 1: 100 000 and 1: 50 000 scale maps.

ACRES GICS Data and likely Positional Accuracies

ACRES utilises the MacDonald Dettwiler GICS system, as described above, to provide bulk corrected, georeferenced (path oriented), or geocoded (map oriented) data, where geocoded data is the most highly refined.

Both bulk corrected and georeferenced images are mission dependent, that is their characteristics are dependent upon the particular satellite and sensor which acquired the data. Even after georeferencing and transformation to a common projection, these images still exhibit framing, orientation, scene and possibly pixel size differences. It is particularly important for users to note that bulk processed data is generated in the scene specific Superficial Conic Map Projection and is therefore **not** suitable for mosaicing.

The table at Attachment B summarises the corrections that GICS makes to LANDSAT and SPOT data at the most common processing levels and the estimated positional accuracy of the resulting products. It is important to note that while relief is removed from the modelling procedure to correct level 9 products the positions of individual features are currently **not** corrected for relief. The position of such features may therefore exceed the quoted accuracy. With the future integration of the 9 second (250 meters grid cell) digital elevation model this problem will be negated.

Summary

This paper reviewed the causes of geometric distortion in satellite remotely sensed data and described their removal by using polynomials and the assessment of such polynomials using RMSE and cross-validation. The procedure that the ACRES GICS system for geometric correction and how the resulting RMSE is assessed along with a theoretical analysis of the estimated error in ACRES products.

It is clear that while ACRES is using the best available data and procedures for GCPs the available mapping remains the greatest source of error. In the attached 1988 paper by Sharpe and Wiebe it is indicated that a procedure called *Pass Processing* is available within GICS but has never been investigated. It is the conclusion of this paper that *Pass Processing* can achieve single scene accuracy with the same number of GCPs yet for a number of scenes within a single pass. If these results can be replicated on ACRES GICS then the impact of the available mapping on final image accuracy might be reduced and even removed.

References

Colwell, R.N. (Ed.). 1983. Manual of Remote Sensing (2nd edn), American Society of Photogrammetry. Falls Church, Virginia: USA.

Forster, B.C., Trinder, J.C., Carroll, D., Farrington, R. and Kwoh, L. 1988. Mapping and Urban Multi-experimental Assessment of SPOT - Mapping Results. Proceedings 4th Australasian Remote Sensing Conference, pp.1289-1295.

Horn, J. and Wise, P.J. 1990. The Use of Geocoded Satellite Images for Map Revision. Proceedings of the 8th Australian Cartographic Conference, pp 81-94.

Labovitz, M.L. and Marvin, J.W. 1986. Precision in Geodetic Correction Data as a function of the Number, Spatial Distribution and Success in Matching of Control Points: A Simulation. Remote Sensing of Environment, Vol.20, No.9, pp.237-252.

McGwire, K.C. 1996. Cross-Validated Assessment of Geometric Accuracy. Photogrammetric Engineering and Remote Sensing, Vol.62, No.10, pp.1179-1187.

Puniard, D.J., Horn, J. and Wise, P.J. 1990. Geocoded Image Products for Integration into Geographic Information Systems. Proceedings of the Eighteenth Australasian Conference on Urban and Regional Planning and Information Systems, pp 201-210.

Rabchevsky, G.A. (Ed.). 1984. Multilingual Dictionary of Remote Sensing and Photogrammetry. American Society of Photogrammetry. Falls Church, Virginia: USA.

Richards, J.A. 1986. Remote Sensing Digital Image Processing. Springer-Verlag.

Sharpe, B. 1988. Planimetric Accuracy in Satellite Mapping. International Archives of Photogrammetry, Vol.27, Pt.B4, pp341-349.

Sharpe, B. and Wiebe, K. 1988. Reduction of Ground Control Requirements by Pass Processing, Proceedings International Society for Photogrammetry and Remote Sensing, XVIth Congress, Commission IV, Tokyo, July 1988, pp.350-357.

Sharpe, B. 1989. Geometric Processing in MacDonald Dettwiler's Meridian-GICS System. CISM Journal, Vol.43, No.2, pp.127-132.

Welch, R. and Usery, E.L. 1984. Cartographic Accuracy of Landsat-4 MSS and TM Image Data. IEEE Transactions on Geoscience and Remote Sensing. Vol.22, No.3, pp.281-288.

Wise, P.J. 1991. Operational Considerations for Integrating Satellite Data into a GIS. AURISA Monograph No.7, pp.55-60.

Attachment A

RMSE : its meaning and application for GICS

In statistics, the standard deviation of a set of measurements or observations, is calculated to give a measure of the dispersion of the measurements about the mean. The smaller the dispersion the smaller the standard deviation and the greater the accuracy of the measurements.

Standard Deviation (SD) is also called Root Mean Square Error (RMSE). The RMSE is generally quoted as the measure of precision or the closeness with which the measurements agree with each other.

The RMSE or SD of a set of measurements is given by:

$$\sigma = \sqrt{\sum_{i=1}^{n} \left(x_i - \mu\right)^2 / n}$$

where:
σ is the RMSE or Standard Deviation;
μ is the mean or average of all the measurements;
x is a single measurement;
$(x - \mu)$ is the residual of a single measurement; and
n is the number of measurements.

The following form of the calculation is easier for a calculator as neither the mean nor the individual residuals need be calculated.

$$\sigma = \frac{1}{n}\sqrt{n\sum x_i^2 - \left(\sum x_i\right)^2}$$

It is also possible to state the level of confidence that the measurements all fall within a set range of the mean of the measurements. For example, if the measurements fall within $\pm$ 1.645σ then the confidence level is 90% (1.645σ equates to a 90% confidence level, 1.960σ to 95%, 2.326σ to 98%, 2.576σ to 99% etc). As a numerical example if the RMSE of a set of measurements, calculated using the formula above is say 10 (σ = 10) then to check that all the measurements are within a 90% confidence level 1.645σ is calculated giving 16.45. So, provided no measurements is greater than 16.45 then it can be said that there is a 90% confidence level that the measurements are acceptable.

In pre calculator times or when taking the square root was complex the values were left squared. Thus, the RMSE value squared was multiplied by 1.645 as above and this value used for comparison. In the case above the RMSE squared of a set of measurements would now be 100 (σ^2 = 100) then to check that all the measurements are within a 90% confidence level 1.645σ^2 gives 164.5.

An example of this methodology is given below :

EXAMPLE

	X	Y	X^2+Y^2	North	South	Nth^2+Sth^2	
	-8.60	7.20	125.80	-9.70	5.60	125.45	
	2.90	-7.90	70.82	4.20	-7.30	70.93	
	1.50	-10.10	104.26	3.10	-9.70	103.70	
	-6.30	5.70	72.18	-7.20	4.60	73.00	
	9.80	12.00	240.04	7.70	13.50	241.54	*suspect
	3.70	2.10	18.10	3.30	2.80	18.73	
	4.80	-3.40	34.60	5.30	-2.60	34.85	
	-10.50	-2.40	116.01	-9.90	-4.20	115.65	
	0.50	-3.00	9.25	1.00	-2.80	8.84	
RMSE squared			**87.90**			**88.08**	
RMSE			**9.38**			**9.38**	
90% confidence level of RMSE squared or 1.645* RMSE squared			**144.59**			**144.89**	

In the above example the value RMSE squared is 87.90 and 88.08 respectively requiring all measurements values squared to be no greater then 144.59 or 144.89 respectively (1.645 times RMSE squared) to give a 90% confidence level the measurements. By inspection one measurements appears suspect.

Sources

ERDAS Imagine *Field Guide*.

Rowntree, D. 1981. Statistics without Tears. Pelican.

Kennedy, J. & Neville, A. 1974. Basic Statistical Methods for Engineers and Scientists. Harper & Rowe.

Attachment B

GICS Corrections applied to optical data and positional accuracy versus processing level

		GICS Processing Level						
Correction	**Name**	**0**	**1**	**4**	**5**	**8**	**9**	**10**
Radiometric sensor calibration	relative calibration applied	No	Yes	Yes	Yes	Yes	Yes	Yes
	dead detector replacement (if required)	No	Yes	Yes	Yes	Yes	Yes	Yes
Scene radiometric corrections	relative calibration applied	No	Yes	Yes	Yes	Yes	Yes	Yes
Geometric corrections	detector offsets applied	No	Yes	Yes	Yes	Yes	Yes	Yes
	detector misalignment applied	No	Yes	Yes	Yes	Yes	Yes	Yes
	band to band offsets applied	No	Yes	Yes	Yes	Yes	Yes	Yes
	scan time skew (LANDSAT TM only) corrected	No	Yes	Yes	Yes	Yes	Yes	Yes
	mirror scan nonlinearity (LANDSAT only) corrected	No	No	Yes	Yes	Yes	Yes	Yes
	line length & swath time variation (LANDSAT only) corrected	No	No	Yes	Yes	Yes	Yes	Yes
	orbit and attitude variation corrected	No	No	Yes	Yes	Yes	Yes	Yes
	sensor and attitude control system alignment corrected	No	No	Yes	Yes	Yes	Yes	Yes
	Earth curvature and rotation correction applied	No	No	Yes	Yes	Yes	Yes	Yes
	panoramic distortion corrected	No	No	Yes	Yes	Yes	Yes	Yes
	off-nadir pointing angle (SPOT only) corrected	No	No	Yes	Yes	Yes	Yes	Yes
	scan gap & jitter corrected	No	No	Yes	Yes	Yes	Yes	Yes
	positioning via GCPs only	No	No	No	No	No	Yes	No
	positioning via GCPs & DEM	No	No	No	No	No	No	Yes
Resampling	cross track	No	No	Yes	Yes	Yes	Yes	Yes
	along track	No	No	No	Yes	Yes	Yes	Yes
	map projection selectable	No	No	No+	Yes	Yes	Yes	Yes
Positional Accuracy	LANDSAT MSS (1,2,3)	N/A	±20km	±20km	±20km	±20km	N/A	N/A
(with GCPs from	LANDSAT MSS (4,5)	N/A	±5km	±5km	±5km	±5km	N/A	N/A
1:100 000 scale maps)	LANDSAT TM	N/A	±5km	±5km	±5km	±5km	±60m	±60m
	SPOT XS	N/A	±3km	±3km	±3km	±3km	±60m	±60m
	SPOT PA	N/A	±3km	±3km	±3km	±3km	±60m	±60m

+: The map projection is fixed as the Superficial Conic Map Projection (SCMP)

Reduction of Ground Control Requirements by Pass Processing

Bruce Sharpe, Senior Research Analyst
Kelly Wiebe, Research Analyst
MacDonald Dettwiler,
3751 Shell Road, Richmond B.C.
Canada V6X 2Z9
Commission No. IV

Abstract

Pass processing is a technique for determining geometric correction models that requires an order of magnitude fewer control points than conventional methods for correcting satellite imagery. We present a description of the technique and results for a pass of Landsat Thematic Mapper imagery that contains 15 scenes. We show that with good ground truth only 1/2 GCP per scene on average is required. Good accuracy is still possible with only 4 GCPs to correct the entire 15 scenes. Results for interpolation, extrapolation and correcting areas with no ground truth are discussed.

1 Introduction

One of the advantages that mapping from satellite imagery offers over conventional techniques is that the number of ground control points (GCPs) required is substantially smaller. This is true even if the imagery is processed one scene at a time [2]. In this paper we describe a multiscene technique, *pass processing*, for reducing ground control requirements by another order of magnitude.

Pass processing is a method for determining geometric correction models by using GCPs from a large part of the pass (orbit) containing the desired output scene. Currently, most systems use ground truth which is located in a region the size of one scene.

The goal of pass processing is to achieve accuracy comparable to single scene processing, using the same number of GCPs. The number of GCPs required per scene is then the single-scene requirement divided by the number of scenes in the pass. There are typically tens of scenes available in a single pass.

A related advantage is that the location of GCPs is less critical than for single scene processing. In fact, it becomes possible with pass processing to correct imagery over large areas where no GCPs are available at all.

In this paper, we shall present results of a study to evaluate pass processing techniques when implemented as an extension of MacDonald Dettwiler's standard Geocoded Image Correction System (GICS). Pass processing has been implemented in a GICS for the Australian Centre for Remote Sensing. Measurements were made to determine what accuracy can be achieved for several different distributions of GCPs: uniform, at both ends of the pass and at one end only. The accuracy when only a minimum of ground control was used was also determined.

In Section 2 we give an overview of the pass processing technique. This is followed in Section 3 by a description of our methodology for measuring accuracy. The results of our measurements are presented in Section 4.

Pass processing for the early Landsat satellites was described in [1]. The work presented here extends these results to the Landsat Thematic Mapper (TM).

2 Techniques of Pass Processing

In order to correct satellite imagery, it is necessary to determine the correspondence between pixels in the input imagery and points on the earth's surface. In GICS, this correspondence is embodied in models of the sensor, the earth and the satellite orbit and attitude.

The parameters of the models are determined from manufacturers' data, prelaunch measurements, satellite telemetry, an understanding of the physical processes involved and other *a priori* knowledge. Ground truth is used to provide corrections to the models. Corrections are made in the form of time series polynomials whose coefficients are estimated using a Kalman filter. The measurements which are input to the Kalman filter are the errors in GCP location which are determined by marking GCPs in the imagery.

The approach taken to pass processing was to extend this modelling process from a time scale of one scene to several scenes.

3 Methodology of Measurements

The methodology of accuracy measurement is the same as that described in [2]. We give a brief summary here.

Well-defined features (GCPs) are marked in the imagery to determine their input coordinates, that is, their line and pixel position in the input image. The input coordinates are then transformed to ground location using the models. The ground locations thus determined are compared with ground truth, that is, the locations as determined independently, for example, from existing maps or from field surveys.

Some of the marked points are used to determine the model (model points), while the remainder (check points) are used as independent points at which to measure accuracy.

In all our measurements, the height of the check point is used to compensate terrain effects when calculating the accuracy at that point. Also, the measurements were made using the models directly rather than measuring output products.

Our measurements are reported as two-dimensional RMS absolute accuracies, or mean square error (MSE). Thus if X_i and Y_i represent the errors at check point i in the x and y directions respectively, the total absolute accuracy (AA) is

$$\text{AA} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(X_i^2 + Y_i^2)}$$

4 Measurements: TM

4.1 Test Data

Our test data set consisted of Landsat-5 imagery of Path 28, acquired on April 16, 1984. It contained about 15 scenes (6 minutes 12 seconds of imagery) and covered a region from near Hudson Bay in the north to the Oklahoma-Texas border in the south.

GCPs in the Canadian part of the pass were digitized from 1:50 000 scale maps prepared by Department of Energy, Mines and Resources. In the U.S. part of the pass, US Geological Survey (USGS) 1:24 000 scale maps were used. After outliers were eliminated, 290 GCPs remained. The GCPs in Canada were generally less distinct and more difficult to mark than those in the U.S. Some regions in the U.S. (southern Minnesota and Iowa) were blessed with an abundant supply of county road intersections which served as excellent GCPs.

The region covered by the scene which is the second down from the north has not been mapped yet, so it was not possible to correct or measure the imagery there.

4.2 Reference Accuracies

To obtain a basis of comparison with the accuracy of single scene processing, we divided our pass into 15 scenes of equal length and designated one half of the GCPs in each scene as model points and the other half as check points. There were about 10 of each. The model points were then used to correct each of the scenes, using standard single-scene processing, and the accuracy was measured at the check points. The resulting reference accuracies are shown in column 1 of Table 1. This table shows the results of several tests for each scene and gives summary statistics. The summary statistics are given for the whole pass and for the U.S. scenes only, because the latter had better ground truth and so allowed a better determination of accuracy.

4.3 Uniform Distribution

The first test of accuracy using pass processing was that for the case where the GCPs are uniformly distributed over the pass. One model GCP from each scene, for a total of 14, was selected and used to build a correction model which covered the entire pass.

Scene #	1. Reference Accuracy (m)	2. Uniform Accuracy (m)	3. Interpolation Accuracy (m)	4. U.S. Interp'n Accuracy (m)	5. Extrap'n Accuracy (m)
1	31.7	35.3	21.6		
2					
3	16.0	25.9	28.0		
4	18.5	31.1	24.9		
5	37.5	32.9	34.1		
6	23.3	26.3	29.2		
7	18.4	20.9	20.5		
8	16.5	15.5	17.2		
9	8.1	11.2	12.4	10.1	
10	11.7	11.3	15.1	10.7	9.8
11	12.6	13.3	18.6	14.2	13.0
12	13.1	13.3	17.5	16.6	19.5
13	19.9	14.2	13.4	12.8	22.8
14	13.1	13.0	14.9	13.3	22.4
15	13.8	17.3	1.3	16.1	35.4
All	19.7	21.7	21.0		
USA	14.5	14.7	15.9	13.6	22.0

Table 1: Accuracy of pass processing for various configurations of GCPs.

The accuracy at each of the scenes was then measured at the same check points as were used for the references. The results are given in column 2 of Table 1.

Not surprisingly, pass processing had a levelling effect on the scenes' accuracies. For example, scene 5 caused a degradation of the accuracy of the surrounding scenes. On the other hand, scene 13 benefited from the more accurate surrounding scenes.

The accuracy over the whole pass was worse by about 2 m out of 20 m, while the accuracy in the U.S. scenes only remained the same.

4.4 Interpolation

For this test, we selected the model GCPs from those in the scenes at the ends of the pass. Seven GCPs were chosen from scenes 1 and 3, and seven from scene 15. The resulting model was used to correct all scenes in the pass. The accuracy of each scene as measured at the reserved check points are shown in column 3 Table 1.

The accuracy was generally slightly degraded which is probably due to the influence of the poor quality GCPs from scenes 1 and 3. Nevertheless, the overall and U.S. accuracies only increased by 1 m or so.

To test the accuracy obtainable when better quality ground truth is available, we repeated the interpolation test using only the U.S. scenes. Seven GCPs from each of scenes 9 and 15 were used to build the model with the accuracies shown in column 4 of Table 1. The differences are slight and there is an overall improvement from the reference accuracy of 14.5 m to 13.6 m.

4.5 Extrapolation

We had a choice for this test in that we could have used model GCPs from the poor ground truth and check GCPs from the good ground truth or vice versa. We decided on the former, because the errors in the model GCPs would tend to be reduced by the Kalman filter, whereas it would be hard to get a good estimate of the accuracy if we had to use check points with large errors. Thus for this test, we built the model with 14 GCPs from the first 9 scenes. The accuracy is shown in column 5 of Table 1.

As expected, the accuracy degrades as the scenes get further from the control points. Nevertheless, the accuracy remains at a subpixel level for five scenes beyond the GCPs.

4.6 Accuracy Using a Minimal Number of GCPs

The tests up to this point used 14 GCPs in the model. Since 14 scenes were being corrected, the average GCP requirement is thus 1 GCP per scene. Since one of the main goals of pass processing is to reduce the number of GCPs required, we tested the accuracy obtainable with a minimal number of GCPs. One would expect the accuracy to be worse with a small number of GCPs, but this might be an acceptable tradeoff in situations where GCPs are scarce.

Figure 1 shows the accuracy attainable with a given number and distribution of GCPs. Since good quality ground truth is of prime importance when only a few GCPs are to be used, for most of the tests the GCPs were taken from the U.S. scenes only and the accuracy was measured only there.

The largest errors in a systematic model are due to biases in the orbit, along and across track. As in our other tests, we modelled these errors as attitude bias errors. They can be corrected with a single GCP, preferably situated near the middle of the pass. The accuracy obtained in doing this was 52 m.

Once the orbit biases have been corrected, the linear pitch and yaw bias errors become significant. Either of these errors (but not both) can be corrected with two GCPs. The best accuracy obtained when correcting only the pitch was 51 m. By correcting for yaw instead, we obtained 33 m which demonstrates that the yaw error is the larger of the two. The optimal placement for the two GCPs is at opposite sides of the pass and near the middle of its length.

With three GCPs, it is possible to correct for the orbit biases, the yaw bias and linear pitch. With a good placement of the GCPs, an error of 22 m was obtained.

The next largest error is due to the linear variation in roll. Four GCPs are required to correct all these effects. With good placement of the GCPs, an accuracy of 16 m was obtained.

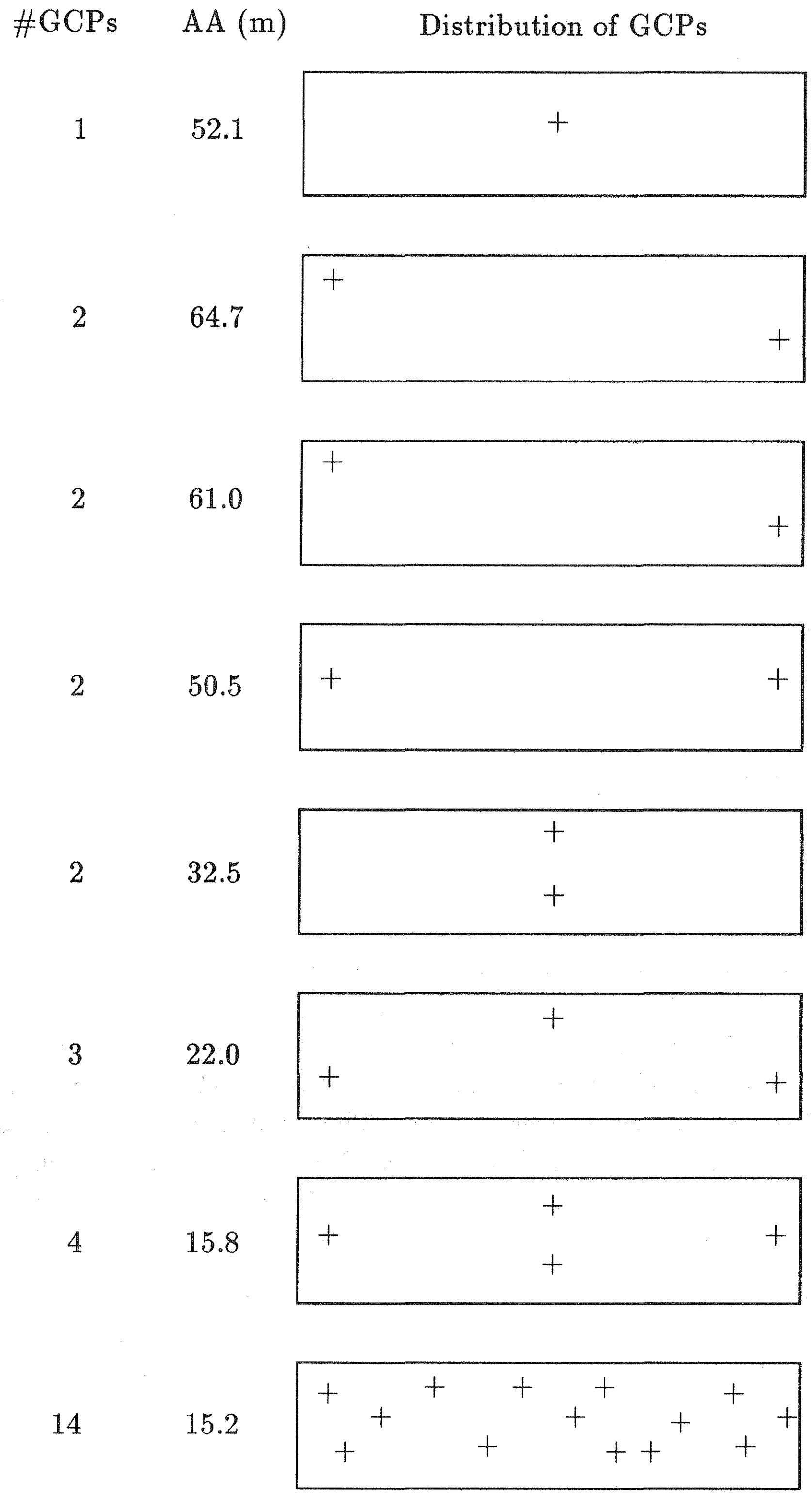

Figure 1: Accuracy using a minimal number of GCPs to correct 7 consecutive scenes.

For reference, we used 14 GCPs uniformly distributed over the U.S. scenes. The accuracy obtained, 15 m, is hardly better than with four GCPs.

Note that since eight scenes were corrected, a model with four GCPs represents a requirement of only 1/2 GCP per scene.

We tested these ideas, although less extensively, for the whole pass. We created models using four GCPs distributed over the whole pass instead of just the U.S. scenes. One of the GCPs came from scene 1 in Canada, and the remainder were from U.S. scenes. The accuracy was measured both in Canada and the U.S. This was repeated five times and the RMS errors were averaged. The results were:

RMS error over whole pass 25.4 m
RMS error over U.S. scenes 16.7 m.

Thus for a slight increase in error (2.2 m over the reference accuracies in the U.S.) we were able to correct 15 scenes of data with only four GCPs, a little over 1/4 GCP per scene.

5 Conclusions

The results of Section Three have shown that pass processing techniques yield accuracy comparable to single-scene processing using the same number of control points.

Single scene processing requires about 6–10 GCPs per scene. With mediocre ground truth, we only needed 1 GCP per scene. With better quality ground truth (the U.S. scenes), only 1/2 GCP per scene was required to achieve an accuracy comparable to that of single scene processing. The most dramatic reduction in GCPs was obtained by using four of them to correct a pass 15 scenes long. The accuracy was degraded somewhat but was still as good as 17 m in the U.S. scenes. No doubt better accuracy could have been obtained if the quality of the ground truth in Canada (which contributed one of the four GCPs) had been better.

Aside from the reduction in the number of GCPs required, we have demonstrated that pass processing increases the flexibility in the placement of the GCPs. By interpolating the model from GCPs at the ends of a pass, we corrected 11 scenes at once with good accuracy (16–21 m) and without using any GCPs from them. Extrapolation was also successful, with five scenes containing no GCPs being corrected to moderately good accuracy (23 m or better) by that technique.

References

[1] Daniel E. Friedmann, James P. Friedel, Kjell L. Magnussen, Ron Kwok, and Stephen Richardson. Multiple scene precision rectification of spaceborne imagery with very

few ground control points. *Photogrammetric Engineering and Remote Sensing*, 49(12):1657–1667, December 1983.

[2] Bruce Sharpe and Kelly Wiebe. Planimetric accuracy in satellite mapping. In *these proceedings*.