EXPERIENCES WITH DIGITAL CAMERAS FOR EARTH OBSERVATION

Dieter Fritsch

Institute of Photogrammetry, University of Stuttgart, Keplerstrasse 11, D-70174 Stuttgart, Tel. +49,711,121,3386, Fax +49,711,121,3297, email: Dieter.Fritsch@ifp.uni-stuttgart.de

Abstract

The paper reviews the methods of digital imaging for photogrammetric purposes. Currently, two architectures compete with each other: the full frame CCD array and the linear array CCD. It seems, that in a long term the full frame will overcome the deficiencies of low spatial resolution and small image format. But it is no question that for the time being three-line imaging is the leading concept for Earth observation. Two systems will be presented which are based on this architecture. The Modular Opto-electronic Multispectral Stereo Scanner (MOMS) of 2nd generation was designed for Earth observation from space, and the Digital Photogrammetric Assembly (DPA) as an airborne digital imager. Both systems have been flown over some testsites, resulting experiences and results are presented.

1. INTRODUCTION

Aerial photogrammetry and optical remote sensing is evolving from the exclusive use of film-based optical sensors to fully digital electro-optical and active electronic sensors with multispectral capabilities. These sensors can be roughly categorized as frame-based when large area charge couple devices (CCDs) are used for the imaging process, or as line scanners (pushbroom imagers) when several CCD line arrays are arranged in the focal plane of an optical camera system. It is out of question, that the frame-based digital data acquisition has some advantages over the pushbroom principle because of its stable geometry for the full image frame.

In close range photogrammetry the use of digital still cameras automatically involves the frame-based approach. For this application, a great variety of digital cameras is offered by vendors of photographic equipment. The frame-based CCDs vary with resolutions of VGA standard (640x480 pixels - for instance the Apple Quick Take 150) to professional photographic systems (Kodak DCS200 and DCS420: 1524x1012 pixels, and the Kodak highest resolution portable digital camera DCS460: 3060x2036 pixels).

The Kodak DCS200 was the first high resolution stillvideo camera on the market. It consists of a modified Nikon 8008s camera body with a 14 mm x 9 mm CCD sensor (Kodak KAF 1600, 1524 x 1012 pixels, 9 μm x 9 μm pixel size) in the imaging plane. The camera is offered alternatively with a B/W and color CCD sensor, respectively. Digital images can be stored on a 2 MB DRAM or optionally on a 80 MB internal harddisk, which offers storage capability for 50 uncompressed images. The digital images are transferred from the internal camera harddisk into a computer via a SCSI interface. To operate the DCS200 is equivalent to those functions of a modern automatic SLR camera. Experience using the DCS200 and DCS420 for photogrammetric close-range applications are given by C.S. Fraser et al. (1995) and A Grün et al. (1995). Relative accuracies well in excess of 1:100,000 were verified, with the precisions for combined networks surpassing 1:200,000.

The progress in producing Large Area (LA) CCDs gives some hope that the frame-based approach will overcome the deficiency of low spatial resolution and small imaging format - most recently Philips Imaging Technology, Eindhoven/The Netherlands has announced a large area CCD wafer fitting within the boundary of six-inch wafers, and fixing the pixel dimensions at 12 μm x 12 μm with a maximum resolution of 7K horizontal x 9K vertical (M. Halloran, 1996). The size of CCD frame results to 86 mm x 110 mm (corresponds to the image format). This 66 million pixel sensor was for the first time manufactured on the *six-inch-silicon wafer* using a revolutionary sensor design technique which allows sensors to be constructed in a modular fashion. Besides Philips other vendors have announced the development of LA-CCDs up to 5K x 5K size, for instance Dalsa and Kodak. The developments for producing these large format CCDs started in the end of the 1980s and will continue in the future very progressively. They definitely will have great impact on future design of optical Earth observation systems. First experience using a frame-based CCD for photogrammetric airborne applications is given by Ch. Thom/I. Jurviller (1993).

The first generation of optical remote sensing systems was based on opto-mechanical image acquisition, for example the LANDSAT series. When the second generation of remote sensing cameras for Earth observation was under development (at the beginning of the 1980s), those LA-CCDs were not yet feasible. Linear arrays of CCDs were used to record the electro-magnetic energy reflected from the terrain. These CCDs provided a higher spatial resolution and better signal to noise ratio than other scanning devices used before. The line imagery is formed sequentially as the carrier of the camera system is moving along its (elliptical) orbit. One outcome using this technology is the series of SPOT satellites. High spatial resolution imagery in both panchromatic (PLA) mode (10 m) and multispectral (MLA) mode (20 m) enriched the application potential in various areas considerably. The SPOT 1 satellite, which was launched in February 1986, provided a new opportunity in extracting photogrammetric products, for instance the Digital Terrain Model (DTM) and the digital orthoimage. But its stereo capability is realized by using *two-pass stereo*, what means the stereo imagery for a DTM reconstruction suffers from the time lag between the two images. Currently, the SPOT 3 is operating under the same technical conditions as SPOT 1. With the launch of SPOT 5 (probably 2002) the principles and spatial resolution will change (5m PLA, 10 m MLA).

Parallel to the development of SPOT a German optical remote sensing system was under development with the acronym MOMS. This acronym stands for *Modular Optoelectronic Multispectral Stereo Scanner.* This series of digital camera systems is now available as 2nd generation and therefore called MOMS02. In the meantime MOMS02 could successfully be flown onboard the second German Spacelab (D2) mission (April 26 - May 6, 1993) and has proven ist functionality under space conditions. The accuracies of the stereo module are derived using a well-surveyed testsite located in the northern part of Australia (see figure 1 to figure 3). It is important to note, that planimetry can be reconstructed with relative accuracy of about 1:100,000 ($\sigma_{X,Y}$=3 m) and the heights with 1:70,000 (σ_Z=4.3 m) (D. Fritsch et al., 1996).

Nearly the same architecture of MOMS was realized in other optical Earth observation systems and for extraterrestrial applications. The Canadian MEIS camera fits very close to MOMS02 - its characteristics are described in J.R. Gibson et al. (1983). For the mapping of the planet Mars two systems are under development which are also based on the three-line imaging concept: the WAOSS camera and the HRSC system (J. Albertz et al., 1993).

Parallel to the development of MOMS02 an airborne imager using the identical spectral windows was designed and built by Messerschmidt-Bölkow-Blohm GmbH (MBB), now DASA. The system was ordered by the Bundesamt für Wehrtechnik und Beschaffung (BWB), Koblenz, to be used for topographic mapping purposes of the Federal Armed Services of Germany. A first testflight of the stereo module could be succesfully carried out in Autumn 1992 - the results are reported by O. Hofmann et al. (1993). The Institute of Photogrammetry, University of Stuttgart started 1995 with a comprehensive acceptance test of this airborne digital photogrammetry assembly (DPA). This test will be finished towards the end of 1996.

2. EARTH OBSERVATION WITH MOMS02

The main advantage of the MOMS02 camera system in comparison with other operating Earth observation satellites , for example LANDSAT TM and MSS as well as SPOT are as follows. First MOMS02 has the highest spatial resolution of a civil digital Earth observing sensor. Its high resolution panchromatic channel has a ground pixel resolution of 4.5 m considered from an altitude of 300 km. But besides that, it offers for the first time along-track stereo capability - also called *one-pass stereo* - what means the stereo imagery is taken during the same orbit with only a slight time delay for the image triplet. The MOMS02 stereo imagery concept can be seen in F. Ackermann (1993). A stereo image is generated by forward and backward looking lenses with a ground pixel resolution of about 13.5 m (also being considered from an altitude of 300 km). This data is to be fusioned with the data of the high resolution channel. The base line of a stereo scene is about 120 km with a swath width of 37 km, resulting into a base-to-height ratio of about 0.8.

The MOMS02 camera was designed and built by DASA Munich (former MBB Munich) in close cooperation with the Deutsche Agentur für Raumfahrtangelegenheiten (DARA) and the MOMS02 science team led by three principal investigators: Prof. F. Ackermann, University of Stuttgart (photogrammetry), Prof. J. Bodechtel, University of Munich (thematics) and Prof. F. Lanzl, DLR Oberpfaffenhofen (combination of stereo and thematics). Both groups - stereo and thematics - were driven by co-investigators (for photogrammetry Profs. H. Ebner, Munich, E. Dorrer, Munich, G. Konecny, Hannover) and a powerful team of 12 young scientists. The general tasks of the science team was software development to process the data taken by the D2 mission, and to fix some characteristic parameters for the flying hardware.

The technology of the MOMS02 camera is based on a combination of the stereo and a multispectral module. Therefore the camera has altogether five lenses. The stereo module carries one vertically looking lens (NADIR) with focal distance of 660 mm for the high resolution channel and two tilted lenses with focal distance 237 mm. The other two lenses are used for multispectral imagery, each has a focal length of 220 mm and two CCD line arrays located in its focal plane to record different spectral windows.

To summarize the MOMS02 technology of the stereo module it consists of four Fairchild 191 CCD line arrays with each 6000 pixels/line, whereby two line arrays have been merged each other for the high resolution NADIR channel. The tilting of the backward (BW) and forward (FW) looking channel is about 21.43 degrees - all three line arrays are sensitive within the panchromatic spectral range of 520-760 nm and have a resolution in radiometry of 7 bit. Table 1 gives an overview on the characteristic parameters of the MOMS02 stereo module. The nominal image size per line was 12 cm and 6 cm, respectively, but actually only 8.5 cm and 5.8 cm have been used.

Table 1: Stereo module parameters MOMS02

4 CCD line detectors	FAIRCHILD CCD 191
	line image format: 12 nom. (8.3 act.) cm

pixel size:10µm x 10 µm	and 6 nom (5.8 act.) cm
high resolution (HR) NADIR channel	12,000 pixels/line (only 8,304 are used)
backward (BW) channel and forward (FW) channel	2,976 pixels/line for MODE 1 - HR stereo, 5,800 pixels/line (MODE 3 - MODE 5)
convergence (stereo) angle	21.43 deg
focal length	HR: 660 mm BW/FW: 237 mm
radiometric resolution	7 bit
geometric resolution (nominal altitude of 300 km	HR: 4.5 m BW/FW: 13.5 m

Table 2 summarizes the characteristic parameters of the four multispectral channels, their spectral sensitivity was optimized to provide for an optimal vegetation discrimination. Originally it was planned to obtain a multispectral resolution of 9 m but last minute data rate constraints did not allow for. Due to these constraints it was not possible to record in all stereo and multispectral channels simultaneously, because the maximum data transfer rate was restricted to 100 Megabit/second. In order to be able to manage high data rates the data were compressed from the original 8 and 7 bit to 6 bit.

Table 2: Multispectral module parameters MOMS02

4 CCD line detectors	FAIRCHILD CCD 191
pixel size: 10µm x 10 µm	line image format: 6 cm and 5.8 cm
high resolution (HR) NADIR channel spectral range	6,000 pixels/line 520 - 760 nm
multispectral channels	5,800 pixels/line
spectral range	440 - 505 nm 530 - 575 nm 645 - 680 nm 770 - 810 nm
focal length	220 mm
resolutions	radiometric: 8 bit geometric: 13.5 m (from 300 km altitude)

For reasons of data transfer the MOMS02 camera was originally to be operated by seven data take modes (see table 3). The digital imagery is stored onto a high density digital tape recorder which allows image data recording up to 5.5 h data take duration.

During the D2 mission from April 26 till May 6, 1993 image data could be recorded within a latitude of ±28.5 degrees. The weight of the Spacelab was about 6000 kg, therefore the Space Shuttle was not able to reach a higher inclination than the latitude of Cape Canaveral. During this mission the MOMS02 Science Team was in close contact with the shuttle to have control on the data takes dependent on the wheather conditions which were available in real-time in the German Space Operation Centre (GSOC) Oberpfaffenhofen (near Munich).

Altogether 48 data takes were made: 10 in normal stereo mode (1), 5 in an by 30 deg inclined stereo mode (1-30), 13 in combination of the high resolution panchromatic channel with the multispectral channels (mode 6), and other combination as indicated. The total recording time exluding calibration was about 4 1/2 h with a total area coverage of approximately 7,000,000 km^2.

Table 3: MOMS02/D2 mode distribution

Channel/Mode	1	2	3	4	5	6	7
IFOV in μrad	45.45	45.45	45.45	45.45	15.15	42.16	42.16
Mode 1/ pixels #					8,304	2,976	2,976
Mode 2/ pixels #	5,800	5,800	5,800	5,800			
Mode 3/ pixels #			5,800	5,800		5,800	5,800
Mode 4/ pixels #	5,800		5,800	5,800		5,800	
Mode 5/ pixels #	5,800		5,800	5,800			5,800
Mode 6/ pixels #		3,220	3,220	3,220	6,000		
Mode 7/ pixels #	3,220		3,220	3,220	6,000		

Figure 1 demonstrates the resolution at a 13.5 m level of the MOMS02/D2 mission for the testsite Australia. This testsite was chosen to verify the photogrammetric accuracy potential of the MOMS02 camera against DGPS check points measured in a field survey. The image gives an impression on the geometric extend of an image scene when one complete image and 1/4 of another scene are composed of.

The first results of the experimental investigations into the quality of photogrammetric stereo processing derived from different scenes, for instance from orbits 115 (Andes) and 75B (Australia) have been presented by some Photogrammetric Institutes of the MOMS Science Team at a MOMS Workshop, July 1995, in Cologne/Germany. These preliminary results can consisely be summarized as follows:

- automated point tranfer was solved feature based as well as area based with the 13.5m ground pixel size for all three stereo channels. Experimentally, the matching precision resulted to about 0.7 pixels and 0.3 pixels, respectively.
- the orientation of three-line imagery and 3D point determination with the area based matching technique led to point accuracies of 6 to 10 m horizontal and 7 to 15 m in height, depending on the block adjustment model.
- the accuracy for the reconstructed DTM rms-values of 10 to 20 m were found.

These figures were verified within the testsite Australia (see figure 1), in which 79 check points were measured by differential GPS. The point identification was in some cases very critical, some missidentifications took place and therefore had influence onto the accuracy analyses of the D2 mission. A totally re-evaluation was carried out during the last 12 month, furthermore the testsite was resurveyed in Summer 1995 with an additional height profile of 3,228 check points. The most recent results are as follows:

- automated point transfer was sequentially solved using feature based matching to determine approximate values, and then carrying out a self-controlling area based matching. Using the lower sampled NADIR channel as reference (13.5 m) the experimental figures in pixel accuracy given before could be increased considerably to 0.15 pixel for the BW channel and 0.23 pixels for the FW channel. Altogether the selfdiagnosis process of the matching module indicated that 92.7 % of the 3,228 profile check points have been successfully matched.

- for the points along the profile an accuracy of 3m was reached for the horizontal positioning, and 4.3 m for the height uncertainty.

These excellent results give optimism for using three-line imaging techniques in further optical Earth observation systems. The relative accuracy of the MOMS02/D2 mission therefore results to 1:100,000 in planimetry, and 1:70,000 for the DTM heights.

3. AIRBORNE EARTH OBSERVATION WITH DPA

The optical module of the Digital Photogrammetric Assembly contains only a double-lens for the stereo module and four spectral lenses for the multispectrale module. This is a slight modifcation of the MOMS02 camera with three lenses for the stereo triplet. All lenses of DPA were built by Leica, Heerbrugg.

Table 4 summarizes the parameters of the stereo module. The same linear array CCD was used as with MOMS02, thus the characteristic parameters change only slightly.

Table 4: Stereo module parameters DPA

6 CCD line detectors (2 per line)	FAIRCHILD CCD 191
pixel size: 10 μm x 10 μm	line image format: 12 cm
NADIR channel BW channel FW channel	12,000 pixels/line (Mode A) 12,000 pixels/line (Mode A) 12,000 pixels/line (Mode A)
convergence (stereo) angle	25 deg
focal length	80 mm
radiometric resolution	12 bit
geometric resolution (nominal altitude of 2.5 km)	0.3 m

Table 5 gives an overview on the parameters of the multispectral module. Their spectral sensitivity corresponds exactly to the spectral windows of MOMS02. The digitised signals are recorded with 8 bit per pixel. An Inertial Navigation System is fixed mounted with the optical module, so that positions and attitudes will be simulteanously recorded together with the stereo and multispectral image data. The optical system is mounted onto a platform SM 2000 of Carl Zeiss. This platform stabilizes the camera system actively, reduces high frequencies and allows for pre-orientation of the camera in the local x,y-plane. The data are recorded onto a high density digital tape recorder DCRSi of Ampex, also the auxiliary data are stored onto that tape.

Table 5: Multispectral module parameters DPA

4 CCD line detectors	FAIRCHILD CCD 191
pixel size: 10 μm x 10 μm	line image format**:** 6 cm
4 multispectral channels	6,000 pixels/line (Mode B)
spectral range	440 - 505 nm 530 - 575 nm 645 - 680 nm 770 - 810 nm
focal length	40 mm
resolutions	radiometric: 12 bit intern, 8 bit extern geometric: 0.6 m (nominal altitude of 2.5 km

The DPA was flown twice - in Autumn 1992 and Summer 1995: the 1992 testsite was prepared and signalized in Laupheim (south of Ulm) to prove the stereo module only. The ground pixel size of the Laupheim aerial flight was 0.31 cm resulting to an image scale of 1:31,250. The results are reported in O. Hofmann et al. (1993). Using about 100 check points measured also by differential GPS rms-values of σ_X=0.35-0.50 m, σ_Y=0.45-0.75 and σ_Z=1.00-1.50 m could be obtained.

For the final acceptance test of the DPA system the Institute of Photogrammetry, University of Stuttgart prepared a new testsite for the flight in Summer 1995. This testsite is located in Vaihingen/Enz and contains more than 200 checkpoints for a comprehensive accuracy and verification test. The evaluations are not yet finished, therefore no results can be presented here.

It is planned, to have a further flight over this testsite and some others in July 1996 to carry out besides the stereo reconstruction and multispectral classification at least a multitemporal analysis based on two time epochs..

4. CONCLUSIONS

The MOMS02 camera system was put under slight modifications directly after the D2 mission to be prepared for a long term operation onboard the PRIRODA module of the Russion space station MIR. On May 5, 1996 the PROGRESS space ship was launched having onboard the MOMS02 camera. After a commissioning phase in June 1996, in which all operations of MOMS02 are tested, the image data stream will start from October 1996 until at least the end of 1997. The orbit parameters of MIR are much better than the ones of the Space Shuttle flight of the D2 mission. MIR moves along an altitude of about 350 - 400 km which allows data takes of about 60 % of the land masses of the Earth. During the MOMS02/P mission the number of operation modes is reduced to 4 - the stereo mode, the high resolution spectral mode and combinations of the multispectral with the stereo channels. Because of the different figures in altitude the ground pixel resolution results in 5.2 - 6.1 m for the high resolution panchromatic channel and 15.9 - 18.2 m for the lower resolution stereo and multispectral channels. An accuracy potential of about $\sigma_{X;Y,Z}$=5 m for the DTM, orthoimages and topographic mapping is to be expected.

One further component for this mission is a navigation package (MOMS-NAV) consisting of a single frequency GPS receiver and a high precision INS allowing DGPS positioning with an accuracy of about ±5 m and attitude determination with ±10 arcseconds. The data takes during that pre-operational mission should allow mapping and updating of GIS databases for medium scales up to 1:25,000. The operation scenario is as follows: data takes will be made on demand by the users; the recorded data are transmitted to Earth via parabolic antennas in Neustrelitz near Berlin and in Moscow. It is expected that this scenario can fulfill several requirements on Earth observation data.

The evaluations of the DPA image flights of July 1995 are not yet finished. First experimental results indicate an accuracy potential of better than 1 ground pixel resolution. A pre-rectification of the three-line imagery using the exterior orientation parameters determined by the onboard INS leads to stable geometric imaging conditions. The integration of DGPS and INS observations comes out with new methods for aerial triangulation.

To conclude the considerations on digital imaging from airborne and space platforms is as follows. At present, three-line imagers offer all the advantages of CCD technology: a better SNR than other scanning devices, and the linear transfer function in contrast to a logarithm curve of film-based systems. For the next years to come (probably until 2005) linear array CCDs can fully resolve the resolution potential of film-based aerial photogrammetric cameras and therefore substitute the analog storage medium.

The design of digital aerial cameras using this technology of three-line stereo and at least four multispectral channels will be a challenge for the vendors of classical photogrammetric data acquisition equipment. One main advantage for the user of digital cameras is already obvious: the slow turn around time due to film development, and expensive optical hard- and software to transfer analog data in digital using scanners are overcome. If the price of the new stereo and multispectral camera system is lower than the price of a classical equipment, but the digital system offers a much broader spectrum of applications, than the success of moving from analog to digital imagery in-flight should be assured.

5. REFERENCES

Ackermann, F. (1993): Das MOMS-02 Stereosegment - Ein hochgenaues System der digitalen Photogrammetrie. Geo-Informations-Systeme (GIS), Vol. 6, S. 16-22.

Albertz, J., Ebner, H., Neukum, G. (1993): Die Kamera-Experimente HRSC und WAOSS der Mission Mars 94/96. In: Photogrammetric Week '93, Eds. D. Fritsch/D. Hobbie, Wichmann, Karlsruhe, S. 121-134.

Fraser, C.S., Shortis, M. R., G. Ganci (1995): Multi-sensor system self-calibration. Proceed. Videometrics IV, Ed. S. El-Hakim, SPIE Vol. 2598, Philadelphia, pp. 2-18.

Fritsch, D. (1994): Synergy of photogrammetry, remote sensing, and GIS - the MOMS example. Int. Archives of Photogrammetry and Remote Sensing (IAPRS), Vol. 30, B1, Ottawa.

Fritsch, D., Hahn, M., Schneider, F., Stallmann, D., Kiefner, M. (1996): Experiences in processing MOMS-02/D2 stereo image data. Int. Archives Photogrammetry and Remote Sensing, Vol. 31, Vienna (in print).

Gibson, J.R., O'Neil, R.A., Neville, S.M., Till, S.M., McColl, W.D. (1983): A stereo electro-optical line scanner imager for automated mapping. Proceed. 6th Int. Symp. Automated Cartography, Vol. II, Ottawa, pp. 165-176.

Grün, A., Maas, H.-G., Keller, A. (1995): Kodak DCS200 - a camera for high accuracy measurements? Proceed. Videometrics IV, Ed. S. El-Hakim, SPIE Vol. 2598, Philadelphia, pp. 52-59.

Halloran, M. (1996): Next for sensors: 7000 x 9000 imaging on an integrated CCD wafer - affordably. Advanced Imaging, January 1996, pp. 46-48.

Hofmann, O., Kaltenecker, A., Müller, F. (1993): Das flugzeuggestützte, digitale Dreizeilenaufnahme- und Auswertesystem DPA - erste Erprobungsergebnisse . In: Photogrammetric Week '93, Eds. D. Fritsch/D. Hobbie, Wichmann, Karlsruhe, S. 97-107.

Thom, Th., Jurviller, I. (1993): Experiences with a digital aerial camera at Institut Gèographique National (France). In: Photogrammetric Week '93, Eds. D. Fritsch/D. Hobbie, Wichmann, Karlsruhe, pp. 73-83.

6. FIGURES

Figure 1: MOMS02/D2 orbit 75B (Australia), scenes 17/18 imaged by channel 6 on May 1, 1993, image size 40.2 km x 156.0 km

Figure 2: MOMS02/D2 orbit 75B (Australia), enlargement of scene 17 (channel 6), image size 40 km x 40 km

Figure 3: MOMS02/D2 orbit 75B (Australia), excerpt of the track on which the DGPS height profile have been measured (image size 2.6 km x 6.8 km)

Figure 4: MOMS02/D2 Digital Terrain Model generated from MOMS02/D2 imagery using the stereo triplet of 13.5 m ground pixel resolution

Figure 1: MOMS02/D2 orbit 75B

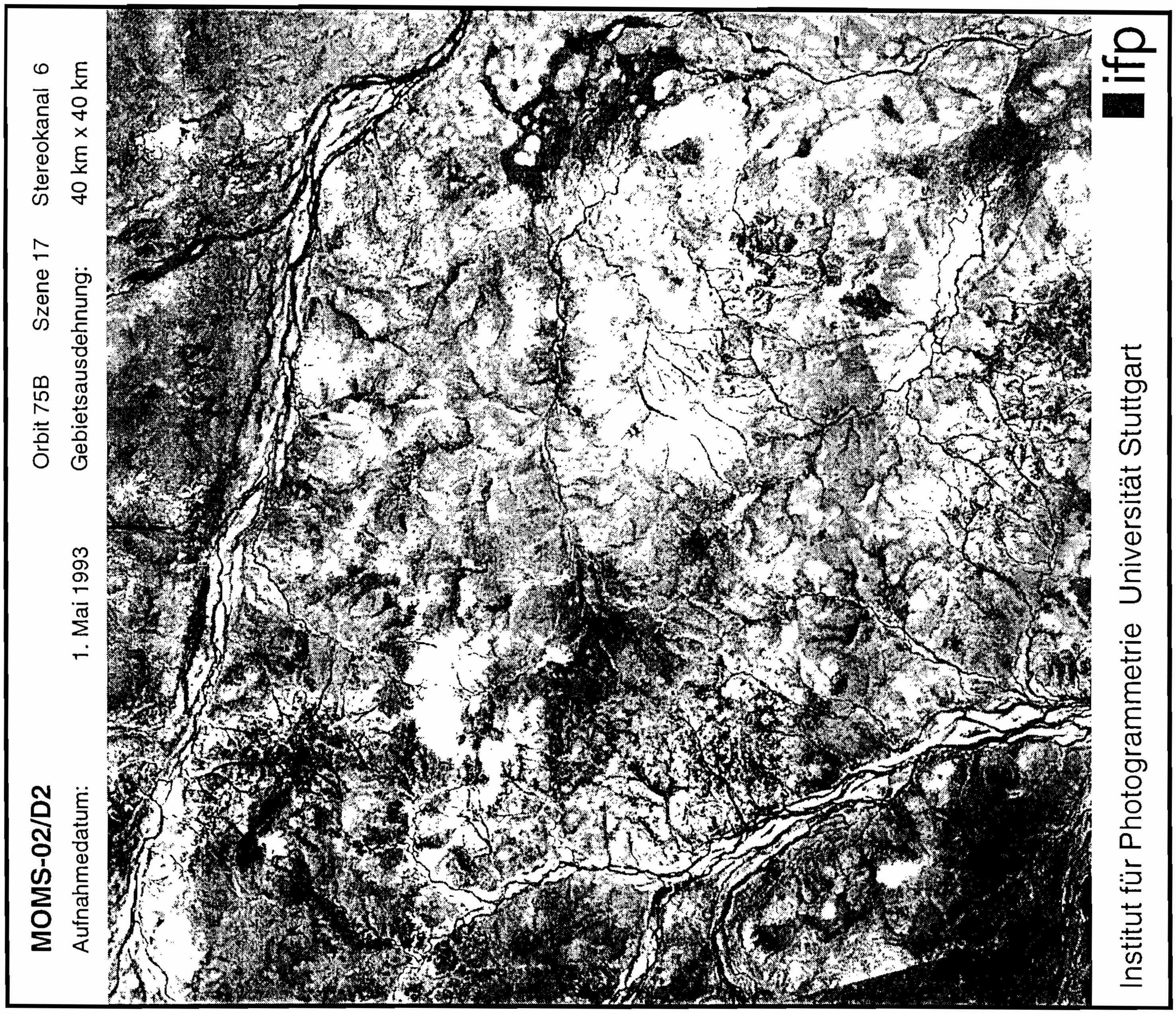

Figure 2: MOMS02/D2 orbit 75B (Australia), enlargement of scene 17 (channel 6), image size 40 km x 40 km

Figure 3: MOMS02/D2 orbit 7: (Australia), excerpt of t track on which the DGPS height profile have been measured

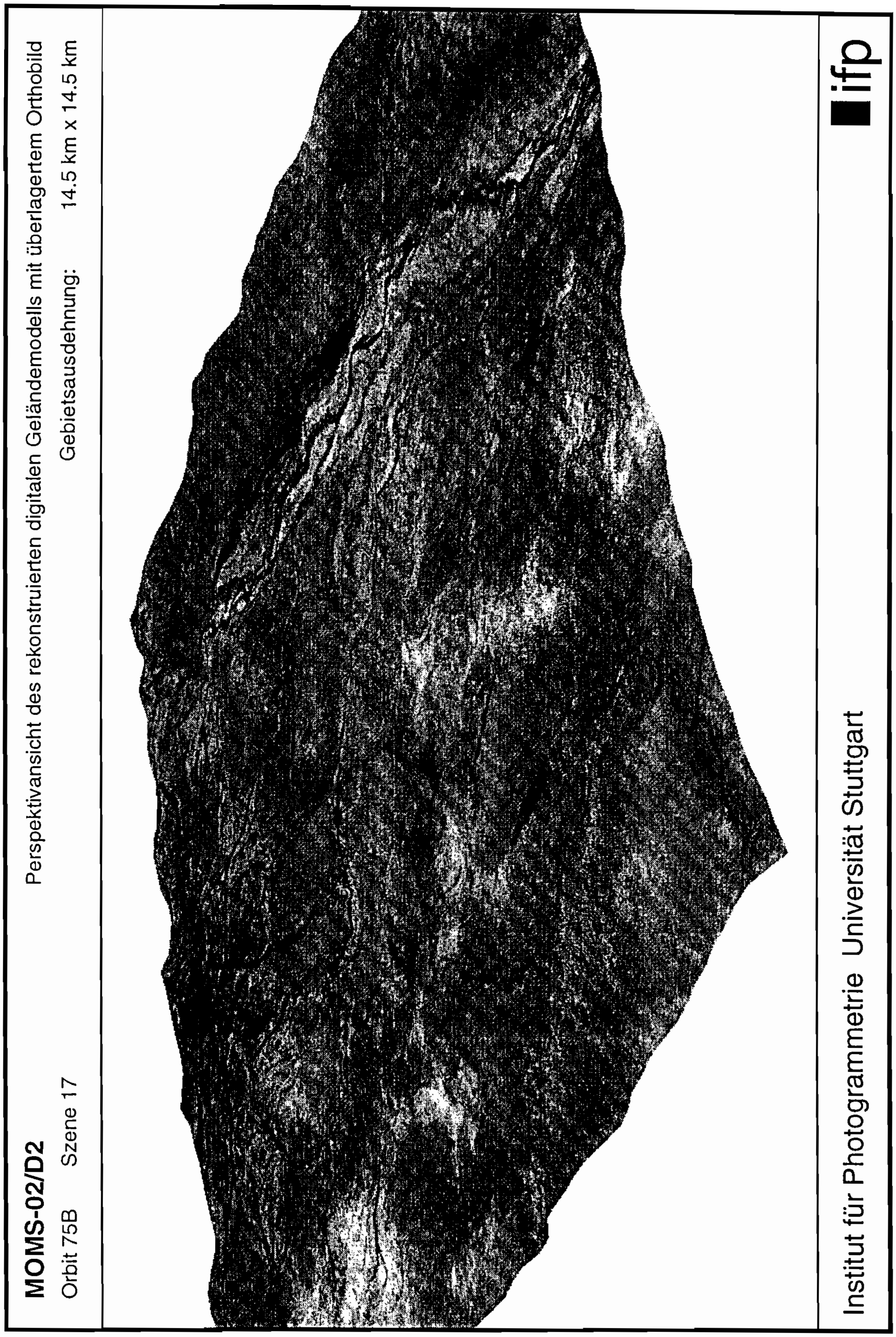

Figure 4: MOMS02/D2 Digital Terrain Model generated from MOMS02/D2 imagery using the stereo triplet of 13.5 m ground pixel resolution