STEREO PROCESSING WITH ATTITUDE-DISTURBED IMAGE DATA

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KEY WORDS: remote sensing, stereo camera, CCD line scanner,DEM, attitude measurement

ABSTRACT

We are now on an intersection point of three developments leading to a new quality of stereo photogrammetry:

- development of metric large CCD-lines,
- highly accuracy attitude measurements and
- nearly unlimited processing and storage capabilities.

In this paper approaches and algorithms for 3-D processing of attitude-disturbed images are published. Therefore an optical fibre gyro system was installed to overcome the problems of attitude inaccuracy.

Using attitude and camera calibration data the image strips can be geometrically corrected. The geometrically corrected images are a necessary data product for further 3-D processing and allow also a simple coordinate measurement and the generation of digital elevation models (DEM).

1. INTRODUCTION

The Wide-Angle Optoelectronic Stereo Scanner (WAOSS) is one of the remote sensing instruments of the Mars-96 orbiter. The basic scientific objectives are the global imaging of Mars' surface and atmosphere for the investigation of meteorological, climatological and related surface phenomena and changes.

These special mission objectives, a highly elliptical orbit and the camera design require a very flexible concept of sensor-signal processing and evaluation algorithms. The development and tests of algorithms with current data are necessary and for this purpose an airborne-sample of the future satellite camera was manufactured and flown (see [1]).

The use of WAOSS on board aeroplanes instead of satellites causes changes in measurement and evaluation procedures, particularly the attitude instabilities of the aircraft (roll, yaw, pitch, ground speed and altitude variation) which are much more pronounced than those of the satellite. A stabilizing aircraft platform was not used for reasons of simplicity, size, weight and funding.

Concerning the data evaluation of an image strip recorded from an airborne camera the principal disadvantage of a line sensor is that the attitude parameters are necessary for each row in the image.

Due to the inaccuracy of the inertial navigation system (INS) conventional photogrammetric methods use additional control points on the Earth's surface to improve the attitude parameters. The application of this approach to images from a line sensor needs a model for the flight path and an iterative improvement for the attitude parameters with additional ground control points (GCP) (see [5]).

The algorithms described in this paper requires no or only a small number of GCPs. Therefore an optical fibre gyro system was installed to overcome the problems of attitude inaccuracy. This measurement approach makes a platform unnecessary.

Using attitude and camera calibration data the image strips of the nadir, the backward and the forward looking line can be geometrically corrected assuming a flat underlying surface. This image product is equivalent to an undisturbed flight over a flat surface. If these strips are processed on the same mean flight path the correction procedure is equivalent to the conventional interior and exterior orientation and gives epipolar-like images.

The geometrically corrected images are a necessary preprocessed data product for further 3-D processing and allow also a simple coordinate measurement with a photogrammetric workstation for example.

This procedure also increases the image quality (e.g. streets become straight lines) and influences the number of matched points. Two different ways for the generation of digital elevation models (DEM) have been analysed:

- matching and DEM generation with geometrically corrected images
- matching and DEM generation using the attitude information directly.

The independence of additional GCPs and straightforward algorithms make an on-line approach for DEM generation or DEM improvement on board the aircraft possible.

2. ATTITUDE DETERMINATION

Known methods are able to evaluate 3-D models from line scanner data only if the attitude disturbances of the aircraft are small compared with the instantaneous field of view (IFOV) of the camera (e.g.[3]).

To overcome this problem it is necessary to measure and incorporate exact attitude data in the retrieving algorithm.This concerns especially the angular attitude data.

The camera was rigidly mounted in the aircraft's tail and the aircraft axis coincided with the camera axis. The

INS was placed in the nose of the Do 228. Deviations between the aeroplane motion and the camera motion were expected and the measurement were in the order of a few arcminutes. To compensate for this a gyro block was mounted directly on the camera base plate. As the attitude angles given by the INS do not have the necessary accuracy, an optical fibre gyro system should be used instead of the installed INS.

Supplementary measurements with GCPs, for example, are necessary for the precise determination of camera orientation in the aircraft and of angle offsets.

During the imaging the following attitude data was recorded: The altitude (GPS and Inertial Navigation System INS of the aircraft), the ground speed (GPS and INS), the flight path angle (GPS), yaw, pitch and roll angle (INS), and the angular velocity (3 fibre optical gyros).

The gyro sampling rate was 1 KHz (compared to the INS witch had a rate of 100 Hz). The possible measurement range is 0 to 400 degree/s and the resolution 50 degree/h. The angular are calculated from the velocities by integration of the angle velocity. The accuracy of the angles is more precise than the IFOV of a sensor pixel.

The evaluation procedure was explained in [2]. The integration of the angular velocity leads to an unavoidable drift rate caused by stochastical velocity errors, which was then corrected off-line by comparing gyro data and INS data. The usual drift rate for 1000 recorded lines is 15 pixel.

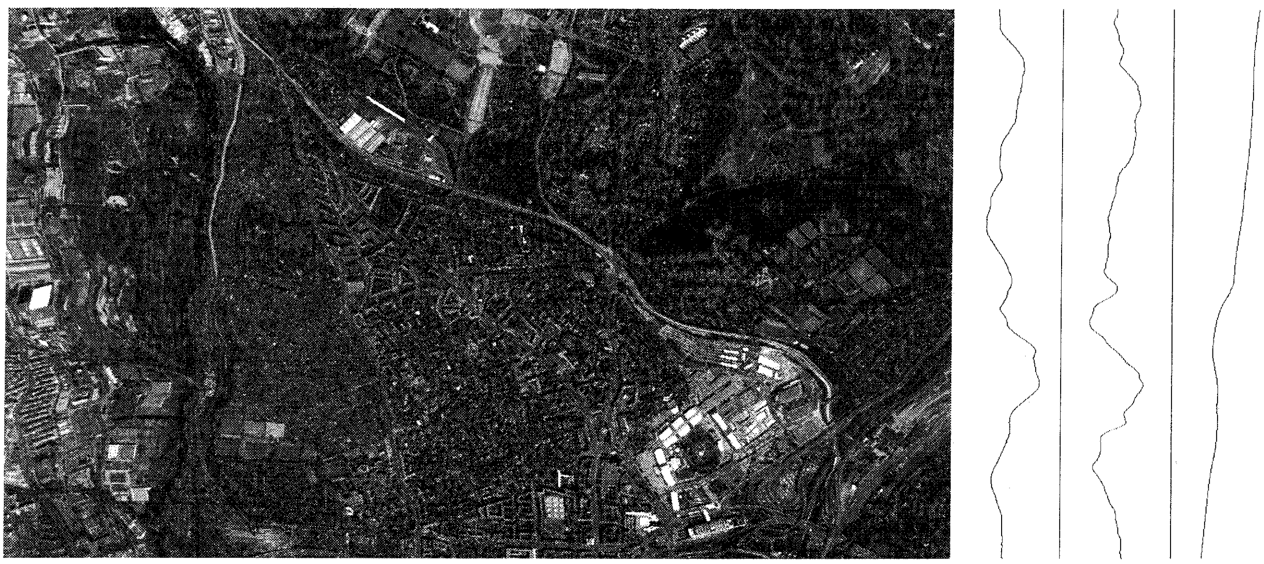

Figure 1 Image of the WAOSS camera

Figure 1 shows an image of the WAOSS camera, which was recorded during a flight over the city of Berlin. The image size is 5184x3000 pixels. The ground pixel size is 1mx1m.

The influence of the aircraft motion is obviously visible in the left margin of the image. The three columns on the right hand side of the figure show the roll, pitch and yaw angular change.The interval for roll angle is [-0.5°,2.4°], for the pitch [4.0°,4.4°] and for the yaw [86°,96°].

3. CORRECTION OF AIRCRAFT ATTITUDE INSTABILITIES

With the knowledge of the attitude parameters a correction of the image strip is possible. The algorithm is processed in two steps:

1. Determination of the geometric relations in the object space for each CCD-line pixel results from the disturbed aeroplane movement

This task is equivalent to ray-tracing from real position and direction into the digital elevation model (DEM). As the original DEM is unknown, an ideal DEM is assumed as a reference plane at $z = z_i$.

The following calculation is made for the object-space. Geometric relations are as follows:

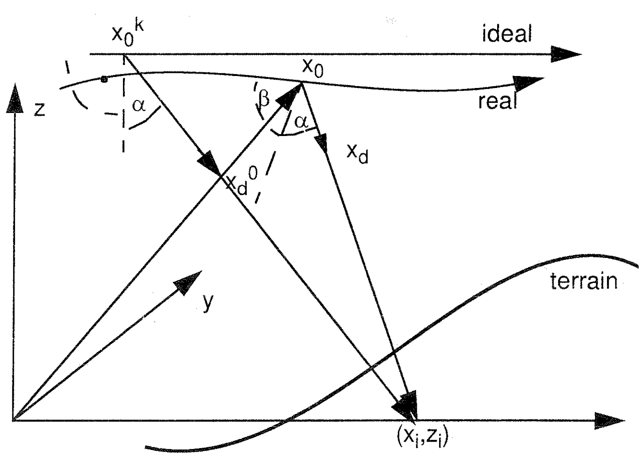

Figure 2 Aircraft attitude instabilities

The intersection point with the surface is

$$\underline{x}_i = \underline{x}_0 + t \cdot \underline{x}_d . \qquad (3\text{-}1)$$

with

$\underline{x}_0$ current camera location

$\underline{x}_i$ intersection point with reference plane at z_i

The actual disturbed direction vector $\underline{x}_d$ is related to the undisturbed by a rotation matrix **M**.

$$\underline{x}_d = \mathbf{M} \cdot \underline{x}_d^0 \qquad (3\text{-}2)$$

M contains the disturbance of the flight path: roll, pitch and yaw, as described before. In the example (Figure 2) the angle β corresponds to the pitch of the aeroplane and the angle α is the stereo angle.

2. Back projection from the intersection point with the reference plane into the image plane of the camera moving on an ideal (undisturbed) linear flight path.

The simplest approach is the projection of the object point into the image space or focal plane on an ideal flight path not affected by disturbances. By this procedure the data will be sorted and corrected.

The back projection procedure only works for some well known, but simple, flight trajectories. It is necessary to find a functional dependence for the projection point of the vector on an ideal flight trajectory $\underline{x}_0^k$ (see Figure 2). So for the whole measured swath the number of parameters for describing the external orientation can be reduced, and they are determined by the flight parameters such as velocity v and height h_f.

The aircraft has linear uniform motion $v \cdot \tau$ on a track at an altitude of $z = h_f$. The question is, which pixel in the row i and in the column j of the image strip sees the point $\underline{x}_i$ on the reference plane. We have the three equations

$$\begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix} = \begin{bmatrix} x_0^k(j) \\ y_0^k(j) \\ h_f \end{bmatrix} + t \cdot \begin{bmatrix} x_d^0(i) \\ y_d^0(i) \\ z_d^0 \end{bmatrix} \qquad (3\text{-}3)$$

- $\underline{x}_0^k(j)$ projection point of the vector on an ideal flight trajectory
- $\underline{x}_d^0(i)$ viewing angle without disturbances

with the unknown parameters t and (i,j).

Because of the 'push broom' principle the numerical order of the lines results from the movement of the aircraft in the object space. The counting of the pixels in a CCD-line will be performed in the image space.

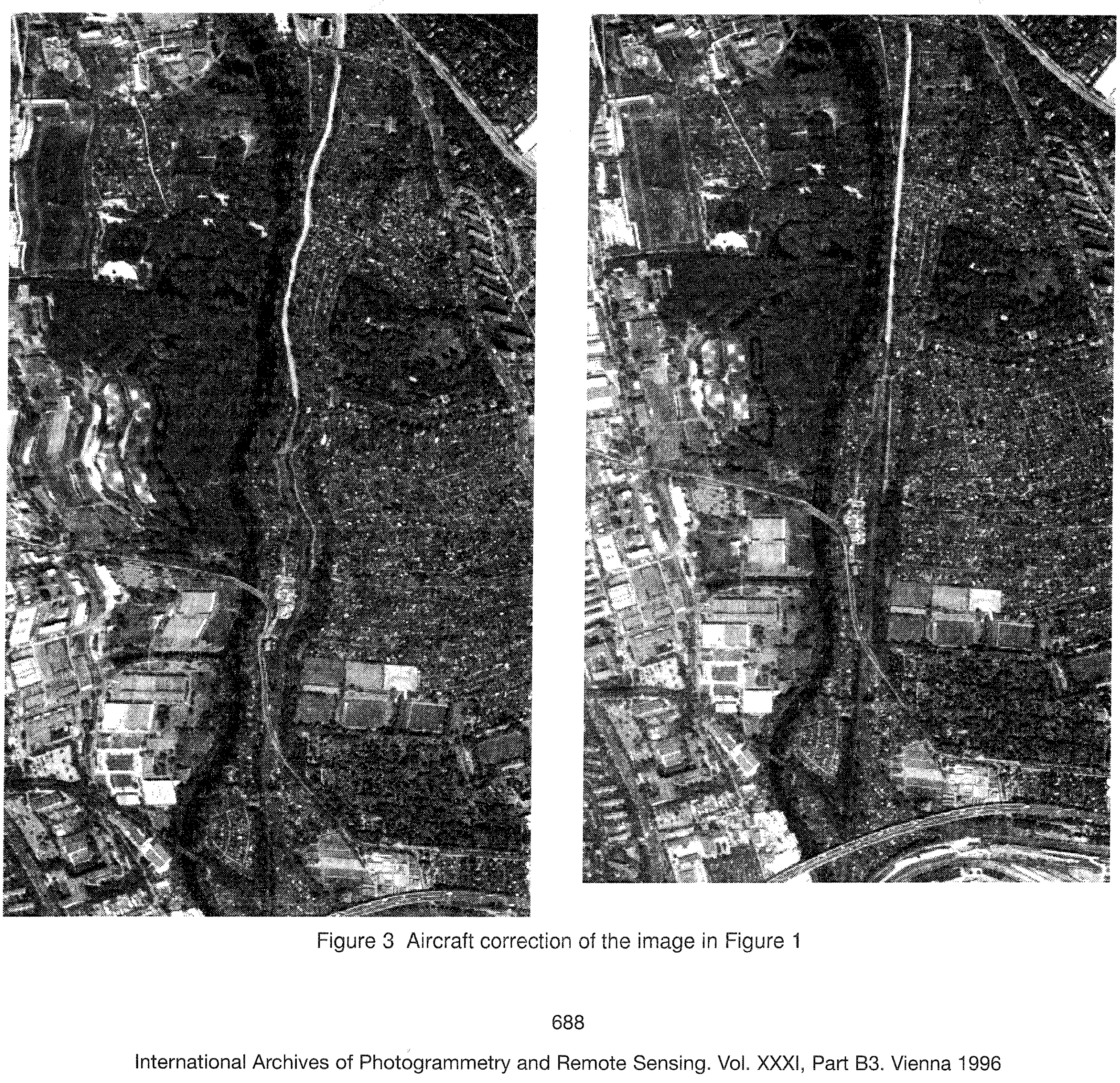

Figure 3 Aircraft correction of the image in Figure 1

The true height at the measured point can be calculated with (4-5) and the known attitude parameters (4-6).

The height error affecting only the row difference of the corrected image is

$$\frac{\Delta h}{h} = 1 - \frac{\delta \overline{x_d}}{\delta x_d} \qquad (4\text{-}7)$$

5. STEREO RECONSTRUCTION

The following procedure was used for the reconstruction of a digital elevation model (DEM) . The first step is finding conjugated points in at least two different images using a matching algorithm. With the knowledge of their coordinates in the focal plane and of the attitude of the sensor, so-called pixel rays can be defined.

$$\underline{x}_{in} = \underline{x}_{0n} + t \cdot \underline{x}_{dn} \qquad (5\text{-}1)$$

$\underline{x}_{0n}$ current camera location,

$\underline{x}_{dn}$ camera's direction vector,

t unknown parameter,

where n is the number of the current line.

Under ideal circumstances the three coordinates of an object point in the terrain are given by the intersection point of these rays. Because of the discretization errors caused by the finite resolution of the camera, there is no intersection point. So an error criterion must be defined to determine the vector with the smallest distance between the rays. This vector gives the 3D-coordinates of the reconstructed point.

$$\hat{\underline{x}}_i = \underline{x}^0_0 + t_0 \cdot \underline{x}^0_d + \underline{\xi}_0 = \underline{x}^1_0 + t_1 \cdot \underline{x}^1_d + \underline{\xi}_1 \qquad (5\text{-}2)$$

$\hat{\underline{x}}_i$ estimated intersection point

$\underline{\xi}_n$ deviation between estimated and real intersection point.

Equation (5-2) demonstrates the idea for two rays. The estimated intersection point between the rays and the terrain is defined as the vector, where the error is minimal.

Figure 6 shows this approach for a CCD-line scanner.

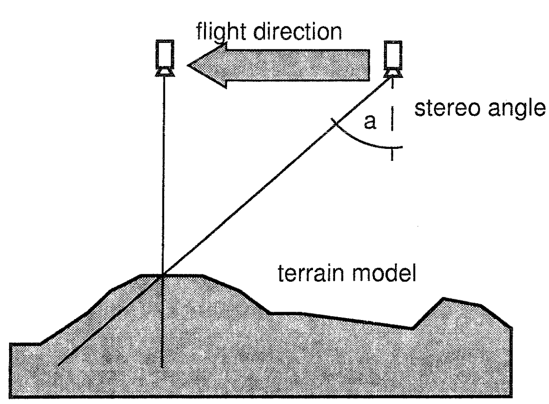

Figure 6 3D-coordinates of the reconstructed point

After the matching procedure pixels of different CCD-lines are related to the same object point. Pixel rays were defined and the three coordinates of the point in the object space where obtained. If a sufficient number of terrain points could be calculated, a DEM can be retrieved by a two-dimensional interpolation algorithm. This procedure was executed with simulated image data and yielded excellent results[4].

Figure 7 shows the different ways of generating digital elevation models using the received image data.

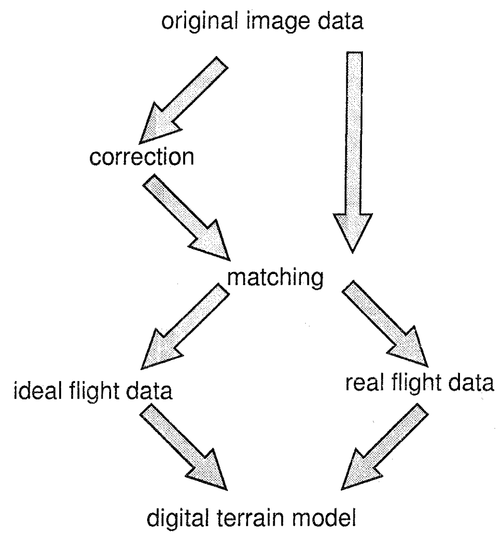

Figure 7 Ways of DEM generation

The first possibility is to correct the disturbed image data as shown in a previous section. The result is an image file without any relevant effects caused by the flight motions, like blurs and pixel shifts. The ideal attitude data can be used for defining pixel rays. After that a DEM can be built. A disadvantage of this procedure is that the correction algorithm can cause height deviations in the DEM as derived in equ. (4-7).

The second way is matching the original, uncorrected images to find conjugated points, and using the original attitude data to define the pixel rays to produce a terrain model. Because there is no correlation between the attitude data of two image strips (the baselength is too large) it gets harder for the matching algorithm to work correctly. The number of retrieved conjugated points decreases with increasing flight motions and depends on the terrain under observation, of course.

So the best way should be to match the corrected images first to obtain the maximum number of conjugated points and to define the pixel rays with the help of the original attitude data. It is just necessary to remember the original pixel position in the focal plane before the correction.

Figure 8 shows the result of the described procedure. Two image strips of a flight over Ronneburg were evaluated and a DEM was generated. In Figure 9 the corrected nadir image strip was laid over the DEM.

The result of a simple approximation is

$$j = \operatorname{int}\left[\frac{1}{v\cdot\Delta\tau}\times\begin{cases}x_i & \text{nadir}\\ x_i\pm\tan\gamma\cdot\left(h_f-z_i\right) & b/f\end{cases}\right] \tag{3-4}$$

and

$$i = \frac{n+1}{2}-\frac{y_i/IFOV}{z_i-h_f}\,. \tag{3-5}$$

The pixel number in the column i is independent of the CCD-line (forward, backward, nadir) chosen. Therefore the geometrical correction creates epipolar-like images.

Figure 3 shows subsamples (400x700 pixels) of the image in Figure 1. The left image is without correction and the right image is the result of the geometric correction. The figure shows that blurring effects in the uncorrected image can be fully compensated by the pixel ordering procedure as described previously. The differences in length of the image strip are caused by the pitch movement.

4. HEIGHT MEASUREMENT IN GEOMETRICALLY CORRECTED IMAGES

The geometric relation after geometric correction is shown in the following figure.

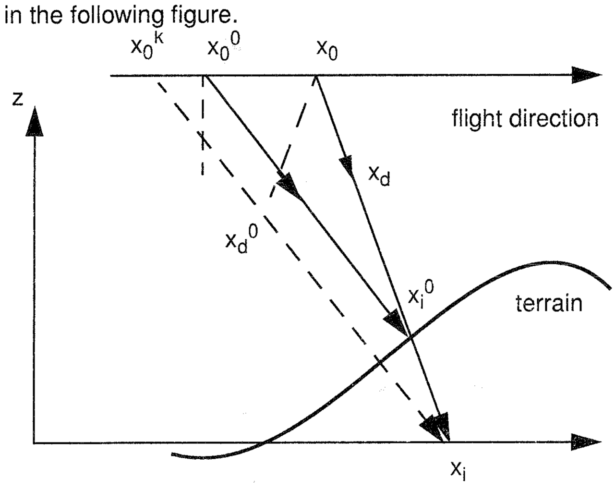

Figure 4 Geometric relation for stereo measurement

Figure 4 shows the pixel shift in a corrected image compared to the ideal and real image in the direction of the flight.

The disturbed ray from a pixel characterized by $(\underline{x}_0, \underline{x}_d)$ intersects the reference plane in $x_i, z_i = 0$.

The row difference between two corrected image strips, starting at the same point, is proportional to the height of the object point. The error of this measurement depends on the chosen reference plane and the attitude disturbance.

The corrected point $\underline{x}_0^k$ is shifted accordingly by the difference between the corrected and ideal image point $\delta x = x_0^0 - x_0^k$. The pixel $\underline{x}_0^0$ sees the terrain point $\underline{x}_i^0$ on an undisturbed flight path. This difference can be calculated using the relation between $\underline{x}_i^0$ and $\underline{x}_i$ and leads to:

$$\delta x = z_i^0\cdot\left[\frac{x_d}{z_d}-\frac{x_d^0}{z_d^0}\right] \tag{4-1}$$

The shift δx is zero if the height of the object point is equal to the height of the reference plane and/or if the attitude disturbance is zero.

If the flight path for each corrected image strip is the same, then the difference between the rows of the two corrected image strips is proportional to the height of the inspected image. The true height depends on the reference plane and the flight disturbance. Different attitude parameters give therefore different corrected images.

Only a correction on the real DEM gives a corrected image independent of attitude parameters.

The height in an ideal undisturbed image can be simply derived from the row difference in a forward and nadir image, for example (see Figure 5)

$$\Delta x_{fn} = \left(h_f-h_i\right)\cdot\delta x_d \rightarrow h_i = \frac{h_f\cdot\delta x_d-\Delta x_{fn}}{\delta x_d} \tag{4-2}$$

with $\delta x_d = x_d^f/z_d^f - x_d^n/z_d^n = \tan\gamma$

results in

$$h_i = h_f-\frac{\Delta x_{fn}}{\tan\gamma} \tag{4-3}$$

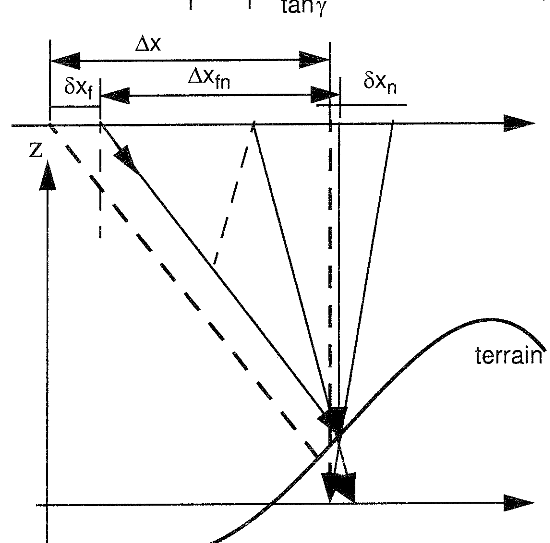

Figure 5 Row difference in an ideal and a corrected image

In the geometrically corrected image an additional part coming from the correction (4-1) influences the result (4-2) and gives a column difference (see Figure 5)

$$\Delta x = \Delta x_{fn}+\delta x_f-\delta x_n\,. \tag{4-4}$$

This leads to a corrected value for the height

$$h_i = \frac{h_f\cdot\delta x_d-\Delta x}{2\delta x_d-\delta\overline{x_d}} \tag{4-5}$$

with the correction

$$\delta\overline{x_d} = \overline{x_d^f}/\overline{z_d^f}-\overline{x_d^n}/\overline{z_d^n} \tag{4-6}$$

Figure 8 Produced DEM

Figure 9 DEM with the corrected nadir image

6. REAL TIME STEREO PROCESSING

The use of very precise measuring instruments for the determination of flight location and position makes possible an on-line stereo processing of data instead of the expensive procedures of the conventional photogrammetry. All iteration procedures can be changed by straightforward-algorithms. The matching algorithm must be replaced by an on-line procedure, where a ray tracer with attitude information gives the start information for related pixels between different image strips, and a fast correlation algorithm finds conjugated points. It is necessary to find a compromise between the accuracy of the information and the number of calculated points.

Applications for the on-line procedure could be change detection (after disasters like earthquakes) or map updating (e.g. for telecommunication).

7. CONCLUSION

The Wide-Angle Optoelectronic Stereo Scanner (WAOSS) built for the Mars-96 orbiter was used on board aeroplanes. Direct and accurate measurement of attitude parameters (roll, yaw, pitch, ground speed and altitude variation) gives the parameters of exterior orientation for each measured CCD-line. The high accuracy of angle determination is strongly related to stochastic drift. The future work is focused on the on-line drift correction and precise determination of angle offset.

Using attitude and camera calibration data CCD-line scanner data can be geometrically corrected. If these image strips are processed on the same mean flight path, the correction procedure is equivalent to the conventional interior and exterior orientation and gives epipolar-like images.

The geometrically corrected images are a necessary preprocessed data product for further 3-D processing and allow also a coordinate measurement with a photogrammetric workstation, for example, and the generation of digital elevation models (DEM).

The independence from additional GCPs and straightforward algorithms makes an on-line approach for DEM generation or DEM improvement on board the aircraft possible without human action.

8. LITERATURE

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