A FLEXIBLE DIGITAL WIDE-ANGLE OPTOELECTRONIC STEREO SCANNER

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ABSTRACT:

The Wide-Angle Optoelectronic Stereo Scanner (WAOSS) is one of the remote sensing instruments of the Mars-94 orbiter. WAOSS is further proposed for integration in the planned ecological satellite ECOS-A by the Space Research Institute (IKI), Moscow. Special mission goals and camera design require a very flexible concept of sensor-signal processing (clocking of the 3 CCD-lines, in-swath stereo mapping, real time data compression) and evaluation algorithms. Comprehensive earth-bound experiments and tests are necessary before the real applications in outer space. Therefore an airborne prototype of WAOSS is used together with 3-axes gyro data registration to obtain stereoscopic views and digital terrain modells of selected test areas. This contribution should point out, how closely related and mutually stimulating space research experiments and earth-bound technical developments can be.

KEY WORDS: optoelectronic scanner, stereo, airborne experiments

1. INTRODUCTION

As part of the Mars'94 project shall fly on a platform with optical sensors also the Wide Angle Optoelectronic Stereo Scanner (WAOSS). Crucial feature of this camera is the in-track stereo capability. That is realized through a three-line CCD arrangement (Fig.1).

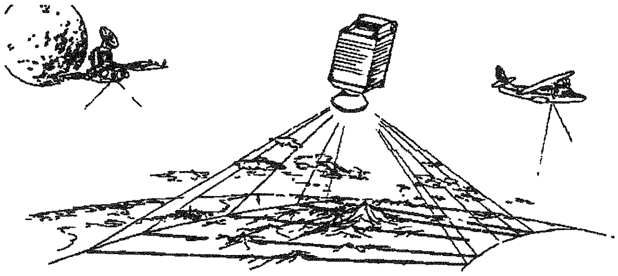

Fig.1

This camera serves for the investigation of large-scale phenomena. In order to reach the special mission goals a highly elliptical orbit was selected.

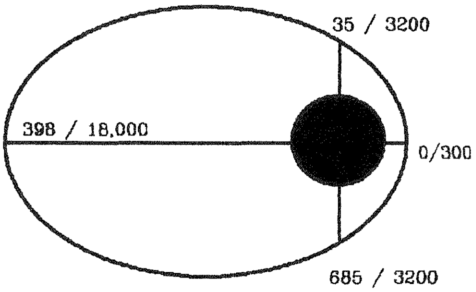

Fig.2

Fig. 2 shows an example of the orbiter motion in the plane of it's orbit. The next point to the Mars surface (pericenter) is 300 km distant and the excentricity 0.708. In the picture are entered the time after pericenter in minutes and the distance of the orbiter to the Mars surface. The scanner switches over a range from -90 to +90 degrees of true anomaly. Within an imaging cycle or measured swath all the radiometric and geometric resolution determining quantities, like PSF and SNR, change. Moreover drastic limits of the data transfer capacity exist. From these limits certain demands for the hardware and for the necessary development of special algorithms follow. They shall be described more exactly in the following:

1.1. Three lines CCD arrangement

The CCD - lines consist of more than 5000 imaging pixels and are arranged perpendicular to the flight direction (see Fig. 3). Through the own movement of the sensor a picture of the surface emerges. The advantage of this attempt is a higher spatial resolution than e.g. with a matrix sensor. A decisive disadvantage and more expenses result from a disturbing movement of the carrier of our camera itself. It makes necessary a position correction of the picture data of each individual line. A characteristic for this line arrangement is the central perspective in line direction and the parallel perspective in flight direction. This requires a modification of the 3-D reconstruction algorithms.

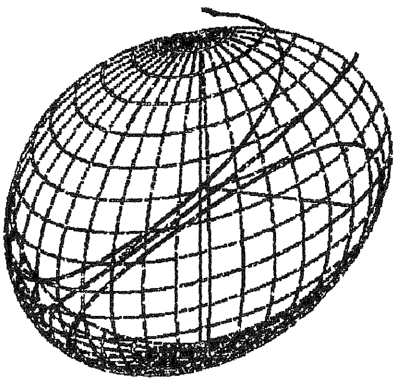

Fig.3

The stereo possibilities are due to the application of a three-line arrangement, with one line looking in nadir direction and the others forward and backward resp. (Hofman, 1986; Konecny, 1986).

1.2. Wide angle optics

The wide angle optics causes a variable PSF and a therefore changeable spatial resolution in line direction. Moreover a geometric distortion is present. The correction of the distortion is carried out along with the position correction described above. In case of a homogeneous light source in front of the sensor the used wide angle optics causes a drastic decrease of the measured signal towards the edge of the image field. It is aimed at correcting this effect already on board. This correction leads to an equalized information depth, independent of the pixel position. But simultaneously the signal - to - noise ratio (SNR) in the picture changes in line direction.

1.3. Limited data rate

Due to the large field of view along the orbit track between +90° and -90° also meaningless information will be gathered. In particular pixels have to be excluded looking into deep space and at the dark side of Mars. Since the intended future orbit around Mars is known in principle, such cases can be anticipated in the imaging concept.
A formation of makropixels particularly in the proximity of the pericenter is possible and for certain imaging modes necessary.
Such attempts make necessary an on- board processor and a skillful data compression.

1.4. Highly elliptical orbit

The most important consequence of the chosen orbit is a variable imaging scale in flight direction. Fig. 3 shows the swath of the nadir line and therefore the spatial resolution at different points along the orbit path. This effect is strengthened through variable clock- and integration-times. The variable clock- and integration-times within a measuring cycle are necessary due to the highly elliptical orbit and the different imaging modes, in order to receive piecemeal comparable images of the surface and nearly square pixels.

In summary it can be stated that the choice of the orbit and hardware demands lead to a variation of all essential quantities, such as scale, ground resolution and signal-to-noise ratio, both in line - as well as in flight-direction. That has consequences for all data processing algorithms. There are pursued, therefore, the following approaches:

1. Development and tests of algorithms also before with actual data. For it an airborne-sample of the future camera was manufactured and flown. This airborne camera contains already all essential components of the future space-instrument.
2. Modelling the camera characteristics on their future orbits, investigating and verifying the camera properties in the lab as well as with real scenes.

The following chapters describe the first experiments with this airborne camera.

2. WAOSS FOR MARS ´94 MISSION

2.1. Scientific goals (WAOSS Science Objectives)

Some of the essential goals are:

- Global imaging of the Mars´ surface and atmosphere for the investigation of meteorological, climatological and related surface phenomena and changes
- Global observation of atmospheric phenomena and their variability with different time scales (days, weeks, months, seasons and years)
- Investigation of the polar caps
- Investigation of selected atmospheric phenomena in medium resolution with the stereo possibilities of the camera
- Investigation of the change of selected surface characteristics also with stereo and, if possible, with photometric quality
- Comparison of the measurements with the earlier missions
- Generation of surface reliefs and preparation of maps in global and regional scales.

2.2. Technical aspects of the WAOSS camera

The main technical data of WAOSS are pointed out in WAOSS Technical Part and summarized in Table 1.

Table 1 Stereo camera WAOSS, technical data

optics (lens):	SPITMO-Russar-96
focal length:	21,7 mm
field of view:	80°
number of CCD-lines	3
spacing of CCD`s	10 mm
convergence angle	24,7°
CCD-line type	THX31516
pixels per line	5184
spacing of pixels	7 µm
instantaneous field of view (IFOV)	0,323 x 10-3 rad
according to orbit data	200 / 300 km :
swath width (nadir-line)	336/503 km
min. ground resolution	65/97 m
spectral channel	400 -700 nm
radiometric resolution	8 bit
Data compression factor	2...20
Data compression method	Digital Cosine Transformation (DCT)
mass	6 kg
power consumption	16 W

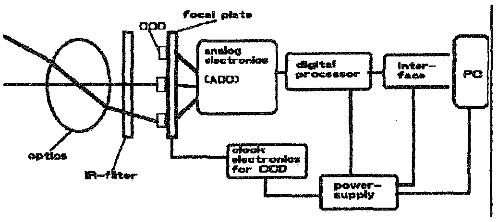

Fig.4

Fig. 4 shows the block diagram of the WAOSS camera. The incidenting radiation is focussed through the optics onto the focal plane. At the focal plane are fixed the three CCD-lines.
An optical filter shall improve the imaging characteristics by cutting off the infrared spectral parts.
The focal-plane is a rectangular ceramic plate. On the substrate gilded printed wiring are brought up in thick-layer technology. The CCD-chips with the dimensions of 27,9 mm x 1,5 mm x 0,375 mm are affixed to the ceramic plate at distances of 10 mm.
The camera produces in the push-broom-mode stereo-triples. The convergence angles are approx. 25° (forward and backward in reference to the nadir

directed line). This principle allows a nearly simultaneous imaging of all pictures of the stereo triples. The time difference between the imaging of the pictures by the forward - and backward directed CCD-lines is short and makes it possible to image under nearly constant illumination conditions.
The analogue data channel (from the CCD-lines exits up to the ADC) is controlled by an ASIC. This ASIC produces also the addresses, under which in the correction value memory the pixel related correction values for the dark signal and the channel offset as well as the sensitivity values for the pixels and the intensity correction values for the pixels in the focal plane are stored. The measured signal is digitized with 11 bit but transfered and stored with 8 bit. The on-board processor analyzes the actual datas and optimizes the amplification - or shift factor for the copy of the 11-bit data to the 8-bit of the transfered data. For the discrimination of surface and clouds additional spectral filters are provided for the forward and backward looking line.

The main tasks of the system electronics are

- Controlling of and reading out the CCD - lines
- Correction of the systematic errors of the CCD - signals and the measuring channels (in the described airborne experiment not yet activated)
- A / D - conversion
- Data copmpression
- Generation of data frames from CCD - data and house keeping information
- Data exchange with the board environment
- Generation of the power supply

3. CAMERA TEST IN THE AIRPLANE

3.1. Airplane instrumentation and test sites

In 1991 the WAOSS - airborne model flew twice on board an airplane of the Cessna type. Table 2 shows the technical data of the camera and table 3 the data of the utilized CCD-lines.

Table 2 WAOSS - airplane instrument, technical data

optics (lens):	modified ZEISS FLEKTOGON 2,8;
focal length:	20 mm
field of view:	60°
spacing of CCD`s	5,4 mm
convergence angle	15°

Table 3 Characteristics of CCD L 143

pixels per line	2048
spacing of pixels	13 µm
IFOV	0,65 x 10^{-3} rad
length of active array	26,624 mm
metric resolution	38 lp/mm
saturation output amplitude Usat	typ.2 V

In the airplane camera all electronic components are utilized already, which will be used for the Mars camera too. The satellite interfaces were replaced for the airplane camera by a board computer. The data compression with DCT is not yet activated.

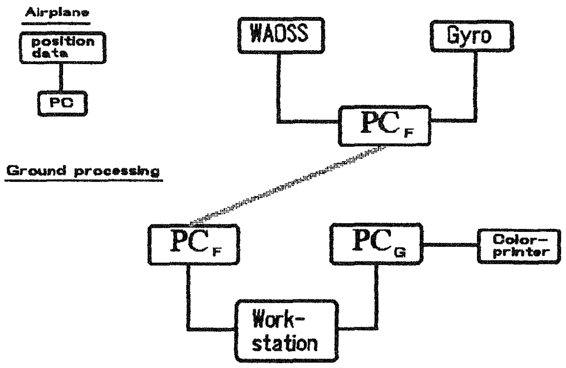

Fig.5

Fig. 5 shows the block diagram of the installed instruments. Besides the three - line camera two gyros measuring roll and pitch movements were mounted on the platform for WAOSS. The flight position system GPS (Global Positioning System receiver), coupled with an independent computer, records the course of the airplane. In parallel to the WAOSS - pictures the imaged scenes were taken also with a camcorder. These records were used for the orientation of the measurements with the line camera and to their documentation. The camcorder has nearly the same aperture angle as WAOSS and for the reduction of the movement smeering a high speed shutter.
The storage of WAOSS data is provided by a separate on-board computer. There are recorded and stored at a time blocks with the three-lines triple. Additionally are inserted the house keeping data (like line number, etc.) and the flight position data into the data stream. Due to the high data rate the measuring data are stored in the RAM of the computer and written after the measurement cycle onto the hard disc. A measuring swath therefore consists of only at maximum 5000 lines with 3*2048 picture elements.

For the verification of the camera characteristics the following standard scenes were analyzed:

1. flat structured area (airport)
2. flat homogeneous area (e.g. lake)
3. spatially structured area (brown-coal open-cast mining).

The open-cast mining has two decisive advantages for investigations with the WAOSS - camera :

1. Its 3-D structure is extremely well measured by photogrammeters standard methods
2. It has (similar to Mars) an underground with poor contrast.

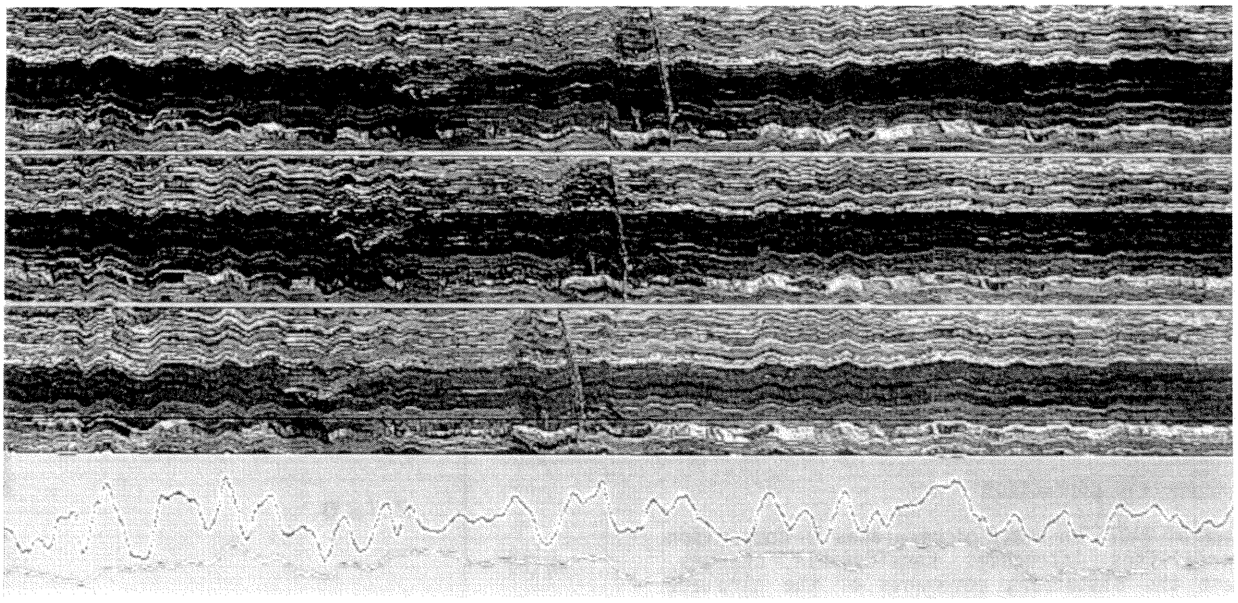

Fig.6

Fig. 6 shows a picture of a swath compressed in flight- and in line direction and the flight-position data. From bottom to top are shown backward-, nadir- and forward looking line. The coal band is the dark stripes. Beside the coal band the rubble is found. In the middle of the picture stripe the approx. 800 m long rubble-transport bridge can be seen. Due to the position of the different CCD-lines in the focal plane, the flight altitude and the clock rate, the bridge in the image is displaced in the individual swaths. The undulatory edge of the coal band is correlated with the roll movement of the airplane.

3.2. Radiometric correction

As already mentioned above one part of the data processing task is carried out with the sensor computer.

On the ground the further processing of the measuring data is performed by PC's and workstations. Besides the decomposing of the measuring data into the three different swaths, in a first step the amplification or shift factor is taken into account.

Before the (geometric) position correction a (radiometric) decalibration of the measuring data is necessary. The processing of the measuring data takes place under consideration of the pixel-dependend dark current and radiometric corrections.

3.2.1. Dark current

The dark current is given essentially through the volume-characteristics of the detector and the preamplifiers on the CCD-chip. The signals of the even and odd detectors on the chip are processed by separate preamplifiers. Therefore the dark current over the line pixels must be subdivided into even and odd pixel.These differ evidently for the explored line up to the factor of about 2. This drastic difference makes it necessary for further investigations of the calibration of the camera to consider the even and odd channel separately.

At a dynamic of approx. 2000 gray levels and a dark current of 100 - 200 gray levels the variance of the noise of the dark current has an amount smaller than 1.

The spectrum of the noise shows no strong dependencies on frequencies or periodicities, so uncorrelated noise can be assumed. Such informations are important for the modelling of the camera characteristics (eg. for the image data restoration).

3.2.2. Edge obscuration and photo response non-uniformity of CCD- elements

These two effects were considered independently of each other in their two correction factors. The determination of these factors occurs separately for the even and odd pixels. To do it the camera is calibrated with a light source (Ulbrichts sphere) which is homogeneous over the whole picture field.

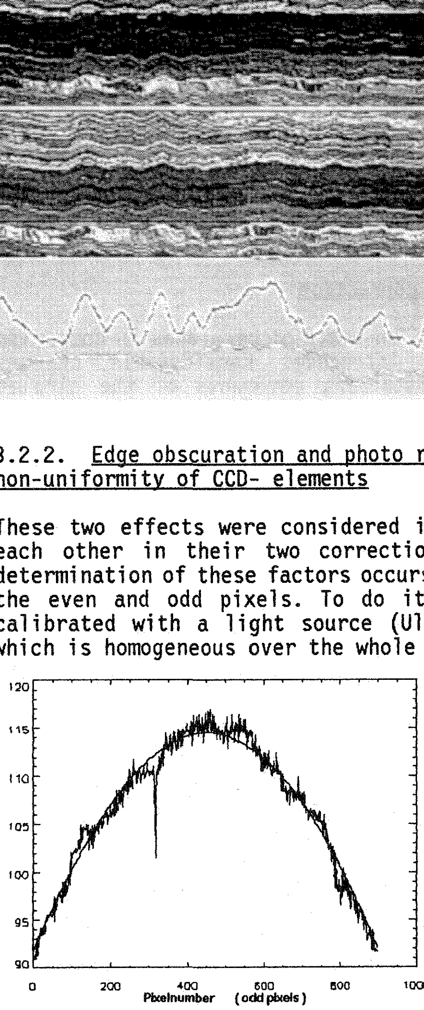

Fig. 7a

Fig. 7a shows the measured edge dependence and a cos - distribution. The angle dependence I(out) is calculated theoretically:

$$I(o) = \cos^3(o) * \cos(i)$$

o and i are the angles in the object- and image-field resp. in reference to a certain pixel on the focal plane. This dependence was calculated with a Ray-Tracing-Program and describes relatively exact the measured data. An example of a ray-trace through

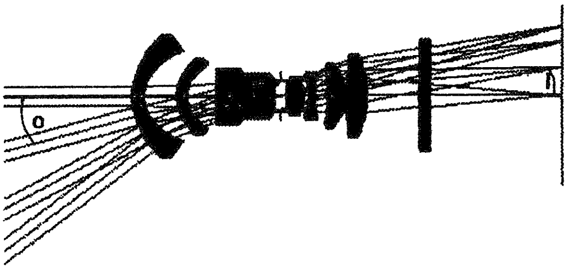

Fig.7b

the optic shows Fig. 7b. Four ray-triples penetrate the optics. It can be seen that the angles in the image field strongly differ from that in the object field. Therefore the cos-dependence follows not easily a simple power 4 dependence.
The edge decrease for the used optics is comparatively small (about 20% from the maximum). At the expense of this small edge decrese one has to cope with a severe distortion of the optics.

All deviations from the edge decrease are summed up in the correction of the non-uniformity of the pixel sensitivity. One finds in these dependency also periodical parts, which may be caused by the detector technology. If one executes the decalibration with the test data, the noise for these lighting conditions can be determined. The noise lies somewhat above the noise of the dark current because of the Poisson noise.

3.3. Geometric correction

The use of WAOSS on-board of airplanes in comparison to satellites introduces considerable changes, because the disturbing movements of the airplane (roll, yaw, pitch) are much more pronounced than those of the satellite.
This movements grasp directly into the sampling process and distort the transfer function of each individual pixel. The movement blurring is determined at least in the same order of magnitude by the angular motions of the airplane as by its translational.
It influences both the geometry as well as the radiometry of the non-preprocessed images.

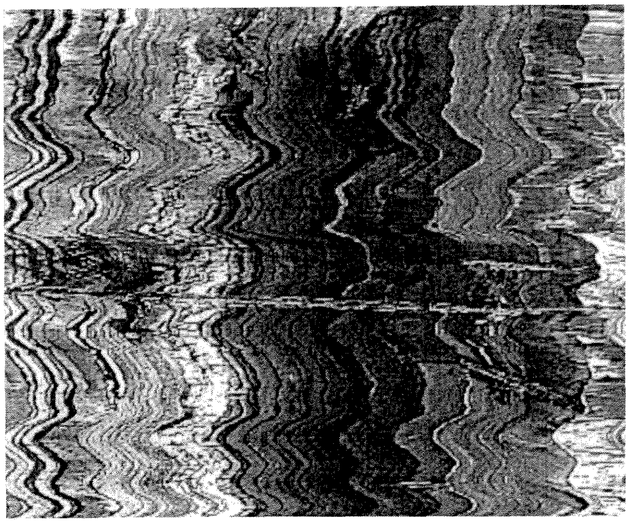
Fig.8

Fig. 8 shows an uncorrected image of the lignite open-cast mining "Welzow - South". Because of the disturbing airplane motion it is not possible to detect details. The flight direction proceeded parallel to the expanded open-coast mining structure. From the edges down to the coal, which is to be recognized as darker stripes in the middle, the height differs by about 100 m.
The stereo reconstruction is affected by the disturbances twofold. The usal picture matching with raw images is not feasible, since a scene in the picture of two stereo lines has been recorded at different times and therefore also with different distortions. For altitude determinations the camera locations and viewing directions are required.
It is evidently necessary, therefore, to measure completely the angular movements, if one wants to accomplish a geometric and radiometric reconstruction of the pictures. The angular resolution of the measurements should be approximatly of an arc minute. That corresponds to the IFOV of a WAOSS-pixel.

In view of the lack of high precision pitch and yaw measurements during the first flights, the pictures were corrected with a simple roll correction. Thereby the picture lines were shifted in correspondence to the measured roll angles. Indeed the quality of the so corrected pictures is relatively bad, because of the low precision of the used gyros and because of the influences of the angular motion for the yaw and pitch axes. Therefore a correlation algorithm was used in a next step. The cross correlation between two neighbouring lines was calculated corresponding to:

$$c_i(l) = \begin{cases} \dfrac{1}{N}\sum\limits_{j=1}^{N-l}(b_{i,j+l} - \langle b_i\rangle) * (b_{i+1,j} - \langle b_{i+1}\rangle) \\ \quad \text{if } l \geq 0 \\ \dfrac{1}{N}\sum\limits_{j=1}^{N-|l|}(b_{i,j} - \langle b_i\rangle) * (b_{i+1,j+|l|} - \langle b_{i+1}\rangle) \\ \quad \text{if } l < 0 \end{cases}$$

(l= -lmax,-lmax+1,..,0,..,lmax-1,lmax)
The natural numbers i and j denote the line and pixel position resp.. The value <bi> stands for the average of the i-th line. The function ci(l) depends on the shift between the i-th and the following line expressed in terms of pixels, denoted by l. Thereby is lmax << N. N denotes the number of pixels per line.
If the line index i is fixed, c(l) has a sharp main maximum, whose amount will be normalised to 1.0 :

$$C_i(l) = c_i(l)/\max\ (c_i(l))$$

If a three dimensional coordinate system with the axes i,l and Ci(l) is chosen, then one gets a mountain range, stretched along the i-axis. The main maxima of an undisturbed image would build a straight ridge in parallel to the i-axis along the line l=0 (no shift between the lines, see fig.9).

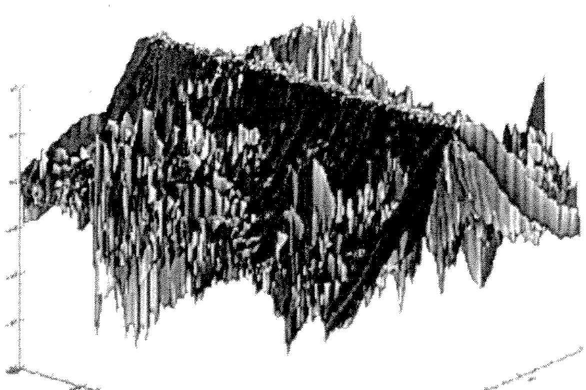
Fig.9

The disturbing angular motion leads to deviations of these maximum positions from l=0. This deviation was used to determine the necessary shift.

Fig 10 shows a picture corrected to the one with gyro data of the roll movement and to the other with correlation processes. With the described process the quality of the pictures could be raised. Further it became clear after these corrections, that in the first place all three angles must be measured and secondly that in order to avoid high-frequency disturbances in the images very fast gyros must be utilized.

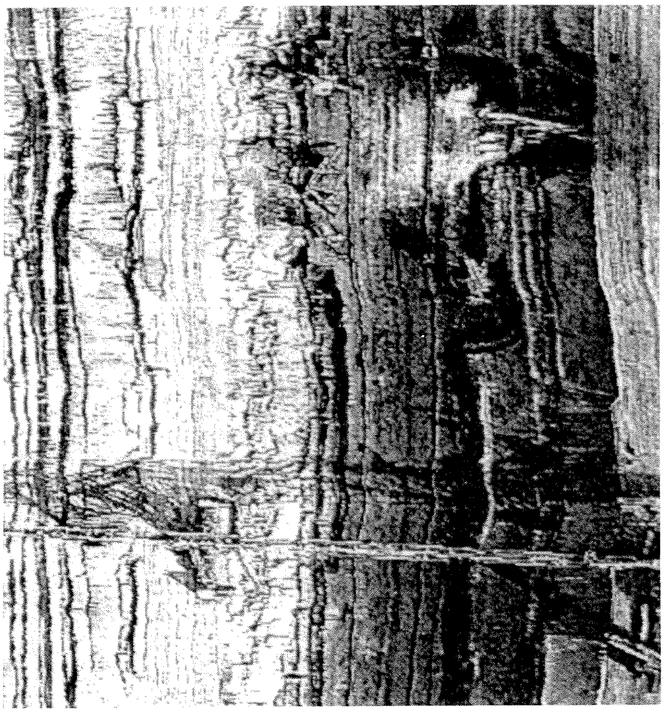

Fig.10

4. CONCLUSIONS AND OUTLOOK

This contribution shows, that the pecularities of the line camera and the chosen Mars orbits around Mars lead to new demands for the evaluation of the data and for the processing algorithms.
Especially it is necessary to get an exact knowledge of the camera under real conditions and to make airplane tests before its future utilization in a interplanetary space mission.
These airplane tests should be continued before the real space mission. Particular attention has to be put to the position correction and 3-D reconstruction algorithms. In this connection considerably more exact position measurements are necessary. Therefore a fiber gyro system should be used instead of the mechanical gyro. To get the altitude over the ground more exact (an essential parameter for the reconstruction) a laser altimeter should be used too.

For the reconstruction a high measuring precision of the relative position of two successive image line triples has priority compared to long time precision over an expanded picture scene. Rates of more than one minute per arc per line clock interval have to be measured. For this purpose three commercial fiber gyros shall be included. They measure rotary rates around an entrance axis with a precision of 50 degrees/hour and work with a KHz sampling rate. Since the required values are integrals of the data, they are requested also with this high clock installment, to keep the angle precision. As this procedure is integrated also over the noise component in the measurement signal, these integrals drift, they behave statistically like a Wiener-process.
Nevertheless the short-time precision of the gyros remains very high. Through the adjustment to the airplanes′ own navigation system the drift can be eliminated however.

To guarantee an optimal correction of the pictures, a particular flight experiment is prepared for 1993. The WAOSS-camera will be installed on board an excellently equipped aircraft Do 228, which is supplied with the Avionik flight test system (AFES). This system offers the possibility to support the determination of the angles by the three fiber gyros with an installed inertial navigation system. The position is determined by a radar- and lasertracking with a precision of approx. 50 cm (sampling rate 20 Hz). The precision of these measurements allows it, to accomplish the off-line correction of the WAOSS-pictures in a quality, which is comparable to a topographical map. That is important to develop the image processing of the Mars-pictures as well as to open new possibilities in real-time photogrammetry.

Finally other possible applications of WAOSS should be discussed shortly:

The WAOSS - concept is based on a most flexible control of the detector and the data acquisition. The data acquisition is followed by a board processor for a primary on board processing of the data. This flexible concept makes it possible to modify the measuring head (with for instants other optics or line arrangements), but also the integration of simple algorithms on board.

With this concept one has the possibility

- to react appropriately and quickly upon changing tasks (other spectral range, another picture size, etc.)
- to fly with small, however easily available airplanes
- to use the instrument as additional payload for spectral scanners, e.g. to get a spatially higher resolving channel or stereo information
- to test of on board algorithms (for Artificial Intelligence and others).

This paper underlines, how closely technical developments for sophisticated experiments in outer space may fit to the solution od earth-bound tasks and to design of the relevant research instrumentation.

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