PARGE: Parametric Geocoding Based on GCP-Calibrated Auxiliary Data*

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ABSTRACT

Nearly all current imaging spectroscopy data are obtained by scanning airborne systems. The stability of such systems is always worse than that of spaceborne platforms. Thus, geometric distortions occur due to variations of the flightpath as well as of the attitude (given by roll, pitch and heading angles) of the plane. These distortions cannot be corrected simply by ground control point based traditional georeferencing procedures since the movements cannot be approximated satisfactorily by polynomial transformations of the image. A pixel by pixel calculation has to be performed instead, to account for the position and attitude of the plane during the scanning process. A georeferencing procedure is described which is based on a parametric approach and theoretically allows sub-pixel accuracy even in steep terrain. The current work resulted in an new algorithm and application for parametric geocoding (PARGE). A ground control point based procedure has been developed to recalibrate the offsets of the attitude data since they usually are given as relative angles. It exactly reconstructs the scanning geometry for each image pixel using position, attitude, and terrain elevation data. The procedure is tested on AVIRIS and on DAIS data and compared to digital topographic data. The geocoding results are of reliable accuracies of down to 1-2 pixels for both data sets.

Keywords: AVIRIS, DAIS, Ground Control Points Analysis, Gyro Calibration, Parametric Geocoding, PARGE, Preprocessing

1. INTRODUCTION

Various projects have been carried out at RSL (Remote Sensing Laboratories, Univ. of Zurich) which require either an exact localization of ground truth measurement, or need the information from a digital elevation model (DEM) in relation to the scanner data:

- *Spectroradiometry*: in-flight calibration of the DAIS (Digital Airborne Imaging Spectrometer)[4] sensor, using GER 3700 spectroradiometer measurements at ground during the overflight,
- *Limnologic imaging spectroscopy*: determination of chlorophyll content and other constituents in Swiss lakes,
- *Atmospheric imaging spectroscopy*: water vapor retrieval over complex terrain and atmospheric correction algorithms using the digital elevation model.

The geocoding procedure described hereafter is planned for use in standard preprocessing chains (e.g for DAIS data) in combination with atmospheric correction algorithms. It is possible to use parameters from the georeferencing procedure for an improved atmospheric correction. Possible linking parameters are the viewing angle per pixel, the absolute distance from the satellite to each pixel location, or the relative airmass between sensor and pixel. Furthermore, other DEM related parameters, such as height, slope or aspect are required for radiometric correction algorithms and can only be used if the image is brought to the same geometry as the DEM. The presented application fully reconstructs the geometry of the scanning process. Thus, it has the potential to provide all required data for further atmospheric and radiometric processing.

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The handling of the auxiliary data (and not the effective processing!) is the core problem of the whole geocoding procedure. First, it is necessary to define a common architecture of the geocoding process to make it usable for most of the airborne scanning systems. Second, tools have to be provided which allow quality analyses, filtering, and recalibration of the auxiliary data. The latter shall be achieved by inverting the parametric geocoding algorithm. Ground control points are used to determine the uncertain absolute calibration of the airplane attitude angles, average height and position.

2. INPUT DATA

A variety of input data are required for the parametric geocoding. The three categories of input data are:

- *Navigation Data:* These data consist usually of position (longitude, latitude, height) and attitude data (roll, pitch and true heading) stored for each line (or even each pixel) of the scanner image.
- *Digital Elevation Model:* The DEM has to be provided in the same coordinate system as the airplane data. The spatial resolution is chosen based on the nominal pixel size of the image. The DEM initiates the final geometry of the geocoded image.
- *Image/Sensor General Information:* FOV (field of view) and IFOV (instantaneous field of view), scanning frequency, starting time, missing lines, and dimensions of the image.

For use with the geocoding package, all data are read using a common user interface (designed in IDL®, RSI Inc.). Afterwards, the data are transformed to the geometrical units (radian and metres) and visually checked.

Often, some parts of these data are not known exactly and must be estimated or interpolated from external sources. This can occur even in generally well documented test sites overflown with high performance sensors. The most critical parameters related to the auxiliary data are the single angular offsets of the attitude data. The absolute origin of the attitude coordinates is seldom known exactly and therefore has to be recalibrated. A procedure to perfom this recalibration is shown in section 4 of this paper.

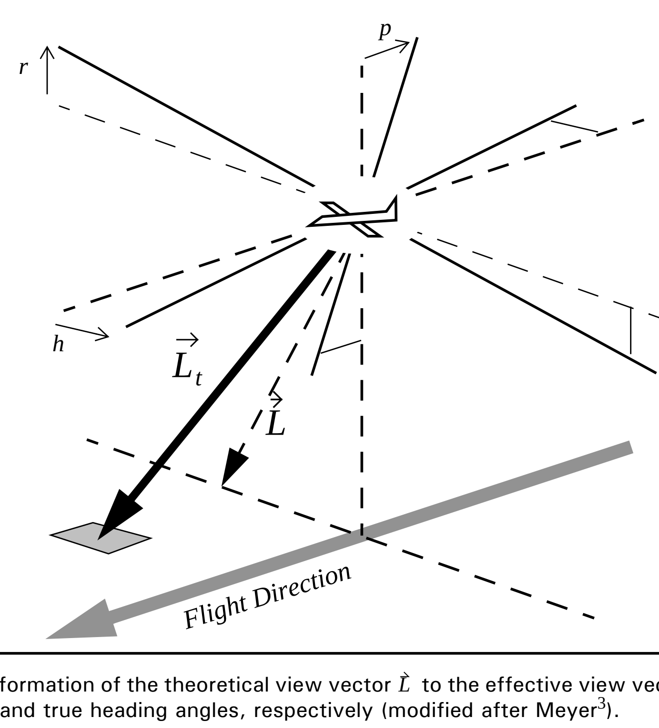


Figure 1: Transformation of the theoretical view vector $\vec{L}$ to the effective view vector $\vec{L}_t$. r, p and h denote roll, pitch and true heading angles, respectively (modified after Meyer[3]).

3. GEOMETRIC ALGORITHM

The parametric processor starts with an estimate of the ‘theoretic view vector’ ($\vec{L}$) which is the imaginary line of sight to the current pixel, oriented from an horizontal airplane facing direction north. This vector has to be turned in three dimensions to get the ‘effective view vector’ ($\vec{L_t}$):

$$\vec{L_t} = \mathbf{R} \cdot \mathbf{P} \cdot \mathbf{H} \cdot \vec{L}, \tag{1}$$

where **R**, **P** and **H** are the coordinate transformation matrices for roll, pitch and true heading, respectively. The calculation order in equation (1) is of interest since matrix multiplications are not commutative – the order to be applied is based on the measurement sequence of the gyros. Equation (1) describes, how the sensor is virtually turned from the north looking flight to the actual position (see Denker[1] and Figure 1). The vector $\vec{L_t}$ then is intersected with the DEM starting at the airplane position $\vec{P_a}$ to obtain the pixel position:

$$\overrightarrow{P_{pix}} = \vec{P_a} + \vec{L_t}\frac{\Delta h}{h(\vec{L_t})}, \tag{2}$$

where Δh is the height difference between the airplane position and the DEM intersection point and $h(\vec{L_t})$ is the height dimension of the effective view vector.

Processing Algorithm

The following steps are performed during the main processing algorithm:

- Calculate the current observation geometry (see Figure 1); the theoretic look angle vector ($\vec{L}$) is calculated between the airplane position and a supposed ‘flat’ DEM, using the instruments FOV and the pixel position information. This vector is then transformed to the effective look angle vector ($\vec{L_t}$), using equation (1).
- Find the Intersection point on the surface; the intersection procedure used in the PARGE algorithm calculates a height profile along the footprint of $\vec{L_t}$ and searches for a point of equal height on $\vec{L_t}$.
- Map the image coordinates; the pixel coordinates of the image (pixel and line number) are written to an array in DEM geometry at the intersection point position. The result of this procedure is a ‘remapping array’ which contains the indices of the raw image coordinates, mapped to the corrected positions on the DEM.
- Gap filling; triangulation and neareast neighbour techniques are used to create a spatially continous image (see below).

In order not to loose too much information from the raw image, the spatial resolution of the final DEM (and image) has to be taken slightly higher than the nominal resolution of the original image data. It is not possible to avoid that some of the image data will be multiply mapped while other parts will be lost because of aircraft motion. If the instabilities are relatively high, there will be a high number of pixels in the final image with no information from the scanner. These gaps have to be filled by image processing techniques in order to achieve an area dependent representation of the image data. Our favoured procedure is the *triangulation method*. The centre pixel locations are triangulated to remap the missing pixels based on a gridding procedure. The triangulation is a true nearest neighbour technique for filling all occurring gaps between the center pixels. Another advantage to this method is its independence of final product resolution. The produced TIN (Triangular Irregular Network) can be used to achieve whatever image final resolution is required.

The final processing step performs the effective production of geocoded images. It is separated from the main processing algorithm. The ‘remapping array’ is applied as an index directly to the original image data to perform the final geocoding. This step is applied band by band which makes the processing of a band sequential raw data cube very fast. The concept also allows one to process any image channel of the original image geometry, and thus also to geocode results of higher processing levels.

4. OFFSET RECALIBRATION FROM GROUND CONTROL POINTS

A ground control point (GCP) based offsets estimation tool was developed for the PARGE application. The inversion of the georeferencing algorithm allows the calculation of the airplane position for each GCP. The transformed view vector is subtracted from the GCP position and stretched by the relative height:

$$\vec{P}_a' = \overrightarrow{P_{GCP}} - \vec{L}_t \frac{h_a - h_{GCP}}{h(\vec{L}_t)}, \quad (3)$$

where $\vec{P}_a$ and $\overrightarrow{P_{GCP}}$ are the position vectors of the airplane and the GCP, respectively, with the absolute heights h_a and h_{GCP}. The differences between the estimated positions $\vec{P}_a'$ and the real navigation data are analysed to statistically obtain the offsets. Auxiliary data offsets can be calculated for roll, pitch, heading, x-y-navigation, height and/or field of view (FOV). The angular and distance offsets for a number of GCP's are evaluated statistically to obtain the corresponding offset estimates as follows (see also Figure 2):

- *Roll*: average of the angular offsets in scan direction,
- *Pitch*: average of the angular offsets in flight direction,
- *X-Offset:* average of the distance offsets in longitudinal direction,
- *Y-Offset*: average of the distance offsets in latitudinal direction,
- *Heading*: minimum correlation of the angular offsets in flight direction (pitch) to the pixel distances from nadir,
- *Height*: minimum correlation of the angular offsets in scanning direction (roll) to the pixel distances from nadir.

For heading offset estimation, the correlation between pitch offset and nadir distance is minimized by iteratively adjusting the true heading average. An analogous procedure is used for the height with the roll offset as indicator.. Because each offset potentially depends on the others, iterations may be done between them; e.g. the heading offset may be iterated together with the pitch offset over sloped terrain.

A height offset can be interpreted as a FOV offset and vice versa. Each is derived from the other by the equation:

$$\phi_1 = 2\,\mathrm{atan}\left(\frac{h_1 \tan\left(\frac{\phi_0}{2}\right)}{h_0}\right) \quad \text{from} \quad h_1 = h_0 \frac{\tan\left(\frac{\phi_1}{2}\right)}{\tan\left(\frac{\phi_0}{2}\right)}, \quad (4)$$

where h_0 is the original flight height, ϕ_0 is the original FOV while h_1 and ϕ_1 are their corrected counterparts. Note that this method can only estimate the average height offset for an entire flightpath.

Flightpath Reconstruction

The flightpath normally is provided with a data set. If no path is available, a flightpath reconstruction procedure is applied based on a number of GCPs: the xy-position of the plane is determined for each GCP, and an average flight height is derived from the statistics of additional GCPs[6]. The following assumptions allow such a flightline reconstruction based on a number of GCPs:

- the flight altitude is constant within the required accuracy,
- the flight velocity is constant within GCP distances, and
- the flight is more or less straight without any hard turns.

The aircraft position then is calculated using a cubic spline interpolation between the position points. Errors may be introduced into this procedure if the height is not constant during the overflight and if the GCP accuracy is lower than the resolution of the resulting image. The procedure needs approximately one or two GCPs for 100 image lines for flightpath calculation and another GCP for the offsets determination within the same area.

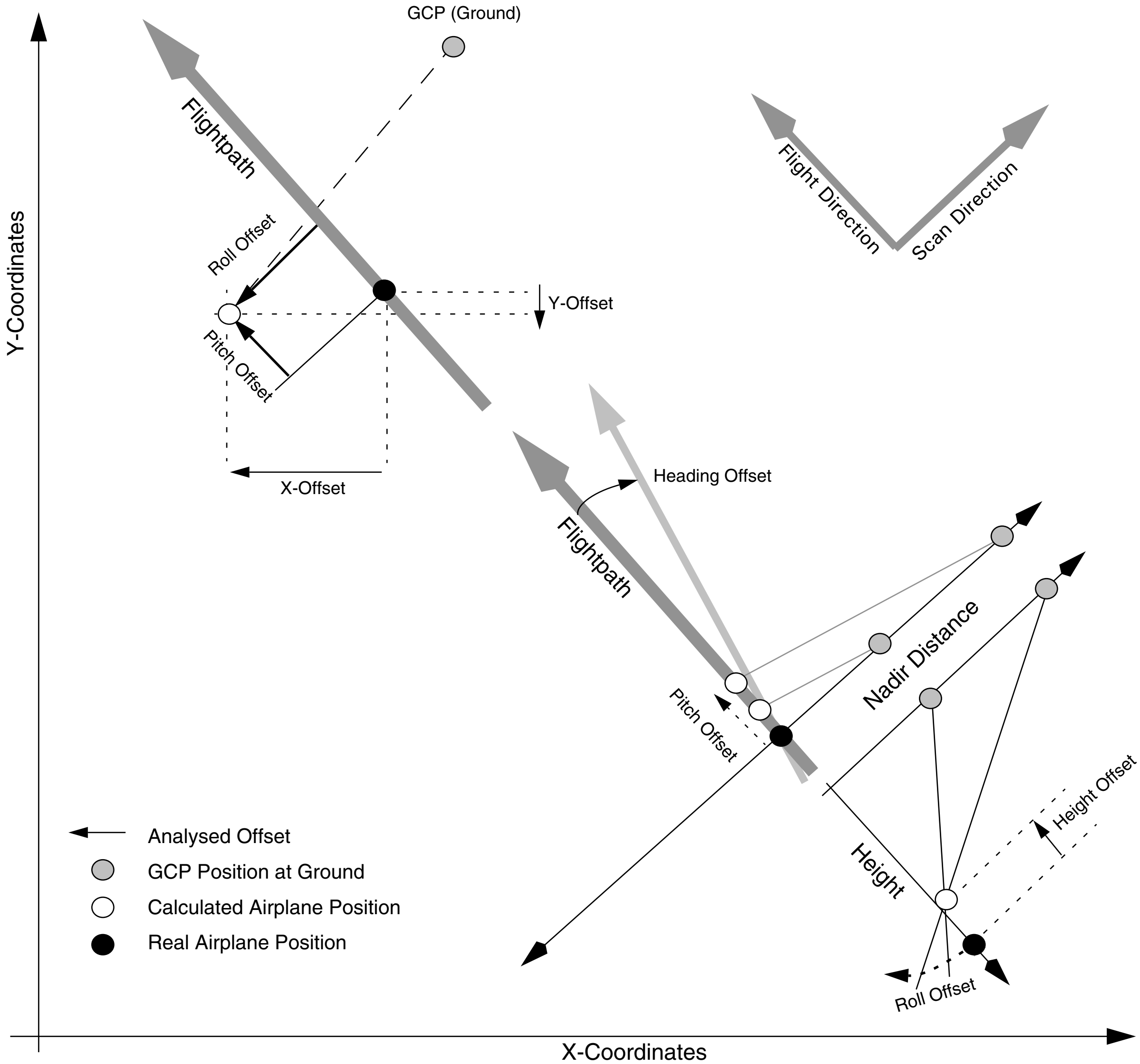


Figure 2: Top: offset analysis for roll, pitch, and X/Y-coordinates based on one single GCP. Bottom: offset analysis for true heading and average height, respectively, based on the offset statistics of multiple GCPs.

5. THE PARGE APPLICATION

The algorithm was implemented based on the requirements for 'real world' hyperspectral sensors such as AVIRIS or DAIS. A main goal was to create an interactively usable application with all main features between raw input data and image output. A consistent data format was created containing image and DEM descriptions as well as all sets of the auxiliary data. The format helps to reconstruct the processing steps and to store intermediate status reports. Some minor viewing and analysis capabilities for the DEM and the image data were introduced too but are not key parts of the package.

All the described features were implemented within an application environment suited for further distribution and operational use.The new PARGE application supports the following features:

- consistent data structure for various airborne imaging instruments
- consideration of the exact navigation data by line or by pixel
- exact correction of roll, pitch and true heading (no small angle approximations)
- ground control point based algorithms for auxiliary data offsets estimation and flightpath reconstruction
- output to desired DEM geometry
- two implemented geocoding algorithms for different accuracy requirements:
  - 1st: sub-pixel accuracy achieved by a DEM-oversampling algorithm (considering the real dimensions of each pixel)
  - 2nd: pixel accuracy using a pixel centre based triangulation algorithm
- nearest neighbour technique prevents data modifications
- fully IDL (Interactive Data Language, RSI Inc.) based and therefore portable application with window based user interface and on-line help system

Further information about the application and its availability may be obtained from the authors.

Processing Timeframe

The whole processing (work and computing) can take from a few hours up to a week per scene, depending on the quality of the auxiliary data available. A typical schedule for an image of 512 x 614 pixels is as follows (e.g.):

1. Get all data, including image, DEM, navigation data and airplane attitude data. Convert them to physical units (radian/metres). Test all data with a quick preview (1h - 6h of work).
2. Check the flightpath and introduce a number (5 - 20) of ground control points. Possibly reconstruct the flightpath (1h - 8h of work).
3. Calculate or test the offsets of the attitude data, using the selected ground control points. (2h - 4h of work).
4. Run the centre pixel georeferencing on a subset of the image and check the position on the DEM (15 - 30 min.).
5. Run the main geocoding processor on the whole image (30 min. - 2h runtime, depending on the computing speed).
6. Remap single bands and afterwards the whole cube (10 - 50 min. runtime).

Based on the above estimates, a fast processing would be possible within about 5 hours of work and 1-2 hours of run-time. This time increases proportionally with the required geocoding quality and the number of lines to be processed. Additionally, missing or corrupted auxiliary data may cause substantial delays in processing.

6. RESULTS

Application to AVIRIS Data

The new algorithm was applied to AVIRIS 1995 data over complex terrain in Camarillo, California. There was no differential GPS system mounted during this campaign, and the internal navigation system (INS) of the airplane provided only poor resolution at low absolute accuracy on the position. It was therefore necessary to reconstruct the flightpath from the image data using the described procedure. The roll angle was set to zero because AVIRIS roll compensation was switched on. These two restrictions led to a lower geocoding accuracy than potentially attainable.

The fast pixel centre based algorithm could be used for the required final USGS DEM resolution of 30m. The processing of the standard AVIRIS image (614x512 pixels) was performed within less than half an hour on a Sun SPARC 20 workstation. This time would increase by about a factor of 4 if e.g. 15 m final resolution would be chosen. The geocoded image is shown in Figure 3 in comparison with a DEM shadow view image and with USGS digitial line-graph data. The ridge lines of the mountains fit within one pixel shift and also the depicted roads agree within 1-2 pixels. An accuracy of ± 50 m is assumed from visual interpretation and from the ground control points residuals beeing below 30 m. This accuracy would increase if the exact aircraft position per scanline would be available.

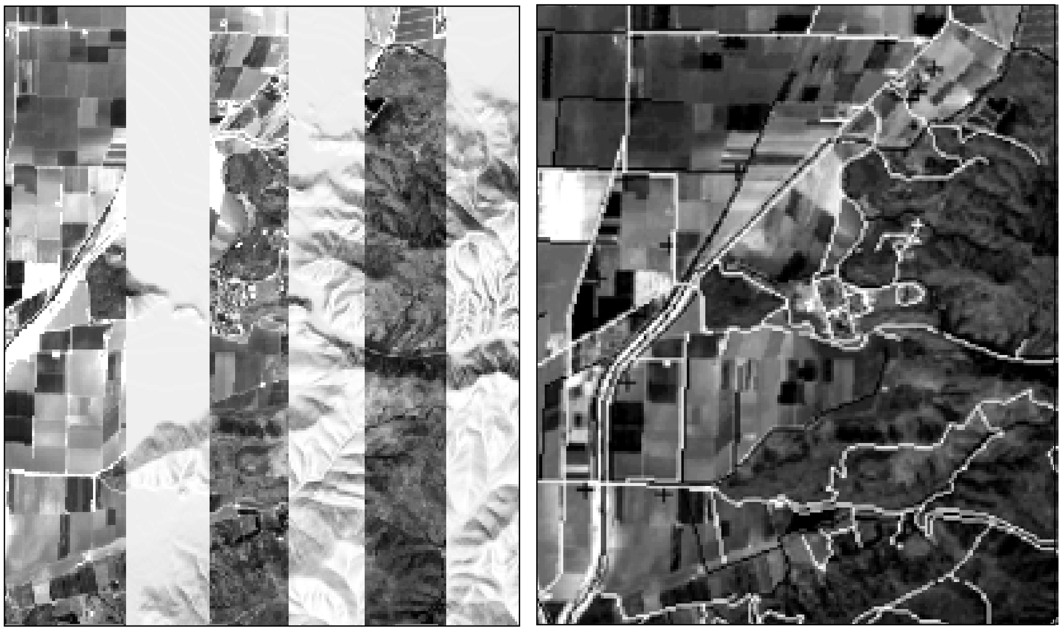


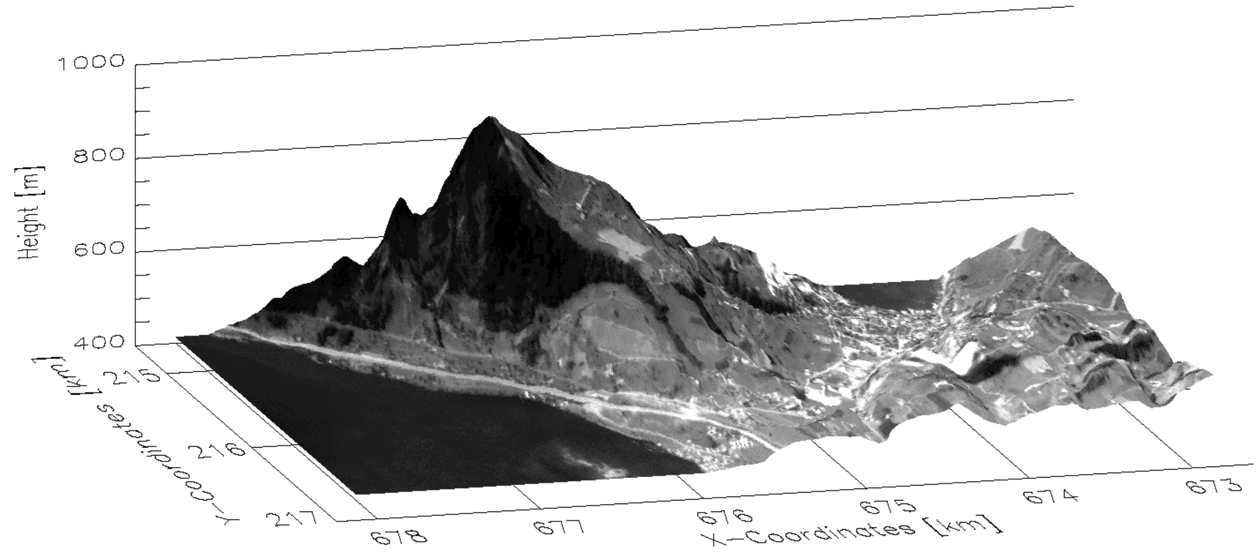
Figure 3: Subsets of the geocoded AVIRIS image of Camarillo (CA) in comparison with a DEM shadow view image (left) and with USGS digital linegraphs (right).

Application to DAIS Data

In 1996 the DAISwiss'96 calibration campaign was carried out in Central Switzerland and over Zurich. The DAIS Sensor of DLR was flown in a DO-228 aircraft at an altitude of about 4000 m above sea level. Its nominal pixel size is 6 m at 512 pixels per line. Since its attitude is not very stable, horizontal distortions of up to 30 pixels can occur within the range of 100 lines. These shifts have to be corrected with the parametric procedure. In the flight campaign of 1996 no exact navigation data were acquired due to technical problems. Therefore, the flight line had to be reconstructed using the above procedure with a set of 20 GCPs. A subset of the resulting image is shown in Figure 6 in comparison with the digital topographic map. The DEM used for this data set was produced by the Swiss Federal Office of Topography. It provides terrain height information at 0.1 m vertical resolution in a 25 m grid.

The error of the geocoded image is in the range of 2 to 8 pixels (50m). However, all attitude effects appearing clearly in the raw image could be removed, making the resulting image useful for further interpretations. Another approach for geometric correction was tested by Reulke[2]. He first orthorectified the WAAC (Wide Angle Airborne Camera) data which was flown simultaneously to the DAIS. The DAIS data then was matched to the WAAC data by a maximum correlation approach. This approach performs well but requires the simultaneous photogrammetric data scanning which possibly may be a source for further geometric errors.

A second test on DAIS data was made in 1997. Test areas in Central Switzerland were flown and several data sets could be registered. During that campaign, the flightpath was measured at an accuracy of better than one metre with a differential GPS on board the aircraft. The remaining main source of errors was therefore the gyro (mis-)calibration. Various analyses showed that the sensor-mounted gyros were drifting during an overpass. The DAIS on-sensor gyro data had therefore to be cross calibrated with the low resolution aircraft INS-gyro information. Still, this attitude determination was far from being perfect for the DAIS data. The results (see Figure 5) prove how important correct auxiliary data preprocessing is for obtaining geometrically corrected data.



DEM and topographic data: DHM25/PK25 ©1997 Federal Office of Topography, Wabern, Switzerland

Figure 4: Overlay of the DAIS geocoded data product on the DEM in Central Switzerland.

An example of an overlay on the digitial elevation model is shown in Figure 4. The elevation model neglects the relative height of the forests what results in shifts along the forest borders in the off-nadir image regions (see Figure 5). The accuracy is within ± 2 pixels (± 10 m) for this data with known flightpath. The residual gyro angle measurement error is responsible for this effects together with the insufficient representation of the surface elevation by the digital elevation model.

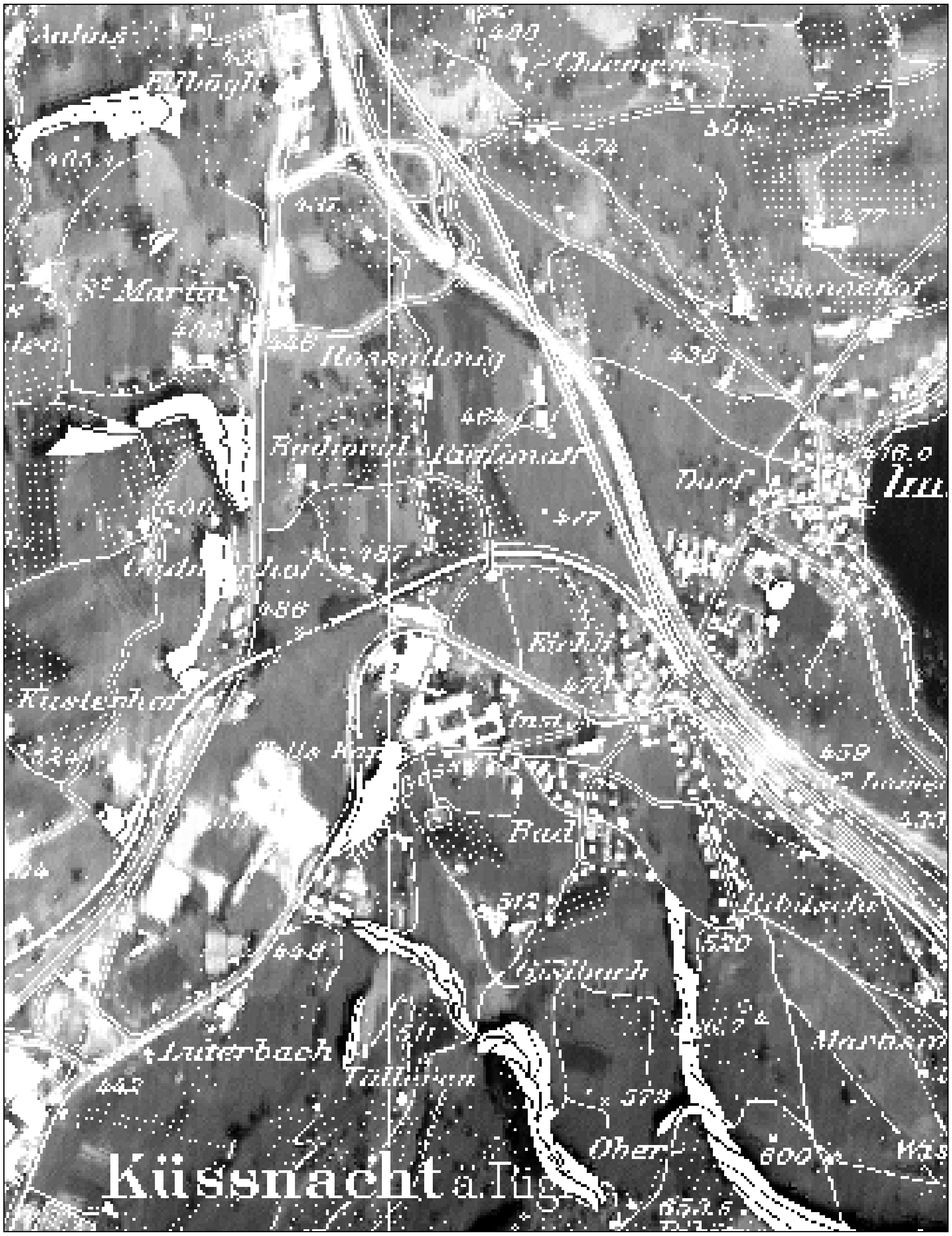
Geocoding Quality Assessment

Quantifying geocoding quality is difficult. Methods typically applied are:

- calculate the location residuals of ground control points which were not used for the prior calculation,
- compare the image results with the DEM along terrain lines or in specific mountainous areas (see Figure 4),
- overlay digital linegraphs or pixel maps on the geocoded results (see Figure 6).

The quality was found to be within the accuracy of the input data. The parametric geocoding was possible at an accuracy of below three pixels (better than 20 m) for DAIS image data with known flightpaths. Distortions occur whenever the DEM altitude does not agree with the surface height (e.g. forests and settlements) and the compared object is located off nadir in the image. Such residual errors could only be corrected by using real digital surface models.

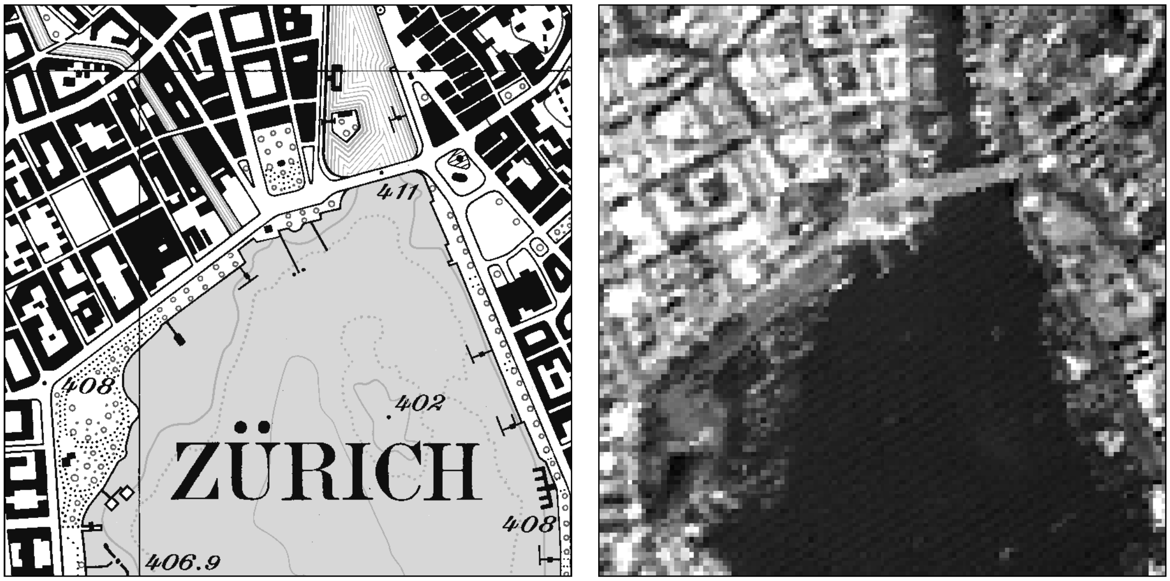
If the flightpath is unknown, the accuracy for DAIS data is within 8 pixels (40-50 metres), while for AVIRIS data accuracies of 1-2 pixels are achieved (20-40 metres). The higher accuracy of the AVIRIS data processing is possible due to the much more stable flight of the ER-2 aircraft at 20 km height, where the flightpath within one scene is approximately linear.



DEM and topographic data: DHM25/PK25 ©1997 Federal Office of Topography, Wabern, Switzerland

200 m

Figure 5: Overlay of the digital pixelmap with the geocoded DAIS data over Kuessnacht, Central Switzerland (resolution: 5m). Errors on the forest borders occur due to the wrong representation of the surface height over forests.



DEM and topographic data: DHM25/PK25 ©1997 Federal Office of Topography, 3061a, Wabern, Switzerland

Figure 6: Comparison of a subset of the geocoded DAIS image with a digital topographic map of Zurich.

7. CONCLUSIONS

A new geocoding processor was implemented using a parametric approach. It allows for correction of attitude and flightpath dependent distortion, even for unstable sensor platforms such as for low level airplanes. The algorithm is now in a test status for hyperspectral sensors. Extensive tests have been performed in winter 1997/1998, whereas a fully operational application is planned for 1999. Currently, the DAIS and AVIRIS sensors are supported with perhaps further airborne systems to be introduced later. It was possible to geocode imaging spectroscopy data in mountainous terrain at accuracies of 20 to 50 m using this GCP based PARGE algorithm.

The DAIS data were geocoded at accuracies of 2-4 pixels using a DGPS measured flightpath. The mediocre quality of the gyro data had to be recalibrated using GCPs and absolute values from the aircraft INS. This procedure can not be extended to higher accuracies since the accuracy of GCPs is limited to approximately ± 15 m. The only solution for spatially high resolved sensors thus is an absolute calibration of the gyros together with differential GPS measurements of the flightpath.

AVIRIS geocoding leads to satisfactory results using USGS DEMs. Digital elevation models of higher accuracy would increase the accuracy of the geocoding at high spatial resolutions. Further work could be done on accurate residual roll determination on roll compensated AVIRIS images. The accuracy of pitch and true heading calibration has not yet been examined by the authors. Another main issue is the introduction of DGPS based flightpath determination for AVIRIS. The used GCP based flightpath determination is only a rough estimate for missing or insufficient navigation data; the accuracy is significantly decreased compared to a (potential) georeferencing with an exactly known flightpath. The results are nevertheless better than those achieved with traditional georeferencing methods applied to images of unstable platforms flown over rugged terrain.

The first release of the fully IDL based ‘PARGE’ package has breen made available to selected users for well defined purposes and for testing. It is not yet suited for fully operational use since it still requires some expertise for accurate data preparation and processing decisions. After testing of the application, the focus will be on a higher automatization level and faster processing time to obtain a real operational system. The latter might be achieved with anticipated faster computers. Another effort has to be made on quality assessment to allow calculation of the accuracy values for each geocoded image.

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