A UNIFIED APPROACH TO PARAMETRIC GEOCODING AND ATMOSPHERIC/TOPOGRAPHIC CORRECTION FOR WIDE FOV AIRBORNE IMAGERY PART 1 : PARAMETRIC ORTHO-RECTIFICATION PROCESS

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ABSTRACT

A combined geometric and radiometric processing chain for hyperspectral data is presented. This paper describes the ortho-rectification solution for the geometric part of the whole problem. A parametric geocoding approach (PARGE) has been chosen. The geometrical model strictly considers all navigational parameters engaging a forward transformation methodology. For the implementation, a number of auxiliary data calibration and tuning possibilities are shown together with the work flow of the currently applied processor. Results of the procedure for HyMap and AVIRIS hyperspectral imagery are analyzed with respect to their absolute accuracy and coregistration errors. The geocoding procedure will be used in standard preprocessing chains in combination with the atmospheric correction procedure ATCOR4 for current and future hyperspectral instruments.

1 INTRODUCTION

Geometrical and radiometrical effects are the main distortions of imaging spectrometry data and need to be corrected for physically based validation of the imagery. The prerequisite for the correction of most radiometrical and atmospherical effects is an accurate description of the scanning geometry for every pixel of the raw image. This situation led to a joint effort between the Remote Sensing Laboratories (RSL) of the University of Zurich and the German Aerospace Center (DLR) Oberpfaffenhofen of inventing a complete and flexible processing system for geometric and radiometric correction for airborne optical remote sensing data.

The main goal of this collaboration has been the synchronization of two procedures for geometric and atmospheric processing and their optimization with regard to the specific characteristics of imaging spectrometry data. Such a smooth ‘geo-atmospheric’ processing chain is a very powerful tool for radiometric processing of well calibrated remote sensing data. The relevant ortho-rectification procedure is described within this first paper, while the atmospheric correction part is explained in a second paper within this very same issue (Richter et al., 2000).

Orthorectification of airborne scanner data can be solved using various approaches. Correlation matching algorithms (Devereux et al, 1990) may deliver adequate results only if the image is highly structurized. In general, all traditional non-parametric approaches (e.g., Bähr, 1976) require a huge number of tie-points to account for the sensor movements and do not achieve satisfying accuracies for airborne data (McGwire, 1996). The number of GCPs can be significantly reduced if parametric approaches are applied.

The “Parametric Geocoding” procedure (PARGE) is based on explicit geometric measurements and theoretically allows sub-pixel accuracy even in steep terrain. It exactly reconstructs the scanning geometry for each image pixel using position, attitude, and terrain elevation data. The algorithm has first been created at RSL starting in 1992 (Meyer, 1994) as an AVIRIS (Vane and Goetz, 1988) specific tool. It then evolved to a generic application dedicated to parametric geocoding of airborne imaging spectrometry data, including extensive Ground Control Point (GCP) based calibration procedures (Schläpfer et al., 1998a/b). PARGE is now available as an operational processing package for orthorectification of airborne scanner data.

A sophisticated methodology is required to achieve high precision with the parametric processing approach. The basic geometric model used for the processing is explained first. The implementation principle including processing work flow and the individual modules are shown subsequently. The outputs of the package including the linking layers for radiometric correction are then depicted. The accuracy of results based on AVIRIS and HyMap (Cocks et al., 1998) imagery is finally given.

2 METHODOLOGY

All airborne optical scanner systems suffer from distortions due to the sensor movement during data acquisition. Even mechanically stabilizing platforms built into the carrier can not solve for these problems since there still are residual movements of the stabilizing systems which become relevant if pixel- or even sub-pixel accuracy is required. For non-stereographic imagery (as most of the current imaging spectrometers are), the only physically exact solution for this problem is the parametric geocoding approach. Its fundamental relationships have been first described by Derenyi and Konecny (1966) and further refined by Konecny (1976a/b). For this paper some minor modification have been made to the formulation of this geometrical model which mainly concerned computing efficiency.

2.1 Geometric Model

The scan process can be geometrically described by a linewise data acquisition definde by one parameter set of (*x*/*y*/*z*/roll/pitch/heading) per image line. The geometric model applied in this paper starts with an estimate of the ‘theoretic view vector’: $\vec{L_0} = (x_0, y_0, z_0)$, which is the imaginary line of sight to the current pixel, oriented from an horizontal airplane facing direction north. The coordinate system is taken such that it corresponds directly to image coordinates, having the *x* (“pixel”) direction across track and the *y* (“line”) direction along track. The latter is set to zero for this starting situation. Note, that the chosen coordinate system is not in line with the common definitions used in aerial navigation. It rather has been chosen from imaging point of view.

The theoretic view vector has now to be turned in three dimensions to get the ‘effective view vector’ ($\vec{L_t}$):

$$\vec{L_t} = \mathbf{R} \cdot \mathbf{P} \cdot \mathbf{H} \cdot \vec{L}_0 , \quad (1)$$

where **R**, **P** and **H** are the coordinate transformation matrices for the attitude angles roll, pitch, and true heading, respectively. Equation (1) describes, how the sensor is virtually turned from the north looking flight to the actual position (Konecny, 1984). This forward transformation is in contrast to the backward rotation as usually applied in digital photogrammetry (e.g., Zhang et al., 1994).

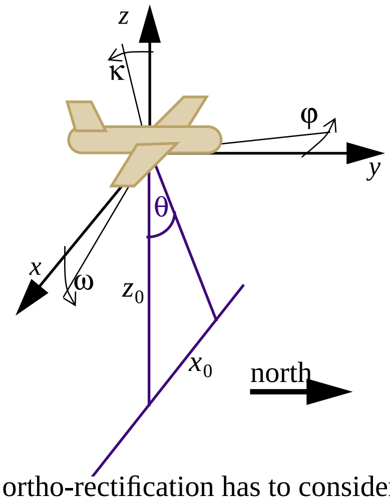

Figure 1: Chosen north facing coordinate system for the PARGE application and theoretical scan situation (situation before virtually turning the aircraft).

Real ortho-rectification has to consider the terrain elevation exactly using intersection algorithms to a digital eleveation model (DEM). Hence, the real view vector $\vec{L}_t$ is intersected with the DEM by starting at the airplane position and calculating a profile of the DEM within the range of occuring altitudes. The real pixel position can then be derived from the coordinates of the intersection point of the DEM profile by propagating the real view vector starting at the airplane position.

2.2 Resampling and correction for panoramic effects

The above procedure retrieves the center pixel positions for each imaged pixel. Resampling has to be applied to this output to achieve a regular grid. For the hyperspectral data, nearest neighbor approaches are preferred in order to avoid producing unphysical spectra, which would occur by applying any interpolation. Spectral integrity is thus preserved while the spatial quality and smoothness can suffer from resampling artefacts. The nearest neighbors are derived by Delaunay triangulation or fast buffering algorithms. The advantage of triangulation is - beside of its higher accuracy - its independence of the final product resolution. The produced TIN (Triangular Irregular Network) can be used to achieve whatever image final resolution is required.

The current procedure accounts for the geometrical panoramic effects by the ‘gap filling’ algorithm described above. Radiometric panoramic effects do not need to be considered because the radiometry is constant for every pixel if a electro-mechanical ‘whiskbroom’ scanners is engaged for data acquisition. For future hyperspectral pushbroom instruments such as APEX (Itten et al., 1998) the IFOV may slightly vary across track and can therefore cause radiometric panoramic effects. Such influences will have to be measured by the laboratory calibration procedure and be corrected in the data calibration process.

3 IMPLEMENTATION

The generic implementation of the parametric geocoding approach includes a broad variety of specialities to be considered with regard of imaging spectrometry data. First, a common architecture for the geocoding process and the used data entities has to be defined. Secondly, tools have to be provided which allow importing, quality analyses, filtering, synchronizing, and recalibration of the auxiliary data. Ground control points are used to determine the uncertain absolute calibration of the airplane attitude angles, average height and position. Finally, dedicated outputs are defined for efficient further processing of the data and for a smooth link to the radiometric processing environment.

The whole implementation of PARGE has been designed using IDL®, (Interactive Data Language, RSI Inc.) and is based on ENVI™ (RSI Inc.) data formats. Thus the current application is platform-independent and can easily be integrated in standard hyperspectral processing environments. A widget-based user interface and a contextual on-line help system further support the end user.

3.1 Input Data

By definition, any parametric approach fully relies on physically measured auxiliary data. The requirements for the indispensable input data are described in Table 1 below. The accuracy is derived by requiring a pixel accuracy of one fifth of the pixelsize for each parameter independently. The reasoning behind this limit is to obtain pixel accuracy for the final results.

Table 1. Parametric Geocoding Data Entities

Group	Parameter	Description	Accuracy Requirement[a]
Sensor	Sensor model	Theoretic view angle θ per pixel center	0.1 mrad
	Sync	Accuracy of synchronization	8 ms
DGPS	x/y	Aircraft coordinates	0.8 m
	z	Aircraft altitude	3 m
	Transform	Transformation to local coordinates	0.1 m
Attitude	roll/pitch	Attitude per image line	0.1 mrad
	heading	True heading to direction north	0.6 mrad
DEM / DSM	altitude	Surface accuracy	3 m
	position	in alignment to the flightpath	0.8 m

a. for IFOV=0.5 mrad / Resolution = 4m / FOV = ± 15 degree / Frequency 25 Hz / Flight altitude 5 km

All coordinates of the DEM and the flightpath have to be transformed to consistent metric rectangular geodetic coordinates to make use of the easy formulation of the geometric model. The spatial resolution of the DEM is chosen based on the nominal pixel size of the image. The DEM resolution initiates the final geometry of the geocoded image. Note, that a digital surface model (DSM) should rather be used than a DEM if high accuracy is required.

Furthermore, the auxiliary information needs to be exactly synchronized to the image data per line. Consideration of the measurements per image pixel might be considered in a later stage of the processor for slow rotating instruments if highest quality attitude measurements are available. A consistent data format is used 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. It is designed in a generic way such that it is easily adaptable to any airborne scanners.

3.2 Process Workflow Structure

The overall process of the PARGE application has been implemented based on the requirements for ‘real world’ hyperspectral sensors such as AVIRIS or HyMap. A main goal was to create an interactively usable application with all main features between raw input data and image output. The interactive elements are required due to the experimental character of data formats and the mediocre quality of most currently available INS auxiliary data for imaging spectrometers.

The workflow structure is depicted in Figure 2. The first steps of the workflow is concerned with the data preparation of image, auxiliary, and DEM data. In order not to loose too much information from the raw image, the spatial resolution of the DEM (and final image) is resampled to a slightly higher degree than the nominal resolution of the original image data. A number of GCPs is required for validation and recalibration of the auxiliary parameters. The applied procedure to perfom this recalibration has already been described by Schläpfer et al. (1998b). It uses GCP statistics to calculate individual offsets for roll, pitch, or heading independently by backward geocoding of the GCP coordinates to a theoretical aircraft position. These offset calculations are necessary for all currently available airborne imaging spectrometry systems and therefore are part of the ‘standard’ processing flow.

In practice, it happens that some of the auxiliary data are completely missing or faulty. The defective parameters can then be interpolated using GCP-based algorithms as e.g. described in Schläpfer et al. (1998a), as long as a good estimate of the remaining parameters exists. Cubic spline interpolation is preferred for the flightpath reconstruction process due to the continous characteristics of the flight pattern. On the other hand, the non-predictable angular movements of the aircraft are better approximated using simple linear interpolations for roll and pitch. Heading and altitude can not be easily interpolated using such algorithms since their respective offsets both can only be approximated if two or more GCPs are available within a limited range of contiguous scan lines.

A consistency check concludes the data preparation – only if severe problems are encountered, the respective sections have to be repeated. The whole auxiliary data status can now be saved for later documentation and re-iteration of the auxiliary parameters preparation. Afterwards, the main processing algorithm as described in the methodology section of this paper can be started. First, the image pixel coordinates (original pixel and line

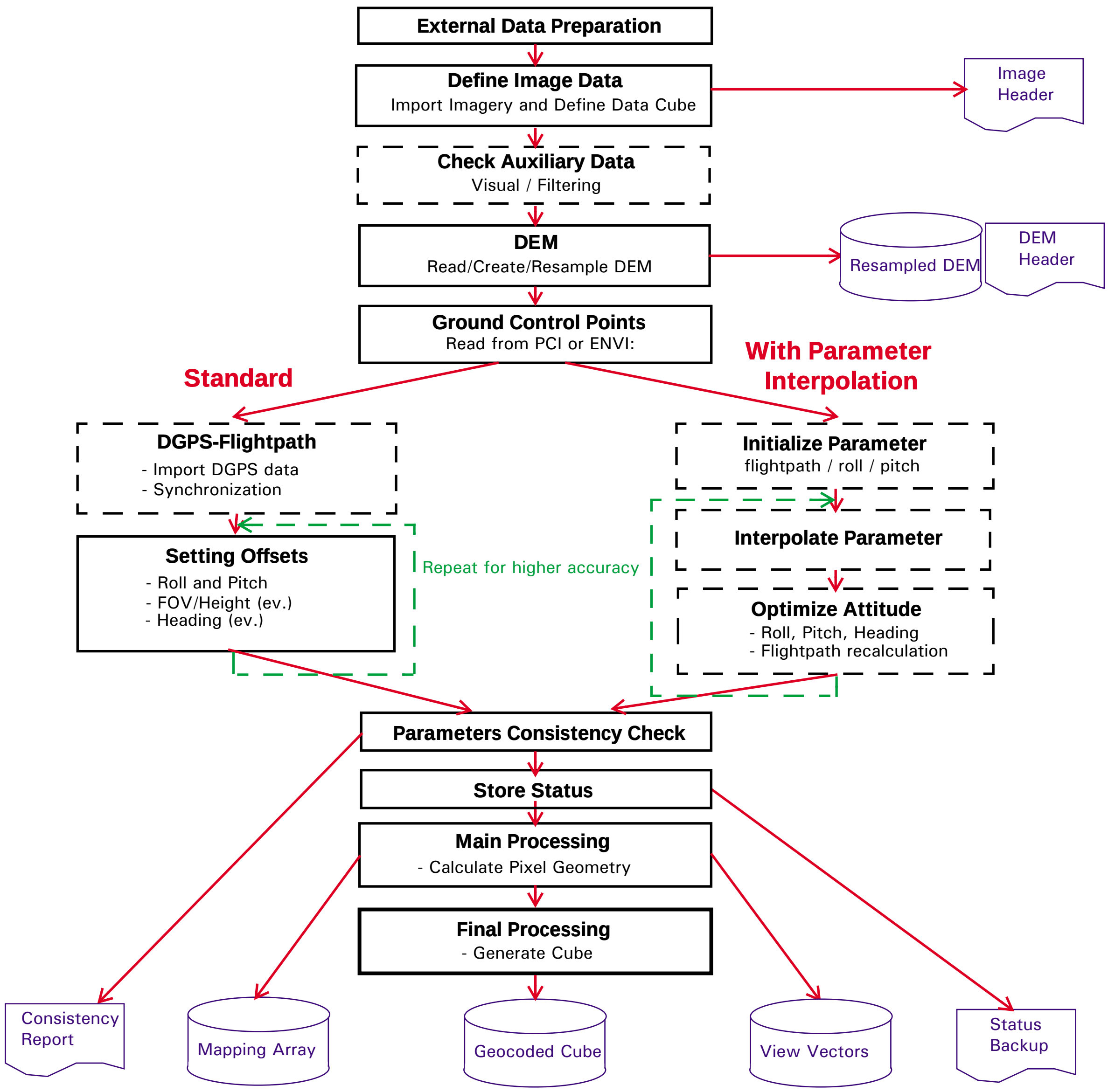

Figure 2: Process data flow of the parametric geocoding as implemented in the PARGE application, including the final outputs of the process.

number) are written to an array in DEM geometry at their geocoded position what results in a 'mapping array'. In parallel, the viewing geometry per image pixel is saved to a separate structure which is describe in detail below. The effective production of the geocoded image or cube is the last step to be performed. The mapping array is applied as an index directly to the original image data to perform this final geocoding. It even may be applied to processed thematic results in order to avoid the large storage overhead of geocoded imaging spectrometry cubes.

A number of outputs are created in the course of the processing workflow:

- *Image Header:* An ENVI™ format header to the raw imagery if none has been available.
- *DEM:* The resampled and resized DEM is stored in ENVI™ format.
- *Consistency Report:* An ASCII report about the consistency of the auxiliary data to the image.
- *Status Backup:* Status information of the geocoding session.
- *Mapping Array:* A two-layer array containing the raw pixel and line coordinates for each DEM element.
- *Geocoded Cube:* Ortho-rectified geocoded hyperspectral image in ENVI™ format.
- *Scan Angles:* Data layers in DEM geometry with scan zenith, scan azimuth angle, and the absolute distance from aircraft to the pixel for each geocoded pixel.

The latter provides all required linking layers for later radiometric processing of the geocoded image. Parameters which only depend on the DEM such as slope, aspect, and elevation are derived separately.

3.3 Processing Timeframe

The whole processing (work and computing) can take between less than an hour and up to days per scene. The effort highly depends on the quality of the auxiliary data. Correct auxiliary data synchronization and the correct conversion of the DGPS data to the DEM geometry may require sophisticated (external) tools and specific cartographic knowledge and programs. A typical image of 512 x 2000 pixels at 200 spectral bands needs a pure processing time of 10-20 Minutes on a Macintosh G3 computer or a Sun workstation for the geometric part and another 5-15 Minutes for the production of the geocoded image cube. If considering all additional I/O actions and GCP calibration tasks, a fast processing is thus possible within about 4 hours of work. This time increases proportionally with the required geocoding quality and the number of lines to be processed.

4 APPLICATION TO HYPERSPECTRAL IMAGERY

The PARGE algorithms have been applied so far to the airborne imaging spectrometers DAIS, HyMap, and AVIRIS. Each sensor has its own specialities and problems what lead to a high degree of flexibility in the current application. The achieved results for exemplary AVIRIS and HyMap scenes are given below.

4.1 AVIRIS

The development of the PARGE application has been highly related to the developments of the AVIRIS sensor (Meyer, 1994; Schläpfer et al., 1997). It has been the new low altitude option flying AVIRIS on a Twin Otter aircraft (Green et al., 1999) which pushed the demand for parametric georectification. A full-parameteric standard rectification procedure has been introduced by Boardman (1999) which however does not include ortho-rectification capabilities. The PARGE methodology has therefore been adapted for use with standard AVIRIS data products.

The processing of AVIRIS data can be very time-consuming, e.g., if some of the input data is insufficiently documented or if the coordinate transformation parameters and formats of the GPS systems are not precisely known. The results of ortho-rectified AVIRIS low altitude imagery is shown in Figure 3. It is overlaid on the USGS shaded DEM, calculated at a resolution of 3.75 meters.

The quality of results is evaluated in comparison to the DEM and between the two images (see below). Overall accuracy turns out to be stable throughout the high altitude and low altitude flightlines which consist of

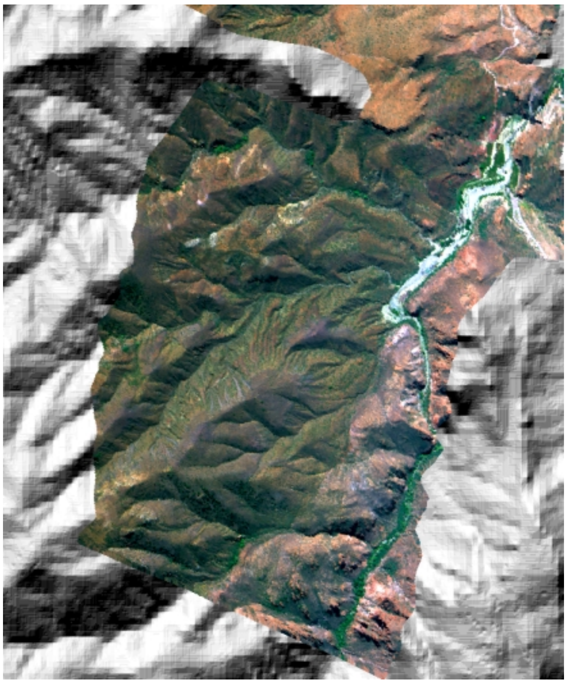

Figure 3: Overlay of the ortho-rectified AVIRIS low altitude imagery on the illumination-shaded USGS DEM.

1478 and 4487 contiguous scan lines, respectively. A relative accuracy of 1-2 high altitude pixels (20 - 40m) has been observed. This accuracy is within the accuracy of GCP measurement in the image. Some distortions are also caused by the non-availability of attitude measurements in high altitude auxiliary data streams and the non-differential GPS measurements of the aircraft position. For the low altitude scene, the residuals of the GCPs indicate an error in the range of down to 10m. Tests on more recent AVIRIS data containing complete attitude and DGPS information have still to be accomplished.

4.2 HyMap

Orthorectification of HyMap data (Cocks et al., 1998) has only be envisaged recently as the data of this Australian sensor has become available to a broad variety of users. An IGI INS has been mounted on the HyMap sensor head for dedicated campaigns in Europe in 1998 and 1999. In mid 1999 a Boeing C-MIGITS system was finally introduced to the HyMap system as standard measurement unit for all navigation parameters.

The ESA campaign in Barrax 1998 was driven by the goal to measure the spectral variability of agricultural areas under varying flight geometry conditions. A number of six data sets has been taken overlapping over the same area. These data sets have been co-registered using the PARGE application. The achieved accuracy based on the 15 GCPs residual was between 7 and 10 meters.

Differences between co-registered images are shown in Figure 4. Area dependent variations of the difference image can be attributed to the BRDF effects due to the 90 degree difference in flight heading. The relief-like appearance of the field borders on the other hand can be clearly attributed to the coregistration errors between the two images. The co-registration errors have been assessed by cross-correlation analysis of all six images. The results are summarized in Table 2. According to this table, the co-registration error for this Hymap imagery is between 1.3 and 2.2 pixels corresponding to 6.5 to 11 meters. This result confirms the residuals as derived from the GCPs.

Table 2. RMS cross correlation difference between six co-registered Hymap Images (pixels @5 m pixelsize)

x	r1_9	r1_12	r1_15	r2_9	r2_12	r2_15
r1_9	0	1.75	1.50	2.11	1.56	1.37
r2_9	2.11	1.94	2.16	0	2.29	1.44

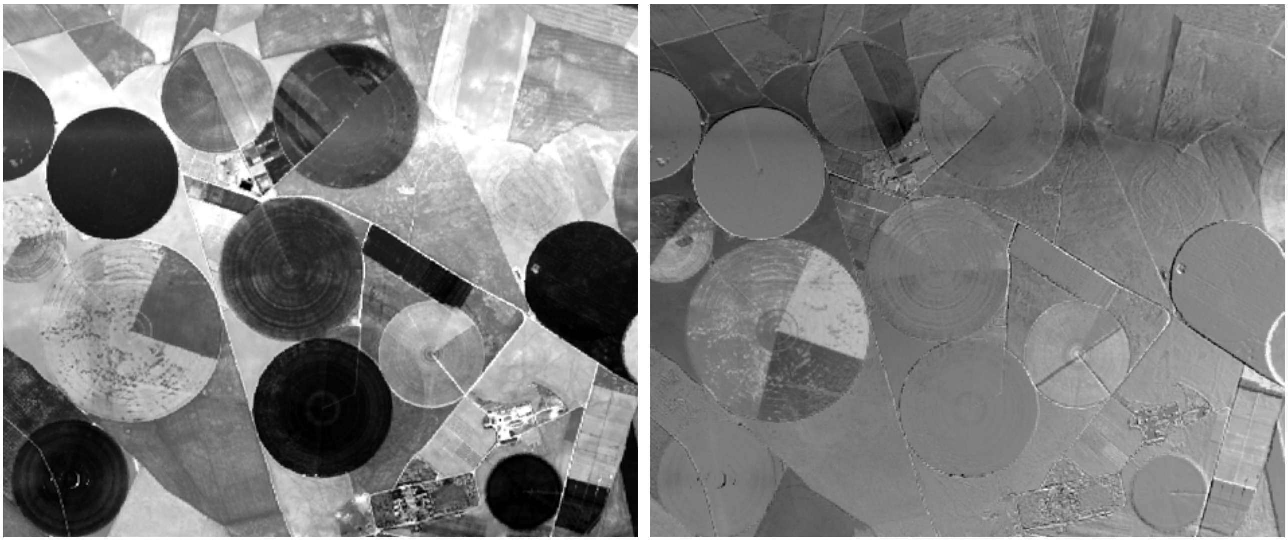

Figure 4: Barrax Co-Registered Hymap data. Left: Raw data at 598 nm wavelength. Right: Difference image between north-south and east-west flight including BRDF effects (Hot Spot) and border effects due to the co-registration errors.

The observed error can be attributed to the non-availability of a digital surface model and the moderate INS system calibration as used in 1998. Also, the number of GCPs were restricted to 15 and the processing had been done in an operational environment without much re-iteration efforts. The results still could be further optimized by adding in-field measured GCPs in relevant areas and by tuning the parameters carefully to fit the best GCPs.

5 CONCLUSIONS

A parametric geocoding methodolgy has been presented which can currently be used for operational processing of hyperspectral data. It allows for correction of attitude and flightpath dependent distortion and includes GCP based data re-calibration capabilities. Current imaging spectrometers such as AVIRIS, DAIS, and HyMap are supported while further airborne systems may be introduced later. The procedure proved to be flexible and operationally applicable to all these instrument even for data sets with partially corrupted or incomplete auxiliary data.

Although the theoretical accuracy of the method is in the sub-pixel range, current real-world results for available imaging spectrometer systems are in the range of 5 to 40 meter. This accuracies are about to increase substantiall as higher quality DEMs, GPS, and attitude data measurements become available. In-field measurements or availability of high accuracy GCPs is another prerequisite which would allow for better calibration of auxiliary data.

The PARGE application has been successfully joined with the radiometric and atmospheric correction package ATCOR4. This integration has been an important step to a complete fully physically based preprocessing chain for hyperspectral data. It will therefore being pursued for future hyperspectral instruments such as APEX. Further information about these applications and their availability may be obtained from the authors.

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