A PROGRAM FOR DIRECT GEOREFERENCING OF AIRBORNE AND SPACEBORNE LINE SCANNER IMAGES

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ABSTRACT:

For high quality direct georeferencing it is important that all geometric parameters influencing the rectification process are taken into account. These parameters are the exterior and interior orientation of the imaging system, the digital terrain model, the boresight misalignment and the mapping coordinate reference system.
For airborne scanner images covering an area of only some miles extension simplifying assumptions can be made without noticeable loss of accuracy; e.g. the position and attitude data can be directly related to the geographic reference system. In airborne applications a high precision navigation sensor system (IMU, DGPS) aligned to the scanner system was used to obtain the parameters of the exterior orientation. Orthoimages were generated with 1-2 pixel accuracy from pushbroom and whiskbroom scanner images.
To rectify space imagery it is necessary to use orthogonal coordinate systems (e.g. Local Topocentric Systems) in an intermediate processing step before finally the result are transformed to a map projection system. Orthoimages were produced from images of the German space camera MOMS-2P.
The software package RECTIFY was developed by DLR and serves as a generic geometry processor for data of different sensor types and navigation systems. It supports all well known coordinate- and map projection systems as well as different geodetic datums. Methods and theory underlying the software package and application examples of airborne and spaceborne imagery will be presented.

1. INTRODUCTION

One of the main processing steps of evaluating remote sensing data is the so called georeferencing or rectification of the acquired scanner data to a local coordinate system with given ellipsoid and datum. Since in most applications of thematic analysis, a rectified data set is required, there is a need for an effective – regarding time and accuracy - and generic – regarding different sensor systems – processor for performing this rectification for any desired sensor imagery. This is especially true when using the image data in Geographic Information Systems (GIS) and for data fusion and analysis with data from different sources or seasons. The accuracy of this rectification result is crucial for overlaying the data with existing data sets or maps and using them for evaluations like change detection, map updating a.o.. In this paper, a direct georeferencing method is shown to achieve a very accurate geocoding of remotely sensed data for the above mentioned purposes without using ground control.
The geometry of the raw data is influenced by several factors:

- The camera´s interior orientation
- The camera´s exterior orientation (position and attitude)
- The boresight misalignment angles between navigation sensor and camera system
- The topography of the earth surface

To perform a direct georeferencing, all this parameters have to be known with sufficient accuracy, this is the main point. If this accuracy is really high enough, then there is no need for using ground control points in the rectification process. The conditions and limitations for this case are also given in this paper. The interior orientation of the camera has to be known in advance by laboratory or in-flight calibration procedures. The exterior orientation has to be measured during the overflight by using GPS (or better DGPS) measurements for position and INS (Inertial Navigation System) for the attitude. The amplitudes of the attitude variations are significantly higher for aircraft movements than for satellite movements. This is due to wind velocity and air turbulence, therefore the distortions of airborne image data can be large if there is no compensation through stabilized platforms or other methods. To get an optimized data set, the read-out frequency of the INS should be at least as high as the line frequency of the scanner and the time synchronisation has to be very precise. The boresight alignment has to be calibrated. The influence of the surface topography is depending on the flight altitude and the field of view of the sensor. Since the total field of view may be wide and the flight altitude as low as 300 meter, even small height variations of the ground will affect the image geometry by shifting the recorded pixel location with respect to the true position and by affecting the pixel size on ground. The height accuracy of the Digital Elevation Model (DEM) should therefore be in the order of the pixel size for airborne data.
As a further requirement for the rectified data, the resampling procedure should be elaborated in such a way that nearly no information loss occurs. To achieve this a method using bilinear interpolation in an irregular grid was applied during the process of georeferencing.

The direct georeferencing process has been adressed by various authors in the last years (Bäumker 2001, Cramer 2001, Ellum 2002, Jacobsen 2001, Mostafa 2001)

2. CONCEPT OF ORTHOIMAGE PRODUCTION

Remotely sensed data, especially line scanner imagery, are geometrically distorted with respect to a mapping frame. The upcoming high precision direct georeferencing systems consisting of a GPS/IMU and one or more imaging sensors can be used for ortho-mapping, when using a DEM (Digital Elevation Model). The utilisation of direct measurements of the image exterior orientation parameters by a GPS/IMU system for image rectification is called Direct Georeferencing and allows a fast automatic ortho-rectification of the sensor data. The concept of a Direct Georeferencing system is illustrated in figure 1.

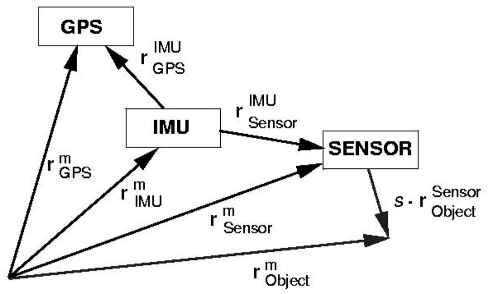

Figure 1 Concept of direct georeferncing

The collinearity concept is the basis for all direct georeferencing formulas, where the coordinates of an object point r^{Sensor}_{Object} measured in the imaging sensor's coordinate frame are related to the coordinates r^{m}_{Object} in the mapping coordinate frame.

$$r^{m}_{Object} = r^{m}_{Sensor} + s \cdot R^{m}_{IMU} R^{IMU}_{Sensor} \cdot r^{Sensor}_{Object} \qquad (1)$$

with the actual position of the projection center of the sensor

$$r^{m}_{Sensor} = r^{m}_{GPS} - R^{m}_{IMU} \cdot r^{IMU}_{GPS} + R^{m}_{IMU} \cdot r^{IMU}_{Sensor} \qquad (2)$$

The lower indices of the vectors ***r*** indicate the position of the points, whereas the upper indices denote the coordinate frame in which the vector is measured. The notation of the indices of the rotation matrices ***R*** indicates the transformation direction where the lower index represents the source system and the upper index the destination system. The meaning of the various parameters is explained in table 1.

m	Index which represents the mapping coordinate frame
r^{m}_{Object}	Vector to the object point on the earth surface in the mapping frame, which has to be determined
r^{Sensor}_{Object}	Vector from image point, which is measured by the sensor pixel location, to the corresponding object point on the earth surface in the sensor frame.
r^{m}_{Sensor}	Vector to the projection center of the sensor in the mapping frame, which is calculated using the integrated GPS/IMU data and the lever arm correction values measured during the hangar calibration procedure. Normally determined during postprocessing step.
R^{IMU}_{Sensor}	Rotation matrix between IMU and sensor coordinate frames, which accounts for possible tilt angles of the sensor mirror or boresight misalignment angles (determined during calibration)
R^{m}_{IMU}	Rotation matrix between IMU and mapping coordinate frames, which is measured by the GPS/IMU system.
s	Scale factor determined by a DEM (or stereo processing techniques)
r^{m}_{GPS}	Measured vector to GPS antenna given in the mapping coordinate frame.
r^{IMU}_{GPS}	Vector from IMU to GPS measured in the IMU coordinate frame during hangar calibration (lever arm determination)
r^{IMU}_{Sensor}	Vector from IMU to sensor projection center measured in the IMU coordinate frame during hangar calibration (lever arm determination)
r^{m}_{IMU}	Vector to IMU in the mapping coordinate frame, which is calculated using the integrated GPS/IMU data and lever arm corrections.

Table 1 Definition of parameters

The whole process of orthoimage production is very sensitive against a non rigorous data handling and is explained in more detail using the basic concept described above (Müller 1999).

2.1 Airborne Sensor Data

Normally the vector r^{m}_{Sensor} (or the vector r^{m}_{IMU}) is calculated in a postprocessing step using the lever arm correction data measured during the hangar calibration procedure with the GPS/IMU software and can be used for a generic orthoimage processor after transforming to the mapping coordinate frame.
Three right handed coordinate frames for the airborne case are introduced

- The navigation coordinate frame (index: nav) is a local level coordinate system with x to the north, y to the west and z vertical in opposite direction of the plumb line. In the case of a moving airplane this coordinate system is not static in respect to a earth centered earth fixed coordinate system (index: ECEF), but changes with the position of the aircraft. The navigation frame is directly correlated to the mapping frame (see figure 2).

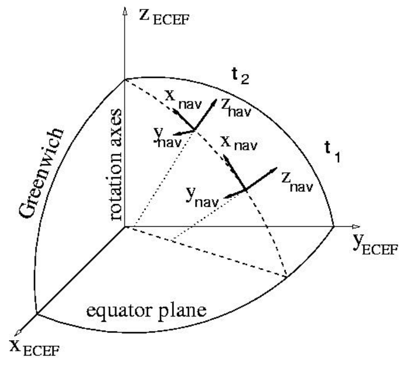

Figure 2 Navigation coordinate frame at times t_1 and t_2

- The IMU or body fixed coordinate frame normally is aligned with the principle axes of the aircraft with x to the nose, y to the left wing and z vertical up of the aircraft, which is a slight different definition to the ARINC 705 aviation norm using a NED (North-East-Down) coordinate frame. The three angles roll ω, pitch φ and heading κ are measured with respect to the navigation frame (figure 3).

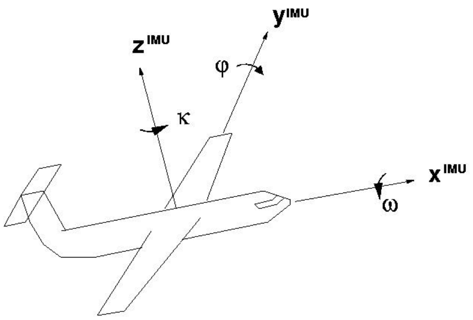

Figure 3 IMU or body fixed coordinate frame

- The image or sensor coordinate frame is located at the projection center of the sensor with x to the top (flight direction), y to the left or right of the image line depending on the scan- or read out direction, when looking from the projection center to the negative z axes (figure 4).

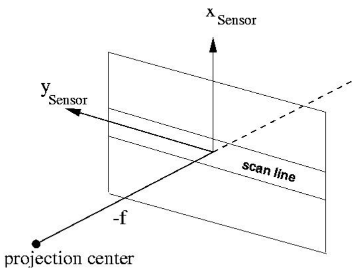

Figure 4 Sensor coordinate frame (with *f* the focal length)

For a mathematically exact definition of the mapping coordinate frame additional transformations are necessary. First transform the navigation coordinate frame, which is a moving local topocentric system (LTS) described by the moving fundamental point, to an earth centered earth fixed (ECEF) coordinate system. Second transform this ECEF coordinate frame to a LTS with a fixed fundamental point usually located at the center of the image stripe.
Using a LTS as mapping frame requires the availibilty of the DEM in this system too. Therefore, without any significant loss of accuracy of the orthoimage, the following approximation for airborne sensor data can be made:

- A map projection like UTM is used as mapping system due to the small swath width of airborne line scanner data.

In this case the attitude angle heading has to be corrected for the meridian deviation using equation 3,

$$k_{\text{geodetic}} = k_{\text{geographic}} - tan^{-1}(sin\Phi \cdot tan(l - l_{cm})) \qquad (3)$$

where Φ is the latitude, λ the longitude of the actual aircraft position and l_{cm} the central meridian of the map projection. The meridian deviation for UTM with 6° zones is up to 2.2°.

The position data r^{m}_{Sensor} are given by longitude, latitude and ellipsoid height with respect to the geodetic datum WGS84. Therefore a geodetic transformation and undulation correction of the position data has to be performed in order to be in the same coordinate system as the DEM, used for the ortho mapping. This transformation of the position data to the reference system of the mapping frame requires the target projection (e.g. UTM, Gauss-Krueger,...), the target geodetic datum given by the earth ellipsoid parameters and the seven parameters for a Helmert transformation and the geoid undulation (see figure 5): Wrong geodetic datum references can result in position errors of hundreds of meter.

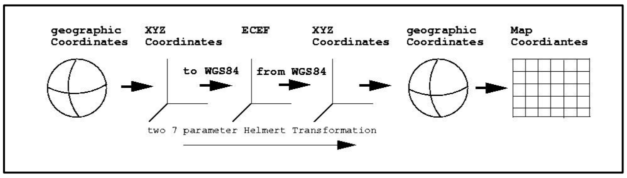

Figure 5 General steps to change the reference system from (longitude, latitude) to a map projection like UTM or Gauss-Krueger. The geoid undulations in respect to WGS84 EGM96 (Earth Gravity Model) can be interpolated from known databases available from NIMA (National Imagery and Mapping Agency). **http://www.nima.mil/**

For the interior orientation two sensor models are distinguished.

Whiskbroom sensors are working as electromechanical scanners with mirrors sweep from one edge of the swath to the other. For the whiskbroom sensor model the recorded pixels are assumed to be on a straight line. For the across track pixel coordinates y_i a constant scan angle increment for successive pixels is assumed. Using the maximum scan angle q_{max} and the number of pixels *N* in one scan line lead to the pixel coordinates

$$y_i = \tan(q_i) \cdot f\,;\, x_i = 0, \text{ with } i = 0, \cdots, N-1$$

$$\text{with } f = \frac{N-1}{q_{\max}} \text{ the focal length} \qquad (5)$$

$$\text{and } q_i = -\frac{q_{\max}}{2} + i \cdot \frac{q_{\max}}{N-1} \text{ the actual scan angle}$$

The maximum scan angle q_{max} is a well known calibration value. Figure 6 shows the model of the whiskbroom sensor.

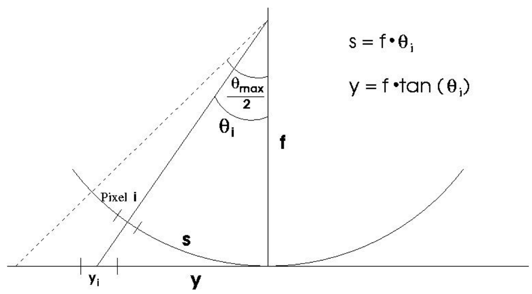

Figure 6 Sensor model for whiskbroom imagers

Pushbroom sensors are electronic scanners using a line detector (CCD) to scan over a two dimensional scene. For the pushbroom sensor model the along track displacement of all recorded pixels of a scanline is set to zero. For the across track pixel coordinates a constant spacing of successive pixels is assumed. The focal length in pixel units is calculated using the maximum scan angle q_{max} and the number of pixels *N* in one scan line.

$$y_i = -\frac{N-1}{2} + i\,;\; x_i = 0, \text{ with } i = 0,\ldots,N-1$$
$$\text{with } f = \frac{N-1}{2} \Big/ \tan\frac{\theta_{max}}{2} \text{ the focal length} \tag{7}$$

Figure 7 shows the model of the pushbroom sensor.

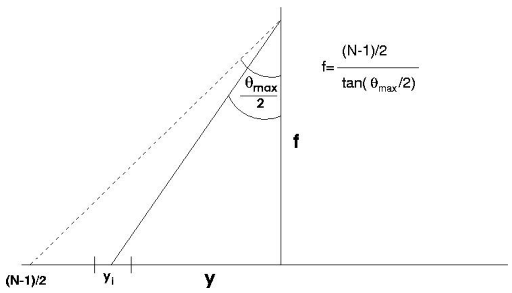

Figure 7 Sensor model for pushbroom imagers

Deviation from these ideal sensor models, like principle point shifts, relative geometric calibration values, etc., determined by laboratory or in flight calibration procedures can be applied to these models.
The determination of the scaling factor *s* is a very critical point in direct georeferencing of single imagery, because the accuracy of the DEM is directly related to the accuracy of the orthoimage, especially for sensors with a wide field of view. For the ortho rectification process only the relative height difference between aircraft altitude and DEM is important. Therefore it is recommended to use the same geoid for the DEM production and the aircraft altitude calculation. In order to get the intersection point of the actual sensor look direction r_{Object}^{Sensor} and the surface, described by a DEM, an iterative procedure can be used, which is illustrated in figure 8. During the processing the reference plane should be always adjusted to a previous found height to avoid multiple intersection points. The iteration stops if the changes in horizontal direction is lower than 0.1 pixel size.

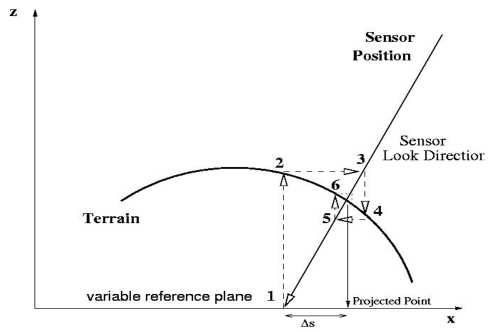

Figure 8 Iterative determination of the intersection point of the sensor look direction and the DEM.

With equation (1) the relation between the object coordinates measured in the image and the real world coordinates in the case of an ideal sensor can be written

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix}_{Object}^{UTM} = f_{geo}^{UTM} \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{Sensor}^{geo} + s \cdot R_{IMU}^{UTM}\, R_{Sensor}^{IMU} \begin{pmatrix} 0 \\ y_i \\ -f \end{pmatrix}_{Object}^{Sensor} \tag{8}$$

where the function f_{geo}^{UTM} describes the projection from longitude, latitude and ellipsoid height to the transverse mercator map projection UTM with geoid heights and R_{IMU}^{UTM} includes the transformation of the attitude angles (meridian deviation). For every scan line of the sensor the six parameters of the exterior orientation (position and attitude) are interpolated using the time stamps of the GPS/IMU data and the image data (for example using the PPS (Pulse per Second) of the GPS receiver or using two different GPS clocks).
The direct method based on transformed polygons is used for the bilinear or nearest neighbour resampling of the orthoimage pixel values. The principle of the resampling technique is shown in figure 9.

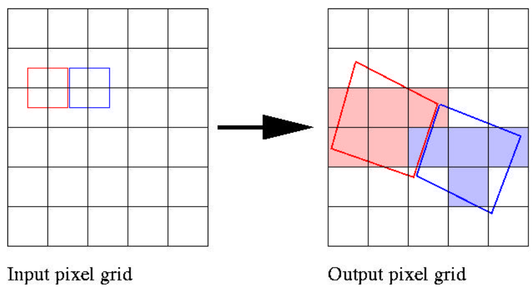

Figure 9 Resampling technique: Polygons are transformed to the output pixel grid and filled with an interpolated or nearest neighbour pixel value

The determination of the boresight misalignment angles is performed by using a calibration field of GCPs. To this end the collinearity equation 8 is linearized by a Taylor series and solved by an iterative least squares fit.

2.1.1 Accuracy of Airborne Orthoimages

For the accuracy assessment orthoimages of three different multispectral sensors (see table 2) were investigated. The image data were aquired from the same test site located at DLR Oberpfaffenhofen.

Sensor	**ROSIS-03**	**DAIS 7915**	**Daedalus 1256**
Type	pushbroom	whiskbroom	whiskbroom
FOV [°]	17.37	51.20	85.92
IFOV [mrad]	0.59	3.3	2.5
altitude above ground [m]	3230	3230	2030
resolution [m]	1.9	10.7	5.1

Table 2: Parameters of the three used airborne scanners

An IGI AeroControl CCNS IIb (Grimm 2001) was used for the determination of the parameters of the exterior orientation. The manufacturers´ instructions of the accuracy of the GPS/IMU system for the position is about 0.1-0.3m using a GPS reference station and about 1-3m using the OmniSTAR Satellite service. The accuracy for the heading angle is 0.1° and 0.01° for the roll and pitch angle.
The line scanners ROSIS-03 and DAIS 7915 were mounted together in the aircraft with the CCNS. The Daedalus 1256 scanner was seperately flown with the CCNS directly mounted and aligned on the base plate of the scanner to minimise the boresight misalignment angles. The lever arm corrections were taken into account during postprocessing of the raw position

and attitude data with the software delivered with the CCNS hardware resulting in the position of the projection centers of the scanners. Unfortunately the OmniSTAR service for the GPS position resulting in a position accuracy of 1-3m, was activated during the Daedalus 1256 data aquisation. For the ROSIS-03 and DAIS 7915 the reference station located on one of the roofs of the DLR buildings could be used with a position accuracy of about 0.1m. For the synchronisation of the elements of the exterior orientation with the image scanlines of the scanners the PPS (Pulse per Second) of the GPS for ROSIS-03 and Daedalus 1256 was used, whereas DAIS 7915 had an independent GPS clock. A DEM derived from the ERS-1/2 Tandem mission with 5-10m vertical accuracy and 25m horizontal resolution served as input for the rectification of the three images. The comparison of this DEM with a DEM (covering only partially the test site) derived from a aerial image stereo pair emphasises the accuracy of the used DEM with mean height differences less than one meter measured at six corresponding points. The boresight misalignment angles were determined with 7 GCPs for DAIS 7915 and Daedalus 1256 and 5 GCPs for ROSIS-03 well distributed over the scanned image area. The accuracy of the GCPs was better than 0.1m. The comparison of the control points (also measured with DGPS) with the corresponding points manually measured in the orthoimages is listed in table 3.

sensor	**DAIS 7915**		**ROSIS-03**		**Daedalus 1256**	
resolution [m]	10.7		1.9		5.1	
control points	22		12		21	
direction	north	east	north	east	north	east
absolute deviation [m]	0.98	-0.57	1.43	-0.04	-0.05	-3.03
RMS [m]	1.68	1.49	1.67	1.21	2.92	3.19
boresight misalignment (ω,φ,κ) [°]	-0.375 0.867 -0.479		-0.399 -1.317 0.140		0.419 0.242 -0.049	

Table 3: Accuracy of the airborne orthoimages and the determined boresight misalignment angles

For the Daedalus 1256 scanner the moment of inertia of the (heavy) rotating scan mirror leads to a non constant rotation speed during a roll movement which is corrected with a linear model.

$$w_{corrected} = w_{measured} + c \cdot \frac{dw_{cmeasured}}{dt} \qquad (9)$$

where *dt* is the time between two scan lines of the Daedalus image, $\omega_{measured}$ the measured roll angle and *c =-1.4* an empirically determined constant. This correction of the roll angle leads to an improvement of 0.95m in the RMS value. There are ongoing investigations on this effect.
The geometric accuracy of the orthoimages is better than a pixel size for all three sensors. Although the CCNS was directly mounted on the Daedalus sensor, the boresight misalignment angles have to be taken into account.

2.2 Spaceborne Sensor Data

The orthoimage production for spaceborne sensor data is explained by means of MOMS-2P imagery. The MOMS-2P sensor (**M**odular **O**ptoelectronic **M**ultispectral Stereo **S**canner) was a German stereo camera mounted on the PRIRODA module of the Russian space station MIR. Its main new feature was the along-track three-fold stereo capability. It delivered approx. 65 million km^2 of high quality and high resolution (approx. 18m ground resolution) imagery during its operation from 1996 to 1999, which is still subject of ongoing image processing to generate digital elevation models and orthoimages in all parts of the world. (Schroeder 2000)
The three-fold along-track stereo principle and multispectral capabilities of the MOMS-2P sensor were highly advantageous for digital elevation model (DEM) generation compared to other satellite systems in orbit. The majority of all data takes of MOMS-2P were imaged with the two inclined stereo and two nadir looking multispectral channels (blue and near-infrared) with a swath width of approx. 100km and a ground resolution of 18m. The data of this mode is well applicable for generating digital elevation models and using the multispectral imagery for creating orthoimages, landuse-classification and further evaluations.
In order to produce digital elevation models and orthoimages from MOMS-2P stereo data a stereo software for workstations has been established at DLR (see also Kornus 1999). This was done in cooperation with the photogrammetric chairs of several German universities. The main steps of the processing chain are:

- Matching for generating tie points between the 3 looking directions of MOMS stereo data; these tie points are input to photogrammetric bundle adjustment and Otto-Chau region-growing
- Preprocessing of orbit and attitude data
- Photogrammetric bundle adjustment for the estimation of the absolute values of interior and exterior orientation of the camera during imaging of the current data strip
- Matching for a very dense tie point distribution using Otto-Chau region-growing method with mass seed points from previous matching
- Forward intersection to compute the ground coordinates of the tie points based on the reconstructed interior and exterior orientation
- Generation of a regular DEM by two-dimensional interpolation
- Calculation of orthoimages based on the regular DEM and the orientation data

The inputs for the orthoimage production are the interior orientation (including the geometric calibration values of the CCD lines acquired by laboratory measurements), the six parameters of the exterior orientation for each image line, the regular DSM (Digital Surface Model) derived from the MOMS-2P stereo data and the image data itself, which will be transformed to the orthoimage. The exterior orientation as well as the DSM is given in the unique cartesian coordinate system of a local topocentric system (LTS), described by the fundamental point and the geodetic datum. The principle of the orthoimage production is based on the forward intersection of the actual sensor viewing direction (pointing vector) and the DSM using the rigorous collinearity equation. The difference between airborne and spaceborne orthoimage production is the use of an orthogonal coordinate system like LTS or ECEF as mapping frame. The LTS coordinate frame is the preferred system, because the interpretation of the parameters of the exterior orientation is more descriptive. Internally the orthoimage processor calculates the object points in this intermediate coordinate frame and then transforms them to map projected coordinates.

2.2.1 Example of MOMS-2P Orthoimage

Figure 10 shows an example of an MOMS-2P orthoimage in the area of Suez Channel in Egypt with the overlay of the shore lines and courses of rivers. The two inclined stereo channels and one nadir channel were used to generate the colour orthoimage. The different channels fit very well (no colour shifts can be detected), which signifies the quality of the orthoimage

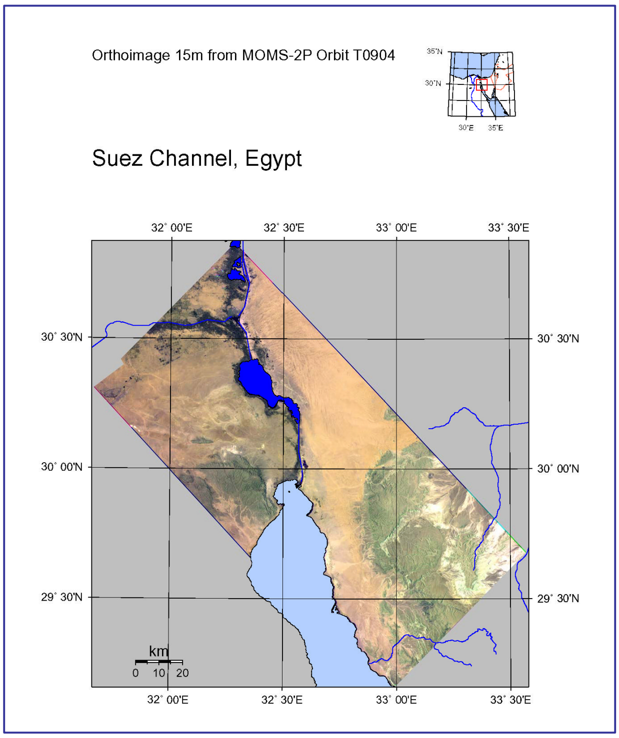

Figure 10 Orthoimage of MOMS-2P with 15m grid size in the area of Suez Channel, Egypt. Projection: longitude, latitude (WGS84)

3. ORTHOIMAGE PROCESSOR

The orthoimage processor RECTIFY, initially developed at DLR in 1996, has a modular software structure, which distinguishes between sensor specific processing steps and pure algorithmic parts, concerning the orthoimage production. A defined data interface between the modules supports an easy rectification of images from a lot of sensors. The features of this tool are the

- support of whiskbroom and pushbroom sensor models or tables for interior orientation
- characterisation of GPS/IMU system like rotation sequence, coordinate system,...
- support of 32 map projections including ECEF and LTS, and 115 predefined geodetic datums or free geodetic datum definition
- possibility of the estimation of the boresight misalignment angles during processing
- bilinear or nearest neighbour resampling technique to a desired resolution of the orthoimage
- automation of the process (batch job capable)
- acceptance of mean height values (operation without DEM)

For an image scene of about 1000x1000 pixels the computation time for an orthoimage is about 30 seconds on a SGI O_2.

4. CONCLUSION

For airborne and spaceborne imagery the same orthoimage processor can be used assuming the data interface to the core processor is standardised and the software is modular structured. The basic concept of direct georeferencing was realised with the orthoimage software RECTIFY including the main sensor models for line scanners, the multitude of map projections and geodetic datum transformations and the determination of the boresight misalignment angles. The achieved geometric accuracy for airborne orthoimages is for standard ground resolutions of about 1-10m in the range of one pixel size, if the boresight misalignment angles are calibrated. The automatic orthoimage processor RECTIFY is foreseen to be integrated in the DLR Data and Information Managment System DIMS.

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