APPLICATION OF ELASTIC REGISTRATION TO IMAGERY FROM AIRBORNE SCANNERS

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Commission IV, Working Group 4

KEY WORDS: Registration, Distortion, Multispectral, Multitemporal, Change Detection, Digital Orthoimage, Elastic Registration, Airborne Scanner Imagery

ABSTRACT

This paper discusses the application of advanced registration methods to airborne scanner imagery. We investigate an elastic registration approach and other locally adaptive techniques for image-to-map registration which show promising results where conventional global polynomial transformations in general do not suffice.
For most applications in remote sensing, rectification and geocoding is essential for the analysis of image data and subsequent fusion with other data. In our case, we want to overlay multitemporal multispectral image data in order to conduct change detection for monitoring purposes.
Comparison shows that locally adaptive registration techniques based on radial basis functions improve the results significantly when compared to conventional global polynomial transformations. The choice of the radial basis function seems to be of minor sensitivity. AKIMA local quintic polynomial registration is slightly less satisfactory although computationally less expensive.

1. INTRODUCTION

Photogrammetry has studied extensively how aerial photographs can be rectified and converted into orthophotos. Bilinear and second degree polynomial transformation functions have proven useful for aerial photographs. However, multispectral remotely sensed data are often recorded by line scanners which are mounted on airborne platforms. Thus, the process of image formation is not instantaneous but depends on the flight path and the attitude of the instrument. Moreover, the mapping itself cannot be described by a lens camera imaging model. Therefore, the ortho-rectification of scanner recorded images – especially aerial imagery with high spatial frequency distortions – by *global* affine or polynomial coordinate transforms is not satisfactory. It is rather necessary to allow for *local* corrections.

Zhang et al. (1994) have approached the problem of rectifying scanner data by trying to reconstruct the flight path and the sensor orientation, which requires continually recorded comprehensive flight data of the scanner carrying airplane. If such data is not available, corresponding ground control points (GCPs) between image and map must be used for matching.

Considering the above mentioned drawbacks of global polynomial registration of scanner data, Ehlers (1994) used a two step approach: First, a global second degree polynomial transformation is carried out. Second, a registration based on multiquadric interpolation (Hardy, 1971) is performed using a radial basis function $U(r) = r$ of the distance r between the current location and all given GCPs. Ehlers & Fogel (1994) mention thin-plate spline radial basis functions and the lack of comparison to Hardy's multiquadric basis functions.

Conventional global polynomial registration techniques use *approximating* schemes, i.e., they establish a global coordinate transformation function which minimizes the sum of deviations at the given GCPs. In contrast, *interpolating* techniques, such as the one used by Ehlers & Fogel (1994) and those investigated in this paper, map each given source control point exactly onto its respective target control point, and the transformation for all remaining points is determined by a certain interpolation scheme. In comparison to the global polynomial transformations, the interpolating techniques investigated here are locally adaptive, although they can be based on global functions.

In this paper, we investigate the application of a one step elastic registration approach, which allows local rectifications, to multispectral airborne scanner imagery. In this context, 'elastic' means the use of thin-plate spline radial basis functions (Bookstein, 1989), which have been successfully applied to the registration of medical images. The transformation consists of a global affine as well as a pure elastic part, where the pure elastic part is a superposition of the radial basis function $U(r) = r^2 \ln r$. This radial basis function has a sound physical interpretation and is well known from elasticity theory. The coefficients of the global affine and the pure elastic part are determined simultaneously by solving a linear system of equations.

We compare the elastic thin-plate spline registration not only to global polynomial registration, but moreover to HARDY multiquadric and AKIMA local quintic polynomial registration. Multiquadric interpolation (Hardy, 1971) is based on a global function (just as elastic registration) and uses radial basis functions of the type $U(r) = \sqrt{\delta + r^2}$, which we have used with $\delta = 0$ and $\delta = 1$. In contrast, AKIMA local quintic polynomial registration consists of a number of local transformations. Following a Delauney triangulation between the given GCPs, quintic polynomials are fitted locally, forming a piecewisely defined but smooth interpolation surface (Akima, 1978, Wiemker, 1996).

Ground control point registration remains important whenever continuous image flight data is missing. Elastic image registration shows promising results on airborne scanner image data. We see the following advantages of elastic registration over conventional global polynomial methods:

- It allows for local corrections which are necessary due to the non-instantaneous image formation process of airborne scanner data.
- It gives the operator improved interactive control. Single features can be 'pinned down' locally to a forced fit while only negligibly changing the global match.
- Sometimes proper elevation data is missing, e.g. for man-made objects and other objects smaller than the resolution of the digital terrain model (DTM). Distortions resulting from these effects can be 'hand-corrected' locally, again without severely changing the global match.

Registration by control point matching will remain important even though attempts to reconstruct flight path and sensor attitude are made. On the one hand, comprehensive flight data will not always be available, particularly not for already archived imagery. On the other hand, even with reconstructed flight path and sensor attitude, a forced fit of certain control points – particularly for significant features of uncertain elevation – may still be desirable as pointed out in the above items. Therefore, elastic registration as investigated in this paper for airborne line scanner imagery could then be the method of choice.

2. ELASTIC IMAGE REGISTRATION USING THIN-PLATE SPLINES

Within the field of medical image analysis, Bookstein (1989) has introduced an approach for elastic registration of 2D images which is based on thin-plate splines. This approach allows to represent local deformations between two datasets. Originally, thin-plate splines have been introduced by Duchon (1976) in the context of surface interpolation. These splines uniquely minimize the bending energy of a thin plate

$$\iint_{\mathbf{R}^2} (g_{xx}^2 + 2g_{xy}^2 + g_{yy}^2)\, dx\, dy \longrightarrow \min \tag{1}$$

and thus have a sound physical interpretation.

The input of the registration algorithm of Bookstein (1989) is a set of N corresponding point landmarks $\mathbf{q}_i = (x_i', y_i')$ and $\mathbf{q}_i' = (x_i, y_i)$ (analogue to the afore mentioned ground control points) that have been located in both datasets. Given this data an interpolating transformation $\mathbf{f} : \mathbf{R}^2 \mapsto \mathbf{R}^2$ is determined which maps one image to another:

$$\mathbf{x}' = \mathbf{f}(\mathbf{x}) = \begin{pmatrix} f_1(\mathbf{x}) \\ f_2(\mathbf{x}) \end{pmatrix}, \qquad \mathbf{x} = (x, y), \tag{2}$$

while forcing the corresponding point landmarks to exactly match each other. The transformation model consists of a global affine part and a pure elastic part, where the latter one is a superposition of certain radial basis functions:

$$\mathbf{f}(\mathbf{x}) = \begin{pmatrix} a_0 + a_1 x + a_2 y + \sum_{i=1}^{N} w_{1i} U(r_i) \\ b_0 + b_1 x + b_2 y + \sum_{i=1}^{N} w_{2i} U(r_i) \end{pmatrix} \tag{3}$$

where

$$U(r_i) = r_i^2 \ln r_i, \qquad r_i = |\mathbf{x} - \mathbf{q}_i| \tag{4}$$

is the fundamental solution of the biharmonic equation in 2D. Thus, with (3) we have an analytic expression of the transformation between the two images. In the following we assume that N corresponding points $\mathbf{q}_i' = \mathbf{f}(\mathbf{q}_i)$ with $\mathbf{q}_i' = (x_i', y_i')$ and $\mathbf{q}_i = (x_i, y_i)$ in an irregular spacing have been specified. Then, the parameters of the transformation $\mathbf{p}_1 = (a_0, a_1, a_2, w_{11}, ..., w_{1N})$ and $\mathbf{p}_2 = (b_0, b_1, b_2, w_{21}, ..., w_{2N})$ can easily be computed by solving a linear system of equations (using $\mathbf{v}_1 = (x_1', ..., x_N', 0, 0, 0)$ and $\mathbf{v}_2 = (y_1', ..., y_N', 0, 0, 0)$):

$$\mathbf{v}_l = \begin{pmatrix} \underline{\mathbf{X}} & \underline{\mathbf{U}} \\ \underline{\mathbf{0}} & \underline{\mathbf{X}}^T \end{pmatrix} \mathbf{p}_l \qquad l = 1, 2 \tag{5}$$

$$\mathbf{v}_l = \underline{\mathbf{L}}\, \mathbf{p}_l, \tag{6}$$

where

$$\underline{\mathbf{X}} = \begin{pmatrix} 1 & x_1 & y_1 \\ \vdots & \vdots & \vdots \\ 1 & x_N & y_N \end{pmatrix} \tag{7}$$

and

$$\underline{\mathbf{U}} = \begin{pmatrix} 0 & U(r_{12}) & \cdots & U(r_{1N}) \\ U(r_{21}) & 0 & \cdots & U(r_{2N}) \\ \vdots & \vdots & \vdots & \vdots \\ U(r_{N1}) & \cdots & U(r_{NN-1}) & 0 \end{pmatrix} \tag{8}$$

with $r_{ij} = |\mathbf{q}_i - \mathbf{q}_j|$ as the distance between the points $\mathbf{q}_i$ and $\mathbf{q}_j$. Note, that the coefficients of the global affine and the pure elastic part are determined simultaneously, i.e., both parts are computed in one step. For this approach a unique solution exists (i.e., we have no local minima), it is in general numerically well-conditioned (i.e., robust), and also computationally efficient. The approach is invariant under translation, rotation, or scaling of either set of landmarks and it is well-suited for user-interaction, e.g., there are no free parameters that have to be tuned by a user.

With the same scheme as set out above, also transformations using other radial basis functions $U(r)$ can be determined. E.g., analogue to the thin-plate spline function $U(r) = r^2 \ln r$ for the 2D case, the function $U(r) = r$ is the solution for three dimensions.

3. APPLICATION TO EXPERIMENTAL AIRBORNE SCANNER IMAGERY

The image data was recorded by a DAEDALUS AADS 1268 multispectral line scanner during campaigns in 1991 and 1995 over the city of Nürnberg in cooperation with the German Aerospace Research Establishment (DLR), at flight altitudes of 1800 m with a nadir ground resolution of 4.2 m (Fig. 2, top). For our example imagery, the recording of this strip of ca. 2100 m ground distance took about 20 s.

All 10 spectral bands of both raw images have been registered to a map of scale 1:25 000. First, a simple scanner specific panorama correction was applied which accounts for the fact that within each scan line the ground coordinate of the observed pixel varies with the tangens of the scan angle. Then, ground control points between raw image and digitized map were fixed by eye appraisal for both recordings. We specified 17 GCPs for 1991 and 33 GCPs for 1995. The same GCP sets were used for all experiments.

We have implemented six different coordinate transformations to perform ground control point registration:

- Global second degree polynomial transformation (Richards, 1993).
- Bivariate Akima interpolation: after Delauney triangulation between the GCPs, quintic polynomials are fitted locally, forming a piecewisely defined but smooth interpolation (Akima, 1978, Wiemker, 1996).
- Elastic registration with an affine part and the thin-plate spline radial basis function $U(r) = r^2 \ln r$ (Bookstein, 1989).
- Registration with an affine part and the radial basis function $U(r) = r$.
- Pure multiquadric registration with Hardy's radial basis function $U(r) = \sqrt{1 + r^2}$ (Hardy, 1971).
- Multiquadric registration with a prior global second degree polynomial transformation and subsequent Hardy's radial basis function $U(r) = \sqrt{1 + r^2}$.

All these interpolation techniques are used independently for x and y in order to establish the proper coordinate transformation functions as determined by the given GCPs. The resampling of the image reflectance values was done following a nearest neighbor scheme which is strongly recommended for multispectral data sets (Richards, 1993).

The schemes as listed above have been applied for image-to-map registration for the imagery of both years 1991 and 1995 (Fig. 2).

4. CHANGE DETECTION BY PRINCIPAL COMPONENT ANALYSIS

Following a common concept in remote sensing, change detection can be conducted for each spectral band by regression of the reflectances measured at different recording times, in our example $T_1 = 1991$ and $T_2 = 1995$, for each pixel in the registered images (see Fig. 1). Each pixel then produces a point in the two dimensional feature space spanned by the two axes of reflectance for T_1 and T_2. Ideally, with no change present in the scene, all these reflectance pairs should be on the diagonal idendity-axis. Due to potential radiometric calibration errors (such as misjudged irradiance and path radiance), the unchanged points might not be on the diagonal axis, but still they will be scattered on an axis given by a linear relation between the reflectance values. This 'no change'-axis can be found as the first component of a principal component analysis (Richards, 1993). Any remaining variance in

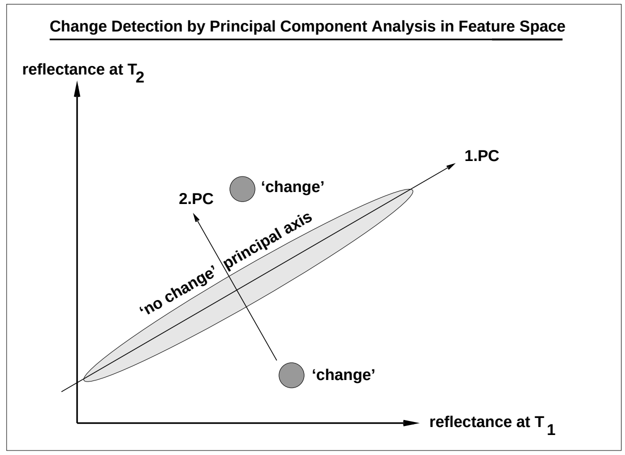

Figure 1: Change detection between overlaying pixels from different years by principal component analysis for each spectral band: areas of 'changed' and 'unchanged' pixels in the feature space.

the direction of the second component is consequently considered as 'change'. Thus the second eigenvalue of the 2 × 2 regression covariance matrix denotes the amount of change between the two images taken of the same scene.

Such detected 'change' is of course prone to errors of the prior registration. The 'change' is a superposition of 'real change' in the ground truth and erroneous change produced by the registration. The quality of the registration is thus crucial to pixelwise change detection. For real imagery we do not know the amount of 'real change'. However, we can utilize the amount of overall 'change' for evaluation of the registration quality, since improved registration reduces the amount of pseudo-change, with the amount of 'real change' as a lower bound.

5. EXPERIMENTAL RESULTS

For each of the above named registration techniques, the map-registered images of 1991 and 1995 were overlayed for each spectral band (for illustration, Fig. 3 shows the overlay for band 6). The difference between global polynomial registration and a locally adaptive one such as e.g. Akima is pronounced and illustrated by the coordinate displacement image in Fig. 4. The difference between the locally adaptive methods, however, is not detectable by eye appraisal of the overall image, and has to be evaluated by means of the principal component change detection.

The overlaying pixels were identified and a regression in feature space was performed. The apparent amount of 'change', i.e. the second covariance eigenvalue, decreases with qualitatively better registration which reduces the number of misregistered pixels. The results are tabulated in Table 1. The 'change'-reduction is given in percent relative to the conventional global second degree polynomial transformation. The results show that the amount of erroneous change is significantly reduced by local Akima registration and even more by the radial basis function techniques, up to 13.5% in single spectral bands. The mean reductions of the various methods indicate that already the local Akima registration is clearly better than the global approach, and the radial basis function methods generally improve the results slightly further.

According to Table 1, we can also state that a pure multiquadric approach without either simultaneous or prior affine or polynomial transformation terms does not better than the global transformation. Global transformation terms are rather crucial, with the radial basis function terms modeling only the distortions of higher spatial frequencies.

The best result is achieved by elastic registration using the thin-plate spline function $U(r) = r^2 \ln r$, however, the difference between the various radial basis functions is not significant when compared with respect to the standard deviations through the spectral bands.

6. CONCLUSION

We have compared five different locally adaptive image registration techniques with conventional global second degree polynomial registration. The methods were compared by application to experimental image data recorded by an airborne multispectral line scanner. The performance of the various methods was evaluated by the reduction of the amount of erroneous 'change', where the latter was measured as the variance of the second principal component in the regression of the multitemporal reflectance values in each spectral band.

The best results were achieved with elastic registration using the thin-plate spline function $U(r) = r^2 \ln r$ which reduced 'change' by ca. 9%. Although, no significant difference in performance can be observed between various radial basis functions. The comparison shows that also local AKIMA registration improves the result significantly (ca. 7%) over global polynomial registration, with elastic registration techniques being slightly better still.

We conclude that elastic registration is a preferable tool for the geocoding of airborner scanner imagery. Local AKIMA quintic polynomials may be used for cases of high ground control point numbers, where the computation time is significantly less than for elastic registration.

ACKNOWLEDGEMENT

One of the authors (RW) was supported by the Volkswagen-Stiftung. We would like to thank Johann Bienlein, Leonie Dreschler-Fischer, Christian Drewniok and Hartwig Spitzer for inspiring discussions. Moreover, we wish to thank Martin Kollewe and Thomas Kollewe for the organization of the image flights. The image data was recorded in collaboration with DLR, Oberpfaffenhofen, particularly with the help of Volker Amann, Peter Hausknecht and Rudolf Richter.

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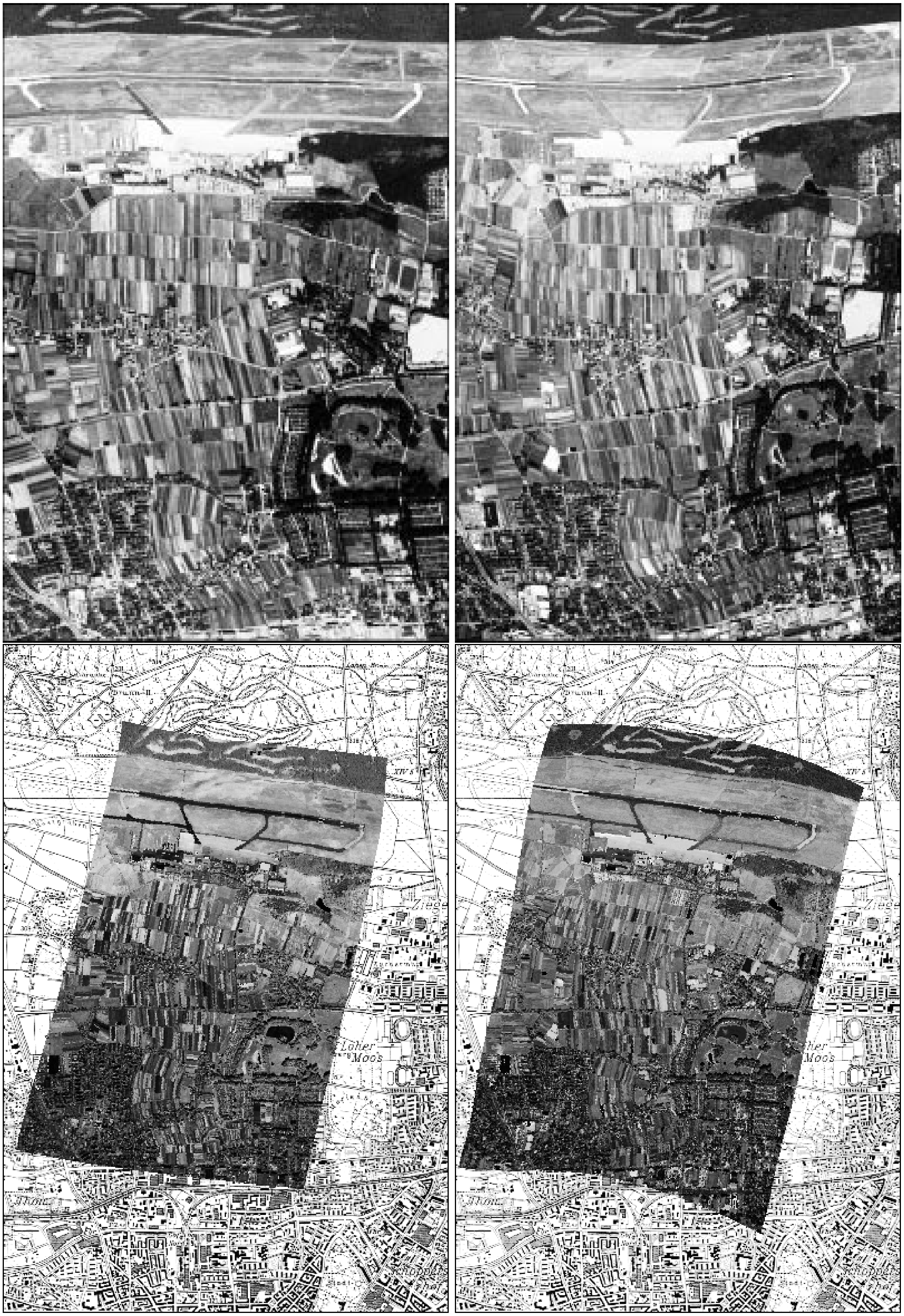

Figure 2: Top: The raw data of 1991 and 1995 (400 × 716 pixels each, 1800 m altitude, 20 s recording time, ca. 2100 m east-west ground distance). Bottom: Registered to map of scale 1:25 000 (using thin-plate spline registration with $U(r) = r^2 \ln r$).

Figure 3: Overlay (addition and rescaling) of the two map-registered images of 1991 and 1995 (using thin-plate spline registration with $U(r) = r^2 \ln r$).

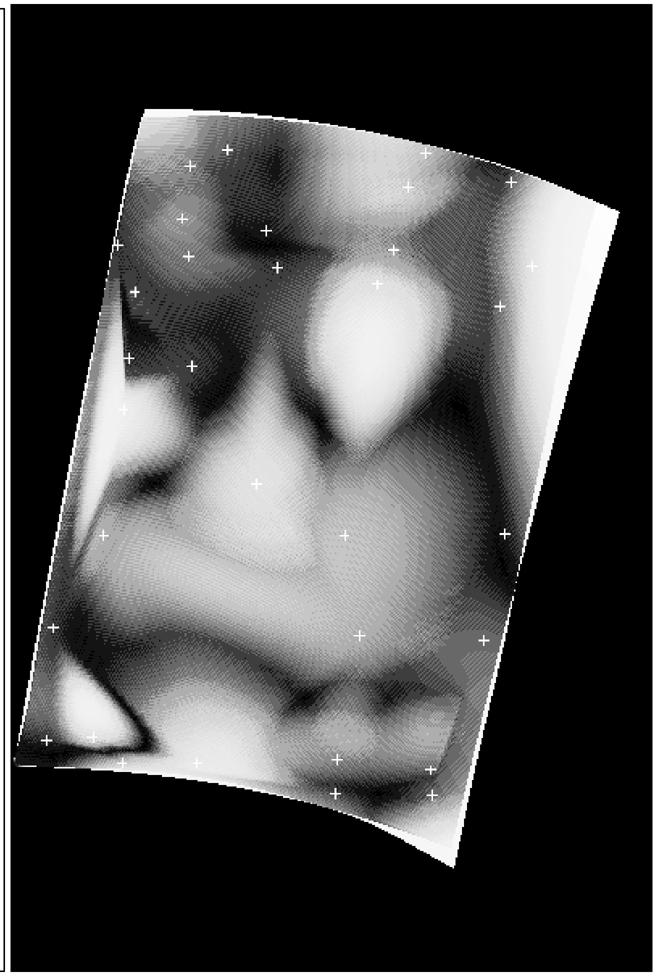

Figure 4: Resampling coordinate displacement image for the 1995 data between global polynomial and local Akima registration (black is vanishing, white is maximum difference, GCPs marked as white crosses).

Variance of Second Principal Component ('Change')											
Spectral Band Number i	1	2	3	4	5	6	7	8	9	10	
Center Wavelength [μm]	0.435	0.485	0.560	0.615	0.660	0.723	0.830	0.980	1.650	2.215	
Global Polynomial Absolute Variance of 2. PC:	26.64	58.42	72.58	103.11	113.80	151.74	533.08	503.06	256.99	264.20	
	Relative Reduction of 2. PC Variance:										mean ± stdev.:
Akima Local Polynomial	–4.3%	–7.4%	–7.0%	–6.6%	–5.6%	–5.4%	–7.1%	–9.3%	–9.2%	–4.3%	–(6.6 ± 1.8)%
Affine + $r^2 \ln r$	–5.4%	–8.4%	–9.1%	–9.1%	–7.2%	–8.7%	–9.4%	–11.9%	–12.0%	–6.0%	–(8.7 ± 2.2)%
Affine + r	–4.9%	–8.5%	–7.9%	–8.2%	–5.9%	–6.8%	–9.9%	–13.5%	–12.5%	–5.3%	–(8.3 ± 2.9)%
$\sqrt{1+r^2}$	–1.0%	–3.2%	–1.2%	–0.6%	–0.1%	+1.6%	–1.8%	–2.2%	+2.4%	+4.9%	–(0.1 ± 2.4)%
Polynomial + $\sqrt{1+r^2}$	–5.2%	–9.3%	–9.3%	–8.8%	–7.8%	–7.5%	–8.1%	–10.1%	–10.7%	–5.3%	–(8.2 ± 1.8)%

Table 1: The variance of the second principal component is considered as the amount of 'change' between the two images of the scene. Erroneous 'change' is reduced by improved registration techniques.