AN AUTOMATED SYSTEM FOR SUB-PIXEL CORRECTION AND GEOCODING OF MULTI-SPECTRAL AND MULTI-LOOK AERIAL IMAGERY

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Abstract

The requirement for high resolution multi-spectral, multi-look geocoded data in local environmental change detection and monitoring systems is well recognised. Currently we must look to aerial sources for resolutions greater than 5m per pixel, using photography and scanner data such as ATM, ASAS or CAESAR. Unfortunately such aerial scanner data tends to suffer severe distortions from terrain relief, aircraft vibrations, flight path variations and the scanning techniques themselves, thus requiring extensive geometric correction before utilisation. Traditional methods have involved the manual selection of tie points between the image to be corrected and some ground truth (a digitised map or orthoimage usually,) followed by a polynomial warp. Such methods, however, are generally insufficient for rigorous geocoding and are highly labour intensive when selecting a few tens of well distributed points. In this paper refinements to a previously described automated control point generation system are presented, along with an automated system for geometric correction based upon an initial low order polynomial warp combined with stereo-matching to enable full geocoding of every image pixel. Maximum retention of data integrity is ensured through the use of a single level of resampling. Results from a prototype, semi-automated version of the system are presented, and the application of the system to satellite data is briefly discussed.

Keywords: **Airborne Scanner, Change Detection, Image Processing, Rectification, Registration**

1. Introduction

The immense potential of airborne multi-spectral sensor and imaging spectrometer data has been recognised by the remote sensing community since the mid-1970s. The high resolutions afforded by such instruments (typically five metres per pixel or better) coupled with the high spectral resolution can reveal much about the nature and structure of an imaged scene [Goetz *et al*, 1985]. When this data is further combined with angular, or directional, information obtained either through use of a radiometer with off-nadir pointing capability or through collection of multiple flight line data over the target site, investigation of the biophysical properties of the surface becomes feasible [Barnsley and Muller, 1991.]

The use of airborne data for such purposes, though, has been hampered by a general inability to *accurately* geocode such imagery, or even register it to aerial photography [Kindelan *et al*, 1981, Devereux *et al*, 1990, Teillet *et al*, 1990, Irons *et al*, 1991, Irons *et al*, 1992]. This has largely been due either to inadequate modelling of the distortions caused by turbulent motion of the aircraft, for instance using low order polynomials to describe what is essentially a semi-chaotic process, or the *a-priori* requirement of a Digital Elevation Model of the area at or near the same resolution as the scanner data itself [Teillet *et al*, 1990, Guindon *et al*, 1990, Muller, 1992]; rarely available and computationally or manually expensive to produce. Work has been performed using data either in its raw form or partially registered [Barnsley et al, 1990b], but inferences from both inevitably contain errors resulting from the difficulties in extracting from differing view *exactly* the same sample area for comparison. Accurate pixel level or sub-pixel geocoding/registration would enable individual pixels to be studied, which could mean individual plants or trees in some cases, and would avoid the tedious, time consuming manual operation of selecting and sectioning approximately coincident areas from different parts of different images, each suffering different distortions; without pixel level registration one can never guarantee to be comparing exactly the same set of image samples. A rigorous multi-dimensional segmentation therefore requires accurate registration to fully utilise the information available from multi-spectral, multi-directional, and even multi-sensor data.

The work presented here forms one step towards the eventual goal of developing an automated, large scale environmental monitoring system [Muller, 1989b, 1992]. Airborne scanner data and aerial photography have been chosen as the input data forms in order to achieve change detection at resolutions of five metres or less [Muller *et al*, 1991]. This paper deals specifically with the problems of multi-image registration using as little *a-priori* information as possible whilst attempting to maintain maximum automation.

2. Multi-Spectral, Multi-Directional Sensors

[Barnsley and Muller, 1991, Irons *et al*, 1992] and a number of other authors have reported the demand for multi-directional data to investigate the anisotropies in radiation reflected from the Earth's surface. Such knowledge will be important to the correct interpretation of data from the forthcoming MISR off-nadir pointing spectrometer to be mounted on the polar-orbiting Earth Observation Station (EOS-A) with the MODIS-N instrument [Goetz and Herring, 1989, Salomonson *et al*, 1989, Barnsley and Morris, 1990, Diner *et al*, 1991].

Currently, airborne sensors such as the NASA Goddard Space Flight Centre's ASAS instrument, the Dutch CCD Airborne Experimental Scanner for Applications in Remote sensing (CAESAR) instrument and the British NERC funded Daedalus 1216 Airborne Thematic Mapper (ATM) instrument are used for multi-spectral and multi-directional studies [Barnsley, 1984]. A brief description of these three sensors is included here so the reader may appreciate the causes of the distortions encountered within this form of imagery.

ASAS is a pushbroom imaging spectroradiometer acquiring 29 spectral bands (465-871 nm) with spectral resolution of 15 nm and nominal spatial resolution of 4.25 metres cross-track (full Field Of View (FOV) 25°) and 2 metres along-track from an altitude of 5000m. Multi-directional imagery is obtained as the aircraft passes over the site, using the along-track pointing capability in 15° steps to limits (until recently [Nwosu and Muller, 1992]) of +/-45° [Irons *et al*, 1991, Irons *et al*, 1992].

CAESAR is a pushbroom scanner developed by the Dutch National Remote Sensing Programme. It has three nadir view cameras seperately acquiring red, green and infrared, and three forward looking cameras also seperately acquiring red, green and infrared, but at different angles (45°, 52° and 59°.) Over land, CAESAR can achieve resolutions of $0.5m^2$ per pixel from an altitude of 2000m. [Looyen *et al*, 1990, Looyen *et al*, 1991]

The ATM instrument is a nadir-viewing whiskbroom scanner with a very wide cross-track field of view (86°). Multi-directional data is obtained by running a set of parallel, closely spaced flight lines over the area of interest and extracting the overlapping scene areas. ATM has 11 spectral channels, including the bands used by Landsat TM, ranging from 420 to 1300nm [Barnsley, 1985, Kay, 1988].

3. Registration and Geo-Coding: The Problems

Any remotely sensed image will contain a distortion characteristic of the sensor used in its acquisition, unless it has been removed through some form of pre-processing. For vertical aerial photography this is a radial distortion centred on the principal point of the photo. For pushbroom scanners such as ASAS it is a radial distortion across track only, so pixels at the outside of the swath represent larger areas on the ground than those at nadir (the resolution decreases). There may be some under or oversampling along track if the ground speed of the aircraft does not match the scan line acquisition rate. For whiskbroom scanners where the scanning head (or a mirror) rotates constantly in the across track direction, aquiring one pixel at a time in multiple spectral bands, the distortion is cylindrical across track as the effective imaging surface is not flat, and may also suffer from oversampling at nadir and undersampling towards the edge of the swath (since the scanning head is effectively rotating.) As with any scanner, there may also be under or oversampling in the along-track direction.

If the nature of the distortion is known it can often be modelled and removed from the image data quite simply, often using a simple quadratic polynomial as it is inherently of low frequency; [Kindelan *et al*, 1981] refer to this as *panoramic correction.* To perform such correction properly, however, the imaging characteristics of the sensor (IFOV, scanning method, scanning mirror angular velocity, sampling mechanism etc.) are needed, along with the ground speed of the aircraft to correct for any along-track under/oversampling. Given these requirements, either different programs would be necessary to correct different

Sensor	Flying Height	FOV	Pixel Size At Nadir	Pixel Size at Swath Limit	Ground Height for 1 Pixel offset
ASAS	5000m	25.0°	4.26m	4.47m	20.2m
ATM	3000m	86.0°	6.28m	8.57m	9.19m
CAESAR	2000m	24.3°	0.49m	0.77m	3.55m

Table 1. Heights at Swath Limit Required to Produce a Terrain Distortion of One Pixel (across-track.)

sensor geometries, or one large program containing several generic camera models and flexibility concerning the specific imaging parameters would be required. Obviously it would be preferable to have only one program or system capable of registering any given images, using only such information as could be provided automatically. This idea will be addressed later.

These *panoramic,* low frequency distortions are not the only form of deformation contained within airborne scanner data. Far more difficult to characterise and correct for are the higher frequency distortions introduced by:

- o terrain relief (medium to high frequency) and
- o perturbations in the flight path of the aircraft caused by:
  - air turbulence causing roll and pitch variation;
  - drift of flight heading;
  - aircraft vibration.

The low flying heights involved in the collection of airborne scanner data mean that relatively small terrain height variations (on the order of tens of metres) can introduce distortions at least as severe, if not more so, than the characteristic sensor distortion itself (see Table 1.) For nadir viewing instruments this distortion will be across-track only (the *Y*-direction), but for along-track tilting instruments the distortions will also be seen along-track (the *X*-direction.) These distortions cannot be modelled *exactly* without recourse to a Digital Elevation Model (DEM) of similar or higher resolution than the scanner data itself. Some interpolation from slightly lower resolutions would probably be acceptable if a technique such as Kriging [Davis, 1986, Clark, 1979, Day, 1991] was used with a full directional semi-variogram analysis. However, since we are talking of pixel resolutions at the 1-5 metre scale, even DEMs of slightly lower resolution are neither likely to be easily available, nor cost-effective for a photogrammetric operative to produce manually. [Muller *et al*, 1991, Zemerly *et al*, 1992] have performed some work into the automatic production of Digital Elevation Models from aerial photography (DEMs) at these resolutions, but have not yet demonstrated reliable enough results over vegetated canopies, the likely scene content of many directional scanner images.

High frequency distortions resulting from irregularities in the motion of the aircraft, usually due to air turbulence, exhibit themselves as unpredictable localised perturbations acting over a few scan lines, the actual severity of which depend upon the damping characteristics of the aircraft and the amount of turbulence. Examination of the nature of these high frequency distortions by various authors [Kindelan *et al*, 1981, Irons *et al*, 1992, Teillet *et al*, 1990, Bernstein and Hanson, 1983] has lead to the conclusion that it is possible to model neither the flight path of the aircraft nor the resulting image distortions with a low order polynomial. Higher order polynomials are unreliable, and simply do not have the capacity to model the unpredictabilities of turbulence-induced motion.

4. An 'Ideal' Image-Image Registration System

An ideal image to image registration system would conform to at least the requirements stated below. Here, for ease of nomenclature, the reference image will be called the ***base*** image, and the image which is to be registered to the *base* the ***distorted*** image. The requirements are:

- For each pixel in the *base* image within the overlap of the two images, a 1:1 mapping should be found between it and its unique conjugate position in the *distorted* image;
- The error on this mapping should be less than the uncertainty in pixel position within the original image - ie subpixel accuracy to a precision of better than 0.5 (or more realistically 0.3) pixels is required);
- Resampling should maintain data integrity as far as possible, but the actual technique should be variable depending upon requirements (eg. nearest neighbour, bi-linear etc.);
- The techniques used should be equally applicable to all types of imagery and all sensors, and any combination thereof;
- The techniques should require the minimum amount of manual intervention/assistance;
- The techniques should *require* little, or ideally no *a-priori* information;
- The system should have the flexibility to incorporate *a-priori* data if it is useful and available (ie registration of extreme images in stages, using images at less extreme angles to each other for interim registration);
- The system should provide some form of estimate of the accuracy of registration and possibly the quality of resampling of each pixel;
- The system should operate on a timescale of minutes, or a few hours at most for a 512 x 512 pixel scene.

5. Previous Registration Techniques

Previous work towards the registration or geocoding of imagery has usually relied on one (or occasionaly two) of four methods:

i) a polynomial description of the scene distortions (bi-variate polynomial warp surfaces) - ground control points (GCPs) or tie points are located in the image to be corrected and the registration *base* source. A polynomial warp, usually of low order (eg. quadratic or cubic) is then fitted to these points and used to warp the *distorted* image into the *base* image or map;

ii) a panoramic correction of the scene, removing the inherent sensor distortion. Usually accomplished through some fairly simple geometry and resampling, or a low order polynomial warp [Kindelan *et al*, 1981];

iii) a description of the flight path variations, usually polynomial based - the position and attitude of the aircraft are continually recorded throughout the scene acquisition time. These are later used to model the position and attitude of the sensor scan head for each line of the final image, and thus to model and remove any resulting distortions one scan line at a time - potentially a very accurate technique [Kindelan *et al*, 1981, Teillet et al, 1990, Nwosu and Muller, 1992];

iv) the availability of a Digital Elevation Model (DEM) of the scene contents to remove terrain effects at the same time as registering the image to a set of ground control points. Often techniques relying on DEMs still use a polynomial based resampling scheme to resample small areas rather than resampling each pixel individually. [Teillet *et al*, 1980, Guindon *et al*, 1980,].

To address these points briefly before discussing their results, i) will attempt to correct all the distortions found in airborne scanner data in one go, and will therefore give poor accuracy for terrain with any relief and imagery with along-track high frequency distortions. ii) will resample all pixels across-track to the same ground size, and if the ground speed of the aircraft is known, along-track as well. It will not remove distortions due to variations of flight path of the sensor platform. Neither will it remove terrain relief distortions. iii) has the potential to remove high frequency flight path variation distortions. Coupled with ii) it should yield better accuracy than i) alone, although attitude and position measurements are required to at least the frequency of the flight path variations. It will not remove terrain effects. iv) has the potential to remove all distortions from the imagery if the DEM is at the resolution of the individual scan line pixels or higher, and if each pixel can be positively identified in the DEM. In practice a set of control points is found from the DEM and identified in the image. A polynomial warp is either fitted to these points, or they are used to model the flight line of the aircraft and this model then used to obtain a height from the DEM for each pixel in the image. Accuracy is therefore limited by the flight line modelling and the accuracies of both the projection into the DEM and the DEM itself. Method iii) may be combined with method iv) in cases where a sparse DEM or low frequency INS is available to yield better results than from either method alone.

Those authors using method i) have generally concluded that low-order polynomials are inadequate for modelling the type and combination of distortions present in airborne multi-spectral scanner data. Errors at points other than those used to calculate the polynomial are often in the tens of pixels range, comparable to the distortions introduced by terrain [Kindelan *et al*, 1981, Guindon *et al*, 1980]. Experiments using higher order polynomials have been performed, but require a dense set of GCPs well distributed around distorted and distortion-free areas alike. This is a tedious and time-consuming task, often very difficult at high spatial resolutions with available scale maps or DEMs. Experience has shown that such polynomials are still inadequate to describe most examples of multi-spectral sensor imagery, and in fact are highly unreliable away from the control points. In general it seems that polynomials are not capable of modelling the general case of airborne scanner distorted data, even with a large, well distributed set of tie points.

In an attempt to avoid both the problems of polynomials and the requirement for many manually selected tie points, [Devereux *et al*, 1990] developed a production system, largely with ATM imagery in mind, based on a technique involving the Delaunay triangulation of a few initial manual GCPs. The centre of these triangles is calculated and the ground coordinates at each vertex (original control point) linearly interpolated to this point. Each point produced in this manner is then added to the GCP list, to produce a set of *augmented* control points. The triangulation and interpolation is then repeated until the area of each triangle passes below a certain threshold, the intention being to compute a surface composed of many small linear facets describing the distortions present within the image. This assumes, though, that the initial GCPs are sufficiently dense and well distributed that a simple linear interpolation will describe the distortions between them. As has been noted typical high frequency distortions act on the scale of a few scan lines and are highly non-linear. Thus the initial set of GCPs would have to be distributed at intervals of a few scan lines along track and a few pixels across track for this method to work to its full potential - ie the triangle area threshold should be satisfied on the first iteration, the size of the triangles being of the order of the highest frequency distortions. In such a case the method would become analagous to correction using a DEM. With realistic numbers of manual GCPs, though, performance would be expected to be similar to that of a low-order polynomial rectification, possibly yielding better results for flat terrain. With large numbers of GCPs (but not approaching DEM numbers) this piece-wise linear approach would be expected to be better behaved than a higher order polynomial, but still could not describe the high frequency distortions accurately. [Barnsley *et al*, 1990] report performance similar to polynomial rectification using an early version of the software [Devereux *et al*, 1990], finding field boundary flexure even where the four corners of the field were supplied as GCPs.

Panoramic correction has been described and implemented by [Kindelan *et al*, 1981]. They concluded that the method in itself was not accurate, but in combination with a correction based on positional and attitudinal monitoring of the aircraft during flight was capable of accuracies of around 3 pixels for ATM type scanner data.

Experiments using DEMs as a reference for the correction have provided some of the most accurate registrations to date, but the accuracy varies with the use of the DEM - ie whether it is used to augment details of the in-flight attitude monitoring through selection of a few GCPs or whether it is actually used as a dense reference set for the registration. The latter technique has generally been used only for satellite data, as these images tend to have resolutions around the 10 to 30 metre mark, corresponding to the sort of resolutions generally found in large DEMs produced either manually by a photogrammetric operative, from map contour digitisation or from SPOT [Day and Muller, 1989, Muller, 1989a]. Accuracies of either technique tend towards standard deviations of a few pixels [Guindon et al, 1980, Teillet et al , 1980, Teillet et al, 1990].

These severe difficulties involved with *fully* and accurately registering or geocoding distorted airborne scanner data have therefore lead many authors to either:

i) ignore the registration problems and to work as if their data sets were registered by manually extracting corresponding areas from various scenes;

ii) to perform a simple polynomial correction and accept the inaccuracies which inevitably result from poor registration, or

iii) to tailor their research to avoid problems where registration or geocoding might be necessary.

Although the registration system proposed here is not simple, it does have the benefit of being largely automated, and should therefore provide accurately registered data sets with the minimum of manual effort. Once an entire data set is registered the task of extracting common areas from the multitude of different angular and/or spectral images involved becomes trivial; one need only find the image coordinates of the area of interest in one imge, and then that area will be at the same coordinates in all of the remaining scenes. Indeed complete registration would enable fully automatic multi-dimensional segmentation and analysis of entire scenes with ease, removing a large burden of image manipulation from the human operator.

Imagery	# Interest Points	# good tie points	# bad tie points	# iterations	% good points
KFA / KFA	9984	237	0	1	100
Aerphoto/ATM	750	37	0	3	100
Aerphoto/ registeredATM	500	106	0	6	100
ASAS / ASAS	1000	175	0	1	100
ASAS / ASAS	800	121	0	1	100
ASAS / ASAS	800	169	0	3	100

Table 2. Recent results of the automatic tie-point generation scheme.

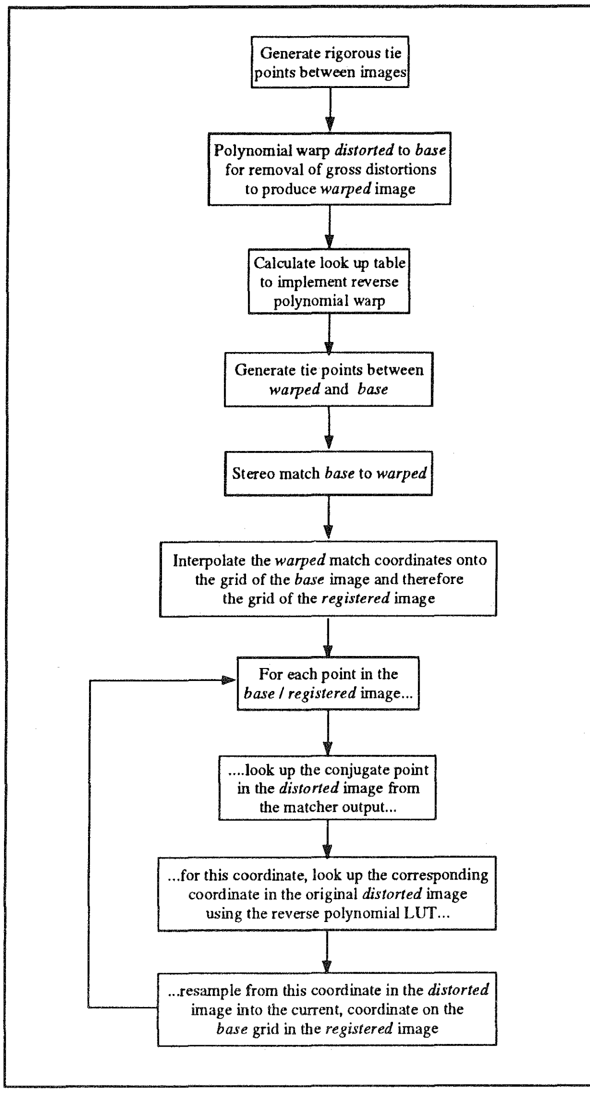


Figure 1. Flowchart of the image to image registration process.

6. A Rigorous Registration Technique Based on Per-Pixel Image Correlation

A registration process is presented which conforms as far as possible to the ideals of Section 4. It also attempts to address the problems of the registration schemes discussed in Section 5.

The novelties of this technique are that it:

i) attempts to register *every* pixel in the overlap of the images;

ii) works entirely in image space and therefore requires no ground control tie points;

iii) Requires no *a-priori* information (other than, at present, an intial approximate estimate of the overlap offset between the images.)

This technique is not intended for the registration of images to maps *per se*, but may be registered to map coordinates through

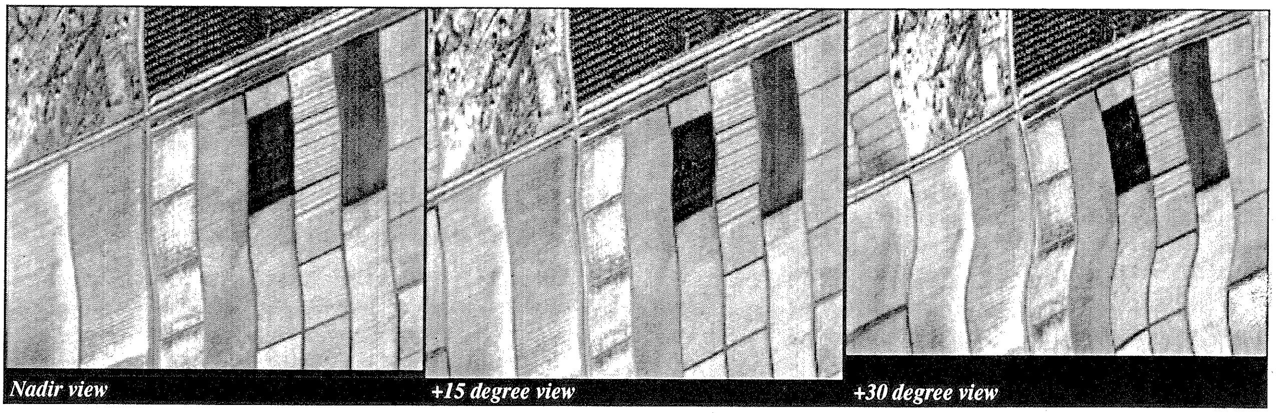


Figure 2. Raw ASAS Images of Maricopa, Arizona (band 21)

the use of an orthoimage. [Allison *et al*, 1991 and Muller *et al* 1991] discuss the production of orthoimages at high resolutions automatically from aerial photography, but their process is vulnerable to the same errors in DEM production over vegetated canopies noted earlier.

7. The Registration Technique in Detail

As before, the terms *base* and *distorted* will mean respectively the orthoimage, or reference image, and the image to be registered to it. *Warped* will be used to refer to the polynomial semi-corrected intermediate image stage. *Registered* then refers to the final image, registered to the *base* image. Figure 1 shows a flowchart of the methodology involved.

The first stage of the registration process is to generate a reliable set of tie points between the *base* and the *distorted* images, every one of which must be correct to within a few pixels. This is performed automatically (apart from the initial very approximate estimate of the overlap between the images) using the Foerstner interest operator [Foerstner, 1986, Foerstner and Gulch, 1987] based tie point generator previously described in [Allison *et al*, 1991]. Since that description the recursive surface-fitting tie point refinement suggested as further work has been implemented, largely to improve the reliability for images where no camera modelling or scene location information is available (or is not used.) Table 2 summarises some of the new results achieved using this procedure - all results took less than 5 wall-clock minutes to generate for images sized around 512 x 512 pixels on an unloaded Sun sparc 2 workstation. For image types such as ASAS, where the header information contains details of the relative scene centres and pointing angles, the initial loose estimate of image overlap could easily be automated. This should also be possible for image types with little or no header information, using the image data alone, and will be investigated more completely at a later date.

Once a reliable tie point set has been generated between the *base* and *distorted* images, the *distorted* image is warped using a quadratic polynomial to remove gross distortions (the 'removal' being relative to the *base* image, of course.) A further set of tie points is then generated fully automatically between the resulting *warped* image and the *base* image. A look up table (LUT) of pixel coordinates is created based on the quadratic polynomial transformation such that for each pixel in the *warped* image, its original location in the *distorted* image can be found quickly, easily and to the necessary sub-pixel precision. This enables correction of the *distorted* image to the *base* image with one level of resampling, despite the intermediate stage of the *warped* image. The LUT approach was used after investigation revealed that simply swapping the *base* and *distorted* coordinates in order to calculate the reverse polynomial transformation gave rise to inaccuracies sometimes approaching three pixels. The initial warp is necessary to enable the fourth stage of the process, the stereo matching of the *warped* image to the *base* image.

The stereo matcher employed here is the Otto-Chau matcher [Otto and Chau, 1989, Muller, 1989a], developed under the Alvey MMI-137 initiative. This is an Adaptive Least-Squares Correlator (ALSC) based on [Foerstner, 1982], [Ackermann, 1984] and [Gruen, 1985, and Gruen and Baltsavias, 1987] for the patch based correlation of individual points within two images, harnessed within a region growing algorithm to allow the matching to proceed automatically from an initial sparse set of tie points. The ALSC algorithm was chosen for its very high accuracies [Gruen and Baltsavias, 1987]. It works by iteratively geometrically and radiometrically distorting a patch from one image relative to a patch from another until the change in the distortion parameters from one iteration to the next falls below a certain threshold or meets a failure condition. If the threshold constraints are satisfied then the points at the centre of each of the patches are said to have been matched. From the distortion parameters of these points the region growing algorithm can then predict the likely location and parameters of the neighbouring matches. These match candidates are then passed in turn to the central correlator to be matched or rejected and the matched region propogates thus [Otto and Chau, 1989, Day and Muller, 1989, Muller, 1989a].

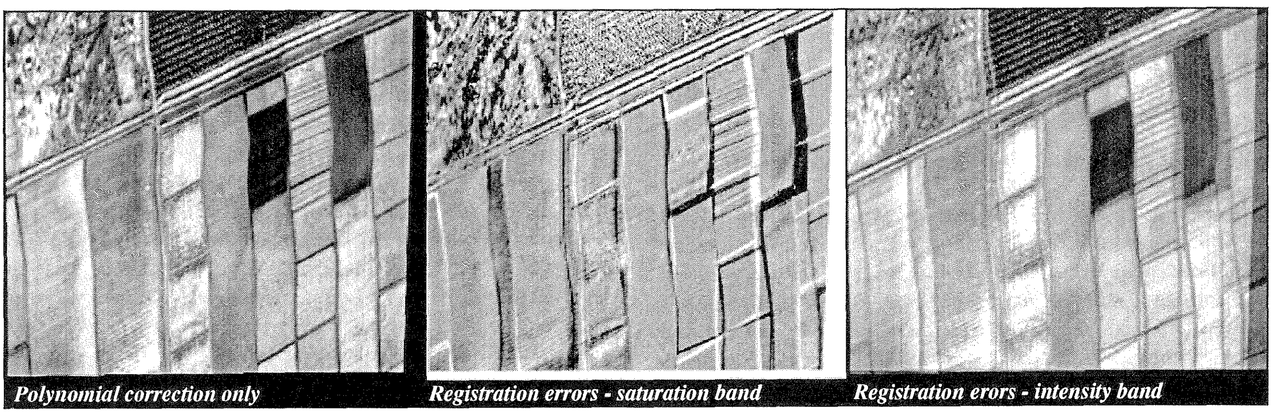
Such a matcher therefore has the potential to locate to sub-pixel accuracy the conjugate point in a distorted image for every point within the mutual overlap of a reference, or base image if the distortions can be described by the distortion model within the matcher. The Otto-Chau matcher currently uses an affine transformation to model the geometric transformation between two image patches. For continuous terrain over small patches this has been shown to be an adequate model for the terrain and sensor distortions present in satellite imagery such as SPOT, Landsat-TM or AVHRR [Day and Muller, 1989, Newton *et al*, 1991, Muller, 1989a], and to a slightly lesser extent to higher resolution (better than 2m) digitised aerial photography [Muller *et al*, 1991a, Allison *et al*, 1991, Zemerly *et al*, 1992]. Being a first order polynomial the affine would not be expected to model the range of expected distortions in airborne scanner data, and experiments have borne this out [Muller *et al*, 1991], hence the distorted image is pre-corrected using the quadratic polynomial described above.

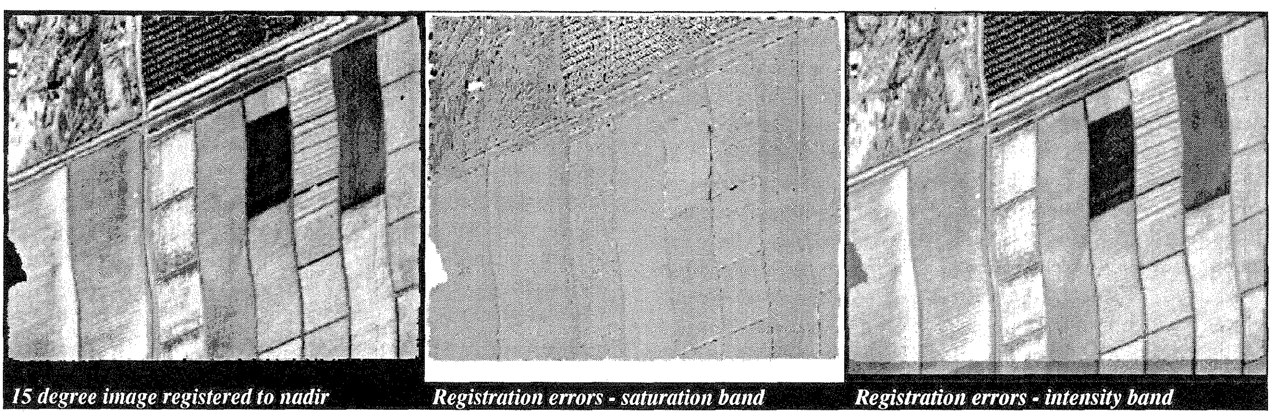
Since the stereo matcher bases its sheet growing in the left image, the output is regularly gridded in left image space, but not in the right. In order to avoid a further level of resampling of the *warped* image, though, which might affect the matching results the *warped* image is generally used as the left, or reference, image in the matching. Therefore the matcher output is regularly gridded in the *warped* image-space and must be interpolated into *base-image* space to enable direct resampling onto the grid of the *registered* image. Kriging is curently used for this purpose, but is very slow, and over the distances being interpolated (typically one pixel or less) may not be significantly more accurate than a simple, fast bilinear interpolation scheme.

Then, for each point (x,y) on the grid of the *registered* image (implicitly the same grid as that of the *base* image) the following procedure is used:

- Find from the stereo-matcher output its conjugate point (x',y') in the warped image;
- Find the corresponding position (x'',y'') in the original *distorted* image from the inverse quadratic polynomial look up table at coordinates (x',y');
- Resample the original *distorted* image grey level value at coordinate (x'',y'') into the output *registered* image, using an appropriate resampling technique for the scale (nearest neighbour, bi-linear, cubic convolution etc.)
- Move on to the next pixel in the registered image and repeat until the registered image is complete.

In this manner a sub-pixel registration is attempted for every pixel within the overlap of the *base* and *distorted* images. The combination of the results of the intermediate stages of the process allows the original raw *distorted* data to be resampled directly into the coordinate system of the *base* image, thus maintaing data fidelity as far as possible.





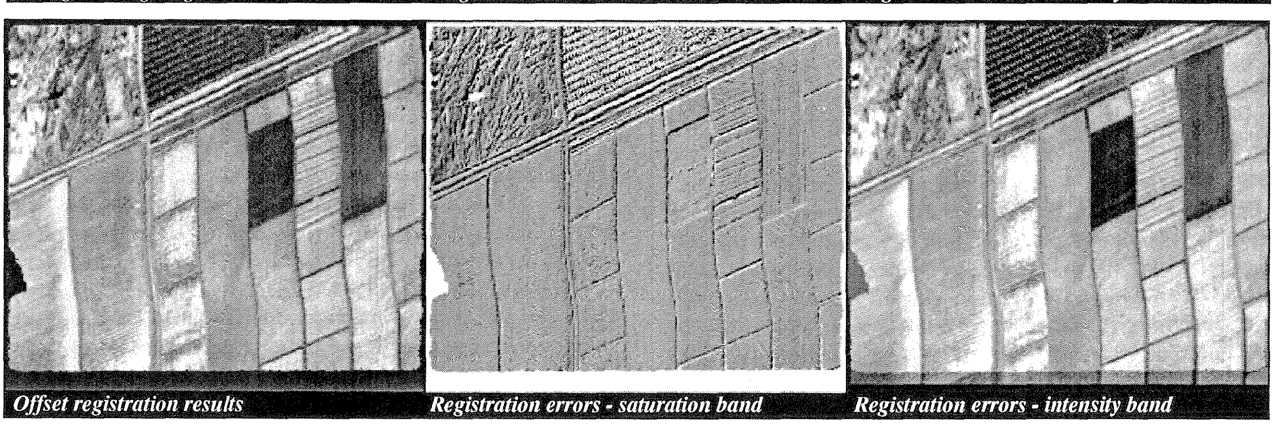
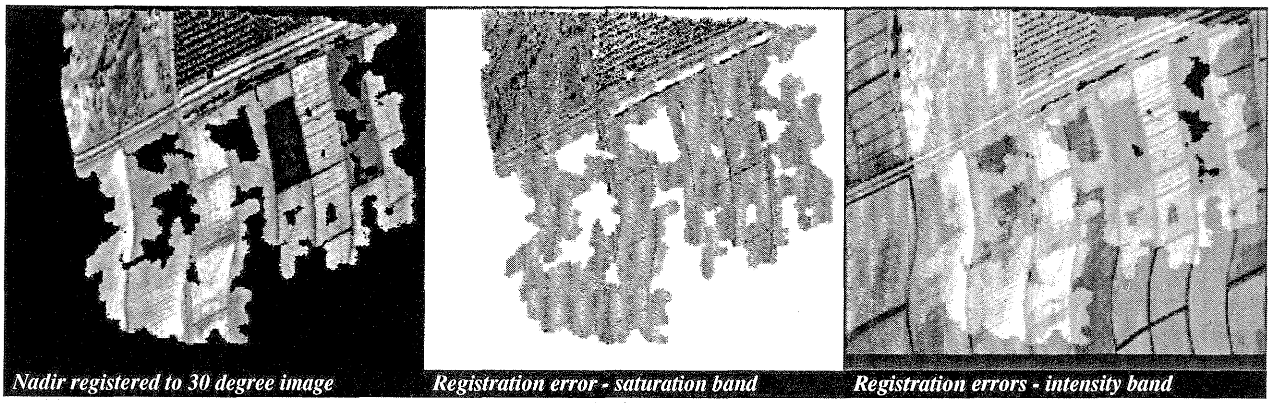


Figure 3. Registration errors for polynomial correction of+15° ASAS view to nadir view (band 21, Maricopa site.)

Figure 4. Errors on full registration of +15° ASAS view to nadir view using the technique presented in this paper.

Figure 5. The effect on the errors of shifting the *registered* data of Figure 4 one pixel down and to the right.



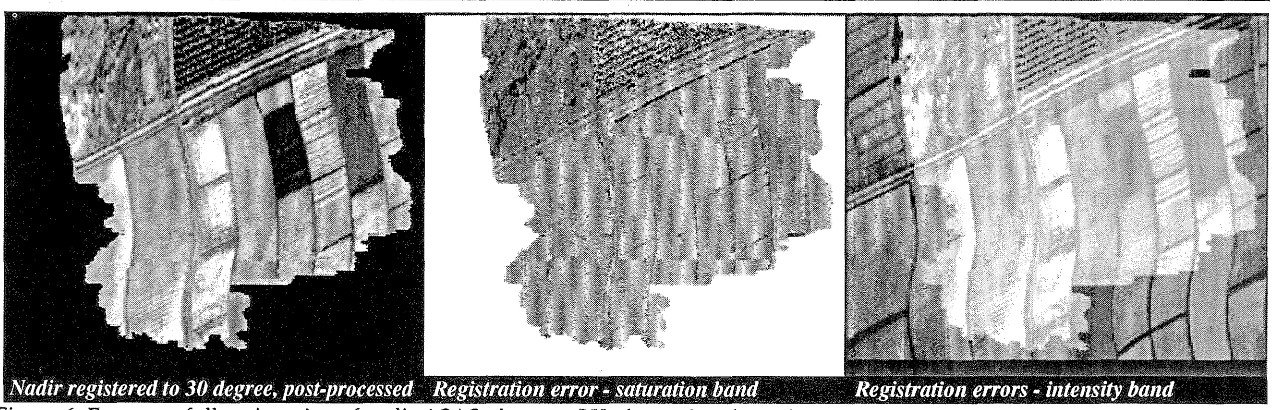


Figure 6. Errors on full registration of nadir ASAS view to +30° view using the technique presented in this paper.
Figure 7. The registration of Figure 6 post-processed to fill in missing data.

8. Results

Results of the registration of various ASAS look angles to each other have been chosen to illustrate typical results from this registration technique, as the registration of scanner data to scanner data represents one of the most difficult problems for a registration system, as the distortions are unlikely to be correlated. Figure 2 shows raw ASAS band 21 (730.6 - 746.3nm) data for three look directions (nadir, +15° and +30°) of a flight over a cotton and bare soil site at Maricopa, Arizona, U.S.A. Each frame contains between 420 and 450 scan lines, depending on the look angle, with 512 samples per scan line. The severe distortion of this imagery is apparent from the curvature of the field boundaries, especially in the +30° frame.

In order to display any registration errors/accuracies using monochrome imagery a variation on the standard technique of an RGB composite of the erence and registered images has been employed. A three band RGB image was assembled using the *base* image as the red channel and the *registered* image for both the green and blue channels, and then transformed to Hue - Saturation - Intensity (HSI) space. The saturation and intensity bands have been found to be particularly indicative of any registration errors.

Figure 3 illustrates the results of attempting to register the +15° view to the nadir view using a quadratic polynomial calculated from 45 automatically generated tie points (all correct.) The registration errors are clearly visible in both the saturation and intensity images: In saturation the black field boundaries correspond to the *base* nadir image and the white boundaries the *registered* +15° data. These boundaries are clearly not coincident.

Figure 4 is the result of the registration using the techniques presented in this paper. Note that the saturation image contains far less information than for the polynomial correction, whilst the field boundaries are now fully coincident in the intensity image. Areas outside the overlap of the images and of failed registration appear white in the saturation image.

Figure 5 illustrates the effect when registration errors are deliberately introduced by shifting the *registered* image one pixel down and to the right and re-computing the HSI transformation. The field boundaries clearly separate into black and white components, giving the scene an almost three-dimensional structure, as if it were lit from below. The difference in the intensity image is harder to see, but on a workstation screen it is blurred compared to the intensity image before the offset. This trend to blurring becomes clearer with larger offsets until the offset is large enough to totally separate objects within the scene, after which the effect shown in the polynomial correction results dominates.

9. Accuracy of the Results

Limited experiments have so far been performed to assess the absolute accuracy of this registration technique. Visual 'blinking' between the *registered* and *base* images on a workstation screen indicates that, apart from a few minor regions of blundering, the registration is accurate to at least the pixel level. Results from other ASAS data sets, ATM to ATM registration and ATM to aerial photograph/orthoimage registration support this assessment. Comparison of edge detected versions of the *registered* and *base* images using sub-pixel techniques such as those of [Canny, 1983] has so far provided insufficient information to quantify sub-pixel accuracies.

A brief analysis of the image grey levels for a number of fields within the Maricopa +15° image before and after registration to the nadir view has been performed to check that data fidelity is maintained as far as possible by registration. Table 3 and Figure 8 indicate that the grey level statistics of the images are changed little by the registration process, the histogram distribution remaining largely stationary and the variance remaining constant to at least 2.7%, a satisfactory invariance. (In fact this figure is somewhat inflated due to the difficulties of locating exactly the same subset of pixels in the registered and raw data for comparison - illustrating the errors introduced when accurate registration of data sets is not performed.) This maintenance of grey level distribution and quality is vital to the accurate measurement of the spectral and angular properties of the images after registration.

Further experimentation is necessary before any real conclusions can be drawn about the accuracy of this technique, but it seems likely that geometrically the system will be good to better than a one pixel error at least, and would be expected to approach the accuracies claimed for the stereo matching technique (significantly less than 0.5 pixels, [Otto and Chau, 1989], or perhaps even less than 0.1 pixels [Upton, 1990].) Radiometrically the process is likely to be no worse than any other resampling scheme, involving as it does only one level of resampling.

	section 1		section 2		section 3		section 4		section 5	
	Raw	Reg.	Raw	Reg.	Raw	Reg.	Raw	Reg.	Raw	Reg.
Mean	45.03	45.05	90.28	90.18	57.01	57.06	99.46	99.55	94.67	94.54
Var	10.13	10.32	8.77	8.84	538.8	534.7	11.29	10.9	94.21	94.95
Max	67	67	100	100	126	125	151	151	134	137
Min	38	38	80	80	12	12	47	47	34	34
N	3570	3696	6016	6500	7566	7568	2420	2322	22022	22230
Δvar%	1.87		0.80		-0.75		-2.65		0.79	

Table 3. Alteration of image grey level statistics by the registration process for five areas of a registered scene.

10. Limitations of the Technique

Since a large portion of the registration process presented is concerned with area based image correlation, images, or areas of images exhibiting extreme geometric or radiometric distortion or low image texture will fail to match and therefore will not be registered [Gruen, 1985, Day and Muller, 1988, Otto and Chau, 1989]. This is apparent from the holes of varying size seen in the registration results in Section 8. Where the problems are global to the imagery rather than just an isolated highly directionally reflecting area and we have a sequence of angular images, the registration of extreme angles may be approached in steps, using the interim angles. For instance, to register a +45° ASAS image to nadir it is sometimes necessary to register the +45° to the +30° look, and the +30° look to nadir, then couple the resulting distortion descriptions to register the +45° to nadir. Direct registration in these cases has tended so far to produce patchy and sometimes incorrect results (large numbers of blunders.)

Where the radiometric or geometric extreme differences are local, or where the stereo matcher simply converges to the wrong solution (*blunders*) isolated holes tend to result, or sometimes areas of mis-registration. These must be detected and either filled in, deleted or marked as containing no data in the accuracy estimates. A post-processing filter is currently under development to address this requirement, based on an analysis of the continuity of the distortion disparities along each scan line within the registered data. This makes use of the facts that, except for genuine scene discontinuities, the distortion along a scan line is continuous, and that there are no high frequency distortions within single scan lines (or if there are, as may be the case with whiskbroom data, they are likely to be small given the scan line integration time, and therefore continuous.) Therefore, discontinuities are detected, deleted and then any holes surrounded by a good distribution of data are polynomial interpolated (and here we are relying on the continuities to provide a relatively low-order polynomial *along* the scan line.) Data is not extrapolated into holes at the edges of the data, as this is considered unreliable.

An initial result from the prototype of this post-processing is presented in figure 7 for the incomplete ASAS Maricopa 30° to nadir registration. No estimate has yet been made of the errors involved with this post-processing. This will be performed by removing sections from accurately registered lines, filling in the resulting holes with the post-processing algorithm and comparing the results with the original true registration results. Initial visual inspection of both the interpolated image grey levels and the interpolated distortion disparity maps look promising, though.

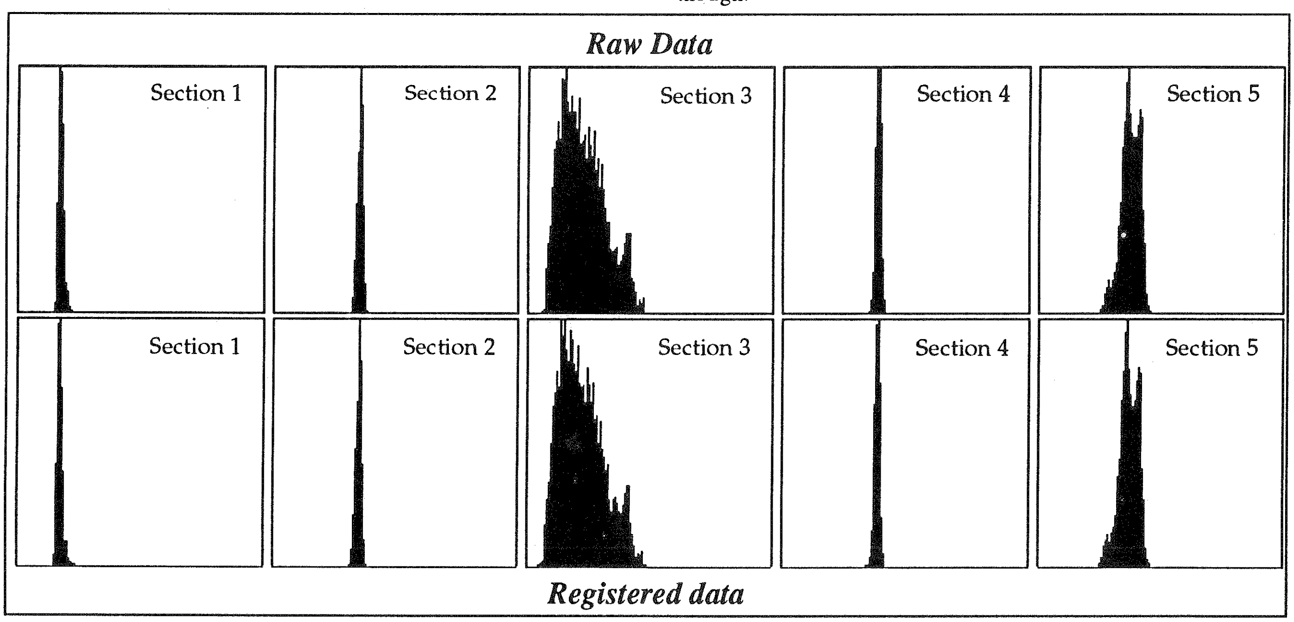


Figure 8. Image section grey level histogram distributions before and after registration to nadir.

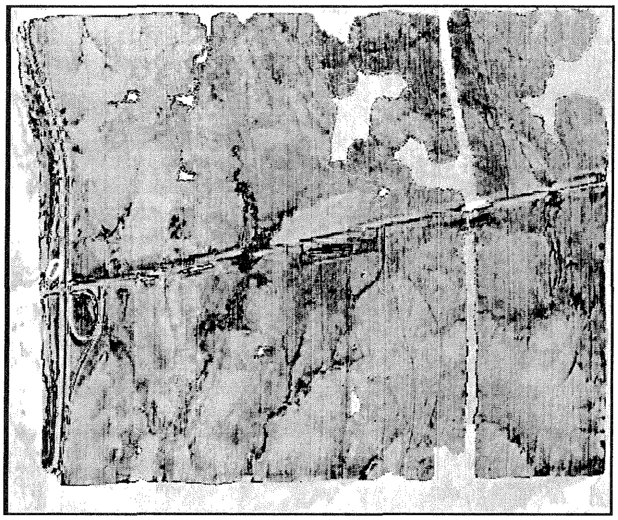


Figure 9. Extraction of angular and atmospheric effects from registered ASAS data of Konza Prairie, Kansas.

11. Extraction of Angular Information

Figure 9 is the result of subtracting an ASAS +30° band 8 image (541.9 - 556.3nm) from the corresponding band 8 nadir image to which it has been registered. No further analysis has been performed, but the clear presence of residual image intensity data indicates that angular information and/or atmospheric scattering is present and may be extracted from registered scenes, thereby allowing analysis using different surface and atmospheric scattering models. This is of great potential use for improved segmentation of such images, and thus for the monitoring of local environmental change over a period of time.

12. Use of Registration Results for Distortion Frequency Analysis

Since the technique presented here potentially registers every pixel within the overlap of two scenes, if a multi-spectral, multi-directional image is registered to an orthoimage then the coordinates calculated for the resampling may be used to produce a relative disparity map of the scene distortions, not just for every scan line, but for every pixel. Analysis of such a distortion disparity map as a function of scan line number could determine the frequency of Inertial Navigation System (INS) sampling and/or laser gyroscope records required to reconstruct sufficiently accurately a flight line so as to enable full scene correction using a camera model. Such a camera model is currently under development by [Nwosu and Muller, 1992], and would provide a faster and more robust system for rectification of pushbroom airborne scanner imagery.

It is even possible that a study of the scan line distortions at a higher frequency than the INS sampling rate may allow some modelling of the response function of the aircraft to turbulence and buffeting, and therefore provide a knowledge-based method of interpolating the INS to higher, more useful frequencies. As an example, the ASAS scanner aquires 48 scan lines per second [Irons *et al*, 1992], and has a primary INS sampling rate of once per second with a supplemental subset of this data five times per second - ie once every 10 scan lines or so [NASA C-130 Handbook]. If we assume that the highest frequency distortions act over one to two scan lines then aircraft position and attitude must be sampled twice within this period in order to attain the Nyquist sampling frequency for full information reconstruction. This is five times the current sampling rate; any *reliable* method of narrowing this sampling gap without having to spend millions of dollars on new INS and GPS systems would therefore be very desirable.

An example of a distortion disparity map is shown in Figure 10, for the registration of two ASAS look angles (+15° to nadir.) The distortions shown actually represent the superimposition of two scenes, but nevertheless illustrate the principle under consideration. A full frequency analysis will be conducted at a later date for properly geocoded images.

13. Incorporation of Other Information

As mentioned earlier, this work forms part of a general automated large scale environmental monitoring system. Other aspects of the work involve the generation of high resolution (less than 2m) DEMs from aerial photography [Zemerly *et al*, 1992], the production of orthoimages from these DEMs and the camera modelling of the flight lines of aircraft using aircraft Inertial Navigation Systems and automatically generated tie points [Allison *et al*, 1991, Muller *et al*, 1991, Zemerly *et al*, 1992, Nwosu and Muller, 1992]. All this information is potentially of great use in a registration scheme, and will eventually be incorporated into the current technique as optional inputs.

Yet another input could be provided by the use of the multi-spectral version of the Otto-Chau stereo matcher [Zemerly et al, 1992, Upton, 1990] for images with inherently sub-pixel co-registered spectral band data. In this case the radiometric distortion parameters of the image patches are minimised n-dimensionally (where n is the number of spectral bands,) thus providing a more stable solution, although in this case parallel processing may be required in order to achieve the desired rates of performance.

14. Future Work

Future work on this system will include:

a) A full eror analysis of the results to date to establish the true accuracy of the technique. One method employed may be to artificially distort an orthoimage using the distortion disparity map obtained from the registration of a scanner image, then to attempt to recover the original orthoimage using the registration process;

b) To improve the reliability of the stereo matcher over surfaces imaged at high resolutions. Currently the prevelance of discontinuities and regularised patches of texture in vegetated canopies causes problems in convergence on the correct solution [Muller *et al*, 1991, Otto and Chau, 1989,

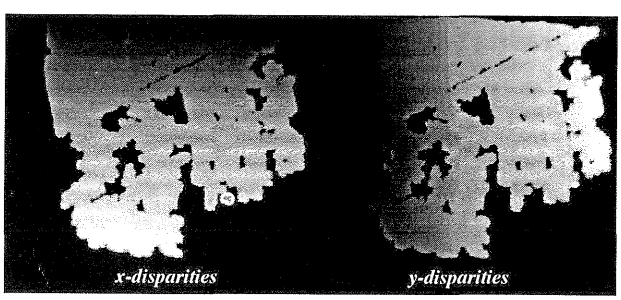


Figure 10. Distortion disparity map for registered ASAS data.

Day and Muller, 1988, Gruen, 1985];

c) To continue the development of the post-processing filter for the registration results by increasing the flexibility of the distortion model along scan lines;

d) To use INS data, header information or a robust, fast global image matching method to automate the initial manual estimate of image overlap;

e) To develop the system so as to be able to incorporate external information from camera models, INS and DEMs;

f) To fully automate the process, including the use of external information.

15. Satellite Applications

The technique of using the Otto-Chau stereo stereo matcher for image registration purposes is not new; it has been in use for a number of years at UCL for accurately registering Landsat Thematic Mapper images to SPOT orthoimages [Pearson, 1991, Newton *et al*, 1991]. The SPOT orthoimages are themselves created using the Otto-Chau matcher to stereo-match two overlapping SPOT scenes [Day and Muller, 1989, Muller, 1989], and the resulting disparity information is passed through a model of the SPOT sensor to convert the pixel disparities to ground coordinates [O'Neill, 1991]. The reverse of this camera modelling may then be used to resample either SPOT scene into ground coordinates, hence creating an orthoimage. This technique addresses the conclusions of [Bernstein and Hanson, 1983], who achieved a maximum error of 1.88 pixels using polynomial resampling, but concluded that in areas of large terrain elevation differences local mappings may be necessary.

There is no reason, then, why this registration technique, or elements thereof, need not be applied to satellite data of all kinds, such as the forthcoming MISR, MODIS and HIRIS EOS-A instruments [Muller, 1992]. Indeed, a modified version of the tie point generation is currently in use for automated AVHRR mosaicing [Newton *et al*, 1992, Mandanayake, *et al*, 1992].

CONCLUSIONS

An image to image registration system designed to require the minimum of manual input has been described, and initial results presented. The registration is capable of rectification of data to ground coordinates through the use of an orthoimage, and has demonstrated the capability to directly register different look angles of multi-directional data to each other without transformation to a separate reference coordinate system.

The results appear to indicate that successful registration is accurate to at least a pixel; further analysis is required in order to quantify the sub-pixel precision expected through the use of the stereo matcher. Where the registration fails, usually due to severe radiometric differences between the images or lack of image texture, a method of predicting the registration parameters based upon local information at the level of the individual scan lines has been proposed. Again initial results have been presented which are encouraging.

It has been shown that a registration technique accurate to the pixel or beyond is capable of extracting a dense along-track and across-track map of any distortions in the data. Analysis of the components of these distortions may be useful in using and interpreting the information from Inertial Navigation Systems with a lower sample rate than scan line acquisition rate. Such information would then be used to achieve one of the aims of this work, to incorporate a camera model for pushbroom airborne scanners in order to achieve a quicker, more robust solution to the problems of geo-coding and registering airborne scanner data.

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REFERENCES

Ackermann, F., 1984, Digital Image Correlation: Performance and Potential Application in Photogrammetry. Photogramm. Rec., 11(64): 429-439 (October)

Allison, D., Zemerly, M.J.A., Muller, J.P., 1991, Automatic Seed Point Generation for Stereo Matching and Multi-Image Registration, *Proceedings International Geoscience and Remote Sensing Symposium*, Helsinki, Finland, June 3-6 1991 (IEEE Catalogue 91CH2971-0)

Barnsley, M.J., 1984, Effects of Off-Nadir View Angles on the Deetected Spectral Response of Vegetation Canopies, *IJRS* 5:714-728

Barnsley, M.J. and Morris, K.P., 1990, On the Relative Utility of MODIS-N/T, HIRIS and MISR for Sampling the BRDF of Earth Surface Materials, Proc. Conf. on Remote Sensing and Global Change, University College Swansea, 19-21 Sept. 1990, pp 19-30

Barnsley, M.J. , Morris, K., Reid, A., 1990b, Preliminary Analysis of a Multiple-View-Angle Data Set, *Proc. NERC Airborne Remote Sensing Campaign*, BGS, Keyworth, O.K., 49-68

Barnsley and Muller, 1991, Meaksurement, Simulation and Analysis of the Directional Properties of Earth Surface Materials, *Proc. 5th Int. Coll. on Spectral Signatures*, Courcheval, France, 14-18 Jan 1991

Bernstein, R., Hanson, W.A., 1983, Analysis and Correction of Landsat 4 & 5 Thematic Mapper Sensor Data, *IBM Corp., Palo Alto Scientific Centre.*

Canny, J.F., 1983, Finding Edges and Lines in Images, MSc Thesis, Dept. of Elec. Eng. and Comp. Sci., Massachusetts Institute of Technology, 146 pp

Clark, 1979, Practical Geostatistics , London & New York, 1st edition,1979. 129 pages.

Davis, J.C., 1986, Statistaical Data Analysis in Geology, Second Edition, Pub. Wiley, 1986

Day, T., 1991, Kriging : 4300, *UCL P&S Internal Report*, Unpublished

Day and Muller, 1988, Quality Assessment of Digital Elevation Models Produced by Automatic Stereomatches from SPOT Image Pairs, *Int. Arch. Potogramm. and Rem. Sens.*, 27(3), 1988

Day and Muller, 1989, Quality assessment of the Otto-Chau stereo-matcher for SPOT imagery, *Mmi137final report*, Department of Photogrammetry and Surveying, UCL.

Devereux, Fuller, Carter and Pursell, 1990, Geometric Correction of Airborne Scanner Imagery by Matching Delaunay Triangles, *Int. J. Remote Sensing*, vol 11 no 12 1990, pp 2237-51.

Diner, D.J., Bruegge, C.J., and Martonchik, J.V., 1990, The Multi-Angle Imaging SpectroRadiometer(MISR) for the Earth Observing System, *IEEE Geosc. and Rem. Sens. Soc. Newsletter*, Sept. 1990

Dowman, Coyle and Ward, 1987, Geometric Correction of Airborne MSS Data, *NERC Research Contract G60/66/09 Report* (unpublished)

Foerstner, W., 1982, On the Geometric Precision of Digital Correlation, *Int. Arch. Photogramm.*, 24(3), 176-189

Foerstner, W., 1986

Foerstner and Gulch, 1987, A fast operator for detection and precise location of distinct points, corners, and centres of circular features, *ISPRS Intercommission Workshop*, Interlaken, 1987, p281-305

Goetz, A.F.H. and Herring, M., 1989, The High Resolution Imaging Spectrometer (HIRIS) for EOS, *IEEE Trans. Geosci. and Rem. Sens.*, GE-27, pp 136-144

Goetz, A.F.H., Vane, G., Solomon, J.E., Rock, B.N., 1985, Imaging Spectrometry for Earth Remote Sensing, *Science*, 228:1147-1153

Gruen, A.W., 1985, Adaptive Least Squares Correlation: A Powerful Image Matching Technique., *S. African Journal Of Photogramm, Rem Sens. And Cart*, 14(3), 1982, pp 175-187.

Gruen, A.W., and Baltsavias, E.P., 1986, High Precision Image Matching for Digital Terrain Model Generation, *Intern. Arch. Photogramm.* Vol 26-3/1 pp 284-296

Guindon., B., Harris, J.W.E., Teillet, P.M., Goodenough, D.G., Meunier, J-F., Integration of MSS and SAR Data of Forested Regions in Mountainous Terrain, *Proc. 14th Int Symp. on Rem. Sens. of Environment*, San Jose, Costa-Rica, 1990, pp 1673-1690

Irons, Meeson, Dabney, Kovalick, Graham and Hahn, 1992, A Data Base of ASAS Digital Imagery, *Proceedings International Geoscience and Remote Sensing Symposium*, Houston, Texas, USA

Iron, J R., Ranson, K.J., Williams, D.L., Irish, R.R., Huegel, F.G., 1990, An Off-Nadir Pointing Image Spectroradiometer for Terrestrial Ecosystem Studies, IEEE Trans. Geosc. and Rem Sens, v29, pp 66-74, 1988

Kay, S., 1988, The Application of Multi-Angle Remotely Sensed Image Data in Agriculture, *Upgrading Report, UCL Internal Report*

Kindelan, M., Moreno, V., Valverde, A., 1981, Geometric Correction of Airborne Multispectral Scanner Images, *15th ERIM Conference*, Ann Arbor, 1981, pp 1539-1549

Mandanayake A., Newton A., Tildsley K., and Muller J-P. Automatic Mosaicing of Satellite Images using Global re-Navigation. WG II/3 ISPRS 1992, Proc. XVII ISPRS Congress, Washington, DC, USA, August, 1992.

Muller, J.P., 1989a, Real Time Stereo Matching and it s Role in Future Mapping Systems, *Survey and Mapping 89*, University of Warwick, 17-21 Aprin 1989

Muller, J.P., 1989b, The GENESIS Project: Automated Satellite Image Understanding Systems, *Keynote Address, 15th Ann. Conf. of the Rem. Sens. Soc.*, University of Bristol, 13-15 Sept. 1989

Muller, J.P., 1992, Global mapping products for the NASA Earth Observing System Programme, Invited paper, Special Session 4, XVII Congress, ISPRS, Washington D.C., August 2-14, 1992

Muller, J.P., Allison, D., Zemerly, M.J.A., 1991, Monitoring Environmental Change using Automated Processing of Aircraft Data, *Progress Report (1.10.89 - 31.3.91) for the Leverhulme Trust*, UCL P&S Internal/Sponsor's report

NASA C-130 Earth Resources Aircraft Experimenter's Handbook, Appendix C - C-130 Data Systems Formats.

Newton, A.C., Muller, J.P., Pearson, J.C., 1991, SPOT DEM Shading for Landsat-TM Topographic Correction,*Proceedings International Geoscience and Remote Sensing Symposium*, Helsinki, Finland, June 3-6 1991 (IEEE Catalogue 91CH2971-0) pp 655-659

Nwosu, A.G. and Muller, J.P., Technical Specifications for A Camera Model for the NASA - Advanced Solid State Array Spectroradiometer (ASAS), Proc. *ASPRS/ACSM Convention, "Monitoring and Mapping Global Change"*, Washington D.C., 3-7 August 1992 (in press)

O.Neill, M.A., 1991, A Kinematic Numerical Model for the SPOT-1 Sensor,, *PhD Thesis*, University College London

Otto G.P., and Chau, T.K.W., 1989, 'Region-Growing' Algorithm for Matching of Terrain Images, Image And Vision Computing, 7(2), May 1989, pp 83-94

Pearson, J.C., 1991, TM Orthoimage Generation from SPOT DEMs, *University College London Photogrammetry & Surveying Internal Report*

Pinz, A.J., 1990, A Computer Vision System for the Recognition of Trees in Aerial Photographs., *Workshop on Multi-Source Data Integration in Remote Sensing*, NASA Conference Publication 3099, J.C. Tilton (ed.), 1991 pp 111-124

Salomonson, V.V., Barnes, W.L., Maymon, P.W., Montgomery, H.W and Ostrow, H., 1989, MODIS: Advanced Facility Instrument for Studies of the Earth as a System, *IEEE Trans. Geosci. and Rem. Sens.*, GE-27, pp 145-153

Teillet, P.M., Guindon, B., Goodenough, D.G., 1990 Integration of Remote Sensing Data Sets by Rectification to UTM Coordinates With the Use of Digital Terrain Models, *Invited paper, Commission III, XIV Cong. Int. Soc. for Photogramm.*, Hamburg, 1980

Upton, M., 1990, Design Analysis Stereo Matcher - Otto-Chau Multi Spectral Images WP4100/2/1, UCL Phtogrammetry and Surveying Internal Report, unpublished

Zemerly, M.J.A., Holden, M., Muller, J.P., A Multi-Resolution Approach to Parallel Stereo-Matching of Airborne Imagery, Proceedings XVII Congress, International Society for Photogrammetry and Remote Sensing, Washington D.C., August 2-14, 1992