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The airborne HRSC-AX cameras: evaluation of the technical concept and presentation of application results after one year of operations

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ABSTRACT

The multi-spectral and multi-stereo HRSC airborne pushbroom scanner provides image data for the generation of digital ortho-images and digital surface models with an accuracy of 10 to 20 cm. Since the first experiments were carried out in 1997, coverage of more than 150 cities and large areas has been acquired and processed in Europe and the USA. Depending on the particular model HRSC-A, HRSC-AX150, or HRSC-AX047 different operational parameters (e.g. spatial resolution and swath width) can be achieved to suit various applications. The data acquisition capability and data processing productivity with this digital system are very high. More than four years of operation of the HRSC-A and one year of operation of the new HRSC-AX have shown that the market perspectives of the system are promising. The application potential covers many of the typical high resolution aerial photography applications and high resolution imagery from optical satellites.

The paper describes the design of the new HRSC-AX based on the experience gained with its predecessor, the HRSC-A and presents operational and performance test results of this new camera.

1. INTRODUCTION

The HRSC (High Resolution Stereo Camera) airborne imaging system together with its photogrammetric processing software provides the geoinformation industry for the first time with an entirely digital and fully automated process to produce digital image data at very high spatial resolution, very high positional accuracy and very high radiometric resolution. The HRSC camera was originally developed for Mars Missions by the Institute of Planetary Exploration of the German Space Centre (DLR) in Berlin-Adlershof. Since the first experiments with an airborne version of this camera, the HRSC-A, were carried out in February 1997, it has been used for various applications ranging from cartography and infrastructure planning to environmental monitoring and internet marketing. In co-operation with different industrial partners, the enormous potential of the HRSC image data for telecom network planning, GIS applications, 3D-modelling, environmental monitoring, mapping/map updating and visualization has been exploited. This new technology has the potential to revolutionise both mapping and photogrammetry. The very promising results obtained with the HRSC-A have stimulated the development of a new generation of airborne HRSC cameras: the HRSC-AX.

2. DESIGN DESCRIPTION

2.1. Experience gained with the HRSC-A

The design and development of the digital airborne High Resolution Stereo Camera HRSC-AX was widely based on the experience with its predecessor, the HRSC-A. The application of the HRSC-A in various projects in different application fields showed the following general results with respect to this new camera technology and to the new methods of photogrammetric processing (see [NEUKUM ET AL 1]):

- the three-line-stereo principle can be applied with a focal plane assembly located behind <u>one single optics</u>

- the aircraft vibration/jitter (i.e. its random motion about the roll, pitch, yaw axes) can be fully compensated a posteriori for line scan cameras using an inertial measurement and GPS system with a recording rate of 200 Hz and a suspension mount/stabilization platform
- the color images acquired under slightly different viewing angles are co-registered at an accuracy sufficient for most of the applications using geometric calibration data and ortho-rectification methods
- the absolute planimetric accuracy is 10-15 cm for image data obtained at 3000 m, the respective vertical accuracy is 15-20 cm; this accuracy can be obtained with an automatic processing and with only a few control points (provided that a highly accurate and long term stable INS/GPS system is used) and which reduces drastically the amount of interactive work in the processing chain
- the use of two additional viewing directions (“5 line-stereo”) stabilises the accuracy of the DTM in critical areas (e.g. very tall buildings, fast aircraft slews) by increasing the number of automatically detected homologous points
- the stereo angle of approximately +20° (nadir to forward stereo) and –20° (nadir to backward stereo) is optimum for many applications; however, additional stereo angles of +12° and –12° are very suitable for specific application fields (e.g. in urban areas with tall buildings at close distances)

2.2. Design of the HRSC-AX cameras

In summary the best "selling points" of HRSC-A data are the very high planimetric and vertical accuracy, the nearly vertical viewing geometry at all points of the image ("true ortho image") and immediate availability of panchromatic, and spectral data (natural color RGB, CIR) and digital elevation information all from the same acquisition. For the design of the new generation of digital airborne HRSC cameras (HRSC-AX) these topics have been extended by the following considerations in order to develop and build a camera system well fitting the specific requirements of current and future airborne applications:

1. The main target of the new development was to enlarge the swath width by more than a factor of two from 5184 pixels per line to 12000 pixels per line. This substantially increases the productivity of acquisition. The pixel size of the new sensor lines is only 6.5 µm. Together with a new optics with a focal length of 150 mm this results in an optimum swath width with a maximum acceptable incidence angle of 80° at the outer edges of the image strip. This is an acceptable compromise between high productivity requirements (large swath swidth) and the “true orthoimage” requirement (narrow swath). It results in a swath of 1560 m for a flight altitude of 3000 m.
2. The geometric resolution (or ground sample distance) required for most of the applications is in the 15 – 25 cm range. However, the demand for even higher resolution below 10 cm will grow in the coming years. Therefore, the HRSC-AX has the functionality to provide this resolution. For line scan cameras, the geometric resolution in across-flight direction is defined by the flight altitude, the focal length of the optics, and the CCD pixel size whereas the geometric resolution in flight direction is solely defined by the product of aircraft speed and exposure time. With the shortest exposure time of the HRSC-AX of 0.6 msec a resolution in flight direction of about 5 cm at a nominal aircraft speed of 300 km/h (compared to 18 cm for the HRSC-A) is achieved.
3. The viewing angle of the color channels has been kept as close to nadir as possible in order to minimize the probability of color seams. For the HRSC-AX with a 150 mm tele optics the green and red channels have a viewing angle of + 2.3° and –2.3° respectively and the blue and infrared channels of + 4.6° and –4.6° respectively (for the HRSC-A these angles were 15.9° for the red and infrared channels).

4. The camera is built in a modular design so that customer requirements concerning specific optics (tele-optics and wide angle optics) and the spectral and stereo bands can be easily adapted.
5. The radiometric resolution is improved by using 12 bit technology throughout the entire camera system. Thus, the user can decide to output all data in 12 bit or to select channels to output in 8 bit reducing the amount of data using various commandable look-up tables. Further reduction of the data rate is realized via macro pixel binning which is freely commandable for all channels.

The HRSC-AX camera system includes 3 main parts:

- the camera consisting of the camera head (optics, filter modules, focal plane modules), the sensor electronics, the digital electronics, the thermal system, and the Advanced Inertial Measurement Unit (AIMU, part of the ApplAnix POS/AV-DG system) which is directly mounted on the camera head
- the platform-adapter which allows the installation of the camera system in various suspension mounts; so far a Zeiss T-AS suspension mount have been used
- the peripheric devices (camera control computer, main power supply, ApplAnix control computer, Sony high speed data recorder) mounted on a rack.

The HRSC-AX technical parameters are given in Table 1.

3. MODEL PHILOSOPHY

Fig. 1: The HRSC-AX camera

Up to now, two models of the HRSC-AX have been built:

- the HRSC-AX150 (in some publications called HRSC-AX)
  with a focal length of f=150 mm and 9 CCD lines a 12000 pixels which are located on 3 focal modules:
  2 modules with 2 panchromatic lines each (stereo and photogrammetry) and
  1 module with 5 lines (panchromatic nadir and 4 color channels);
- the HRSC-AX047 (in some publications called HRSC-AXW)
  with a focal length of f=47 mm and 5 CCD lines a 12000 pixels which are located on 1 focal module (3 panchromatic stereo and 2 color channels)

Both cameras use the same configuration of peripheric devices. Therefore, they can be easily exchanged once the system is installed in an aircraft.
The HRSC-AX047 has been used by ISTAR in an operational way since September 2000 for commercial flight campaigns in the USA. More than 70000 sqkm have been acquired in the resolution range of about 80 cm per pixel.
The HRSC-AX150 has completed a thorough test phase and will be used by ISTAR for commercial applications in Europe starting from July 2001.

Table 1: Technical Parameters of airborne HRSC cameras

HRSC	-A	-AX150	-AX047
camera parameters			
focal length	175 mm	150 mm	47 mm
nr. of CCD lines	9	9	5
nr. of pixels per CCD line	5184	12000	12000
pixel size	7 µm	6.5 µm	6,5 µm
radiometric resolution	8 bit	12 bit	12 bit
minimum exposure time	2.2 msec	0.625 msec	0.625 msec
stereo angle	±18.9 deg	±20.5 deg	±14.4 deg
swath angle	11.8 deg	29.1 deg	79.4 deg
maximum incidence angle	84.1 deg	75.5 deg	5.,3 deg
spectral bands			
Stereo forward (pan)	585-765 nm @ +18.9°	520-760 nm @ +20.5°	515-750 nm @ +14.4°
Photometry forward (pan)	585-765 nm @ +12.8°	520-760 nm @ +12.0°	-
Infrared	925-1015 nm @ -15.9°	770-810 nm @ +4.6°	-
Red	730-770 nm @ +15.9°	635-685 nm @ +2.3°	570-680 nm @ +7.1°
Nadir (pan)	585-765 nm @ ±0.0°	520-760 nm @ ±0.0°	515-750 nm @ ±0.0°
Green	485-575 nm @ -3.3°	530-570 nm @ -2.3°	475-575 nm @ -7.1°
Blue	395-485 nm @ +3.3°	450-510 nm @ 4.6°	-
Photometry backward (pan)	585-765 nm @ -12.8°	520-760 nm @ -12.0°	-
Stereo backward (pan)	585-765 nm @ -18.9°	520-760 nm @ -20.5°	515-750 nm @ -14.4°
spatial resolution			
in flight direction @ 70 m/sec	not less than 15.4 cm	not less than 4.4 cm	not less than 4.4 cm
in flight direction @ 100 m/sec	not less than 22.0 cm	not less than 6.2 cm	not less than 6.2 cm
across flight direction @ 3000 m	12.0 cm	13.0 cm	41.5 cm
across flight direction @ 5000 m	20,0 cm	21.7 cm	69.1 cm
swat width @ 3000 m	0.6 km	1.6 km	5.0 km
swat width @ 5000 m	1.0 km	2.6 km	8.3 km
data rates			
maximum data rate	32 Mbyte/s	80 Mbyte/s	80 Mbyte/s
nominal data rate	12 Mbyte/s	32 Mbyte/s	20 Mbyte/s
system parameters			
suspension mount	Zeiss T-AS		
data recording	Sony tape recorder	Sony tape recorder and/or RAID system	
geo referencing	ApplAnix POS/AV-DG system with INS and GPS		
camera mass	~32 kg	~70 kg	~70 kg
system mass	~300 kg	~300 kg	~300 kg

remarks:
1. the maximum data rate is limited by the data recording devices; for the HRSC-A a Sony high speed tape recorder is used; for the HRSC-AX a RAID system can be added or replace the Sony recorder
2. the nominal data rate is defined for nominal operations by a combination of binning and reduction from 12 bit to 8 bit, all selectable per spectral band/ CCD channel

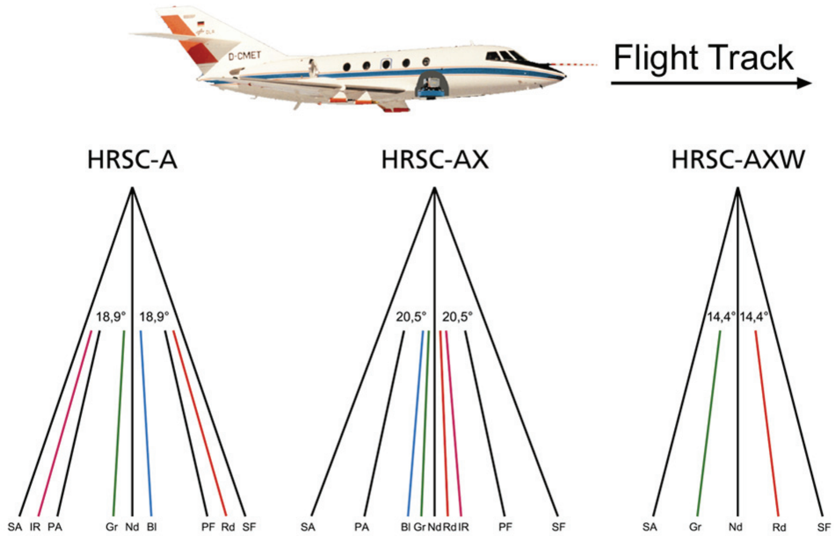

Fig. 2: Viewing geometry of the airborne HRSC cameras

SF- stereo forward
PF- photometry forward
Nd- Nadir
SA- stereo backward
PA- photometry backward
IR- Infrared
Rd- Red
Gr- Green
Bl- Blue

4. PERFORMANCE

4.1. Test flights

The HRSC-AX150 and the HRSC-AX047 have been tested in a number of different geometric test flight campaigns (see SCHOLTEN et al., 2001). In April 2001 a block of 7 flight strips (5 East-West strips and 2 cross strips) over a DLR test field in Ragow (near Berlin) have been flown with the HRSC-AX150 from an altitude of 1,000 m. Using 142 Identical Points (IPs, visible in adjacent strips) and 22 Control Points (CPs, with known reference coordinates) several parameters have been calculated within an adjustment process, i.e.:

- boresight alignment offsets between the axes of the APPLANIX DGPS/INS system Inertial Measurement Unit (IMU) and the camera axes,
- position offsets of the DGPS trajectory solution,
- position drifts of the DGPS trajectory solution, and
- possible timing offsets between the camera and the position and attitude data.

The accuracies computed within this photogrammetric restitution were the following:

- relative accuracy: ± 5.8 cm
  (3D-intersection error of the 5 lines of sight rays defining one IP or CP):
- IPs absolute accuracy: ± 8.9 cm
  (strip-to-strip IP error):
- PPs absolute accuracy: ± 11.6 cm
  (calculated vs. reference error):

These results show the sub-pixel accuracy of the HRSC-AX hard- and software concept (the original ground pixel resolution in this test was 4 cm across-strip and 16 cm along strip). In addition, other conclusions resulted from the test flight:

- there is no degradation in accuracy, if no CPs are integrated. CPs are only necessary to relate computed 3D products (e.g. in a Digital Surface Models) to the sea level height reference.

- only if using DGPS reference stations far outside the testfield, there is a slight degradation of accuracy, which can be eliminated by modelling the position drifts of the DGPS trajectory solution with the help of several CPs
- if adjacent flight strips are flown contrary there is no degradation in accuracy when ignoring the cross-strips

In April 2001 the HRSC-AX047 was also tested over the Ragow test field. Within a block of 6 flight strips, flown from an altitude of 1,600 m, 75 IPs and 45 CPS have been used for adjustments. The accuracies computed within this photogrammetric restitution are the following:

- relative accuracy: ± 23.5 cm
- IPs and PPs absolute accuracy: ± 25.1 cm

These results show sub-pixel accuracy of the HRSC-AX.047 (the original ground pixel resolution in this test was 21 cm across-strip and 20 cm along strip).

4.2. Improvement of performance caused by new technical design

Besides the proven sub-pixel accuracy, there are several photogrammetric aspects which have been influenced by the new design of the HRSC-AX camera generation:

- the 12k-CCD technology allows better coverage due to extended swath width,
- the shortening of the minimum exposure time allows ground pixel resolutions and accuracies in the 5 cm range.
- the placement of the 4 color CCDs close to the nadir CCD avoids occurrence of color seams within the color orthoimage mosaic, which was regarded to be a disadvantage of digital multi-line scanners.

In conclusion, the new HRSC-AX camera generation enables digital aerial data acquisition and photogrammetric processing in the entire resolution and accuracy range of 5 cm to 1m or larger.

5. APPLICATIONS AND PRODUCTIVITY

5.1. Automated Data Production

In cooperation with the Technical University (TU) of Berlin, DLR has developed a completely automated software system for use with the image data acquired by airborne digital line scanners. This software has been operated and improved for processing the HRSC-A and HRSC-AX data. In contrast to conventional stereo-photogrammetry, all data processing is done fully automatically without any human interaction.

5.2. Data Processing

In addition to the automatic processing chain the throughput of a huge amount of data is a big challenge for the processing system. For instance, for an area of 1000 sqkm mapped at 25 cm resolution the overall output data volume of the panchromatic and color mosaics is 84 GBytes. The output data will amount to 16 GB for the 25cm resolution nadir mosaic; 16 GB for each of the 4 multi-spectral bands (with reduced resolution) and 2 GB for a 1m raster 16-bit DSM (digital surface model).

5.3. Productivity

In the course of a single working day (5 flight hours), the HRSC-AX150 camera can acquire up to 2,500 sqkm of 25 cm resolution image data, while the wide angle AX047 model can acquire more than 10,000 sq km of 1m spatial resolution data. A single overflight provides natural colour (RGB),

colour infra-red (CIR) and black-and-white image data of a very high spatial and radiometric resolution having a positional accuracy of 10 to15cm and a vertical accuracy of 20cm from a flight altitude of 4500 m using imagery at 15cm spatial resolution.
In a project carried out in cooperation with the municipality of Berlin, the HRSC-A data sets showed their potential for fast operational orthomap production with high precision. Map scales up to 1:500 could be realised from the high resolution image data.

5.4. Data Products

Typical data products are mosaics of 8-bit or 12-bit panchromatic nadir data having a 15, 25 or 50cm spatial resolution; 8-bit multi-spectral data (blue, green, red, infrared) of 30, 50 or 100cm spatial resolution; and 16-bit DSM (digital surface model) or DTM (digital terrain model) data giving a 30, 50, 100 or 200cm raster grid over the terrain. In addition, anaglyph images or 3D view product mosaics can be delivered, either for interpretation (e.g. in forestry, architecture, disaster management) or for visualization purposes. Virtual overflights and films have been constructed from HRSC 3D and multi-spectral data (e.g. for Vulcano Island).

5.5. Applications and Interpretation

During the last two years, the HRSC cameras (-A, -AX150, -AX047) have been used operationally and many terrabytes of data have been acquired and processed. Simultaneous high resolution multi-spectral orthoimages and DSM data have been generated for many different projects such as 3D-City models, environmental monitoring, exploration, mapping of urban areas, planning and utilities, applications in the fields of forestry and agriculture, mapping of flood hazards, surveys of open-cast coal mines and of coastal zones. Maps in scales of 1:10 000 to 1:500 have been generated using HRSC data.
The potential of the HRSC-AX system for photogrammetric surveys in urban areas has also been shown through its operational use over 150 European and US cities acquiring data for ISTAR's telecom network planning pilot project. In particular, the availability of five stereo observation angles has been especially beneficial for the measurement of man-made objects, including coping with steep surface discontinuities. The high data quality of the imagery allows users to work on a wide range of applications, including those normally conducted using conventional aerial film cameras and those based on the classification of spectral signatures on imagery collected by multi-spectral scanners.
The combination of the high precision digital surface models (DSMs) derived from the stereo data together with the image data produced by the multi-spectral bands of the HRSC camera allows the user to generate high resolution virtual images and videos to be used for flight simulation, disaster management or advertisement.

6. MARKET PERSPECTIVES AND SUMMARY

Two new models of the HRSC are flying in Europe and the USA. Based on this experience, the HRSC camera technology and processing software has proven to be very reliable and very productive and has provided high geometric and radiometric data quality. The data acquisition productivity of the HRSC camera is very high and the market perspectives are very promising. This new digital imaging technology covers a lot of applications formerly served either by conventional high resolution aerial film cameras, airborne spectral and laser scanners or high resolution optical satellite systems. Collaborative projects with industry and administrations show encouraging results for a large variety of conventional and new applications.

The HRSC- Team for airborne applications consists of Prof. G. Neukum, T. Behnke, T. Bucher, Dr. U. Carsenty, Dr. J. Flohrer, C. Georgi, K. Gwinner, S. Hese, Dr. H. Hirsch, A. Hoffmeister, Dr. R. Jaumann, D. Jobs, J. Kachlicki, C. Leser, F. Lehmann, A. Lichopoj, K.-D. Matz, S. Mayer, Dr. J. Nopirakowski, M. Oczipka, F. Oschütz, B. Pforte, Dr. R. Pischel, Dr. E. Ress, Dr. T. Roatsch, F. Scholten, R. Schrödter, V. Speelmann, Dr. S. Sujev, F. Wewel; (all DLR Institute of Space Sensor Techology and Planetary Exploration, Berlin); R. Geng, S. Gentzsch, F. Trauthan; (Remote Sensing Group of the Institute of Geology, Geophysics and Geoinformatics of the Free University of Berlin)

7. REFERENCES

ALBERTZ, J., F. SCHOLTEN, H. EBNER, C. HEIPKE, G. NEUKUM: "The Camera Experiments HRSC and WAOSS on the Mars94 Mission", International Archives of Photogrammetry and Remote Sensing, Vol. 29, Part 81, pp. 216-227,1992.

HOFFMANN, A., F. LEHMANN: "Vom Mars zur Erde - die erste digitale Orthobildkarte Berlin mit Daten der Kamera HRSC-A", Kartographische Nachrichten, 50 2/2000.

LEHMANN, F., HOFFMANN, A., RENOUARD, L., V.D.VEGT,J.W. The High Resolution.Stereo Camera Airborne (HRSC-A), GIM International July 2000, Vol 14

NEUKUM, G.,: “The HRSC-A: Performance Results and Application Potential ” Photogrammetric Week 1999, pp 83-88

NEUKUM, G., E. RESS, T. BEHNKE, I. BIDO, U. CARSENTY, K. EICHENTOPF, J. FLOHRER, C. GEORGI, K. GWINNER, K. HARTWIG, E. HAUBER, S. HESE, H. HIRSCH, H. HOFFMANN, A. HOFFMANN, A. HOFFMEISTER, C. HORNFECK, R. JAUMANN, D. JOBS, J. KACHLICKI, F. LEHMANN, A. LICHOPOJ, K.-D. MATZ, V. MERTENS, H. MICHAELIS, D. DE NIEM, J. NOPIRAKOWSKI, J. OBERST, F. OSCHÜTZ, B. PFORTE, R. PISCHEL, T. ROATSCH, F. SCHOLTEN, R. SCHRÖDTER, S. SUJEW, F. TRAUTHAN, I. WALTER, M. WÄHLISCH, F. WEWEL: “Vom Mars zur Erde” DLR Nachrichten Ausg. 99/g 12625, pp 22-35, Nov. 2000.

RENOUARD, L., F. LEHMANN: "Digital Aerial Survey Data for Telecoms Network Planning Practical Experience with a High-Resolution Three-View Stereo Camera" OEEPE Workshop on Automation in Digital Photogrammetric Production, Paris, 21-24 Juni 1999.

SCHOLTEN, F., WEWEL, F., SUJEW, S.: Einsatz digitaler Kameras im Auflösungsbereich von 5 cm bis 1 m - Die neue HRSC-AX Kamerageneration in der geometrischen Analyse. In Publikationen der Deutschen Gesellschaft für Photogrammetrie und Fernerkundung, Berlin, Band 10 (in press).

WEWEL, F., F. SCHOLTEN, G .NEUKUM, L. ALBERTZ: "Digitale Luftbildaufnahme mit der HRSC - Ein Schritt in die Zukunft der Photogrammetrie" Photogrammetrie-Fernerkundung Geoinformation, 6, E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, Germany, pp 337-348, 1998.

Following pages:

Fig. 3: HRSC-AX150 data acquisition in Munich (2 May 2001)
flight altitude 5000 m, a) 1:2500, b) 1:10000,

Fig. 4: HRSC-AX150 data acquisition in Berlin (3 May 2001)
flight altitude 5000 m, a) 1:4000, b) 1:10000,

Fig. 5: HRSC-AX150 data acquisition near Berlin (25 April 2001)
flight altitude 3000 m, DOM and RGB images

Fig. 6: HRSC-AX150 data acquisition near Berlin (10 Apr il2001)
flight altitude 1000 m, RGB and IGB images

Fig. 3a: HRSC-AX150 data acquisition in Munich (2 May 2001) flight altitude 5000 m, 1:2500

Fig. 3b: HRSC-AX150 data acquisition in Munich (2 May 2001) flight altitude 5000 m, 1:10000

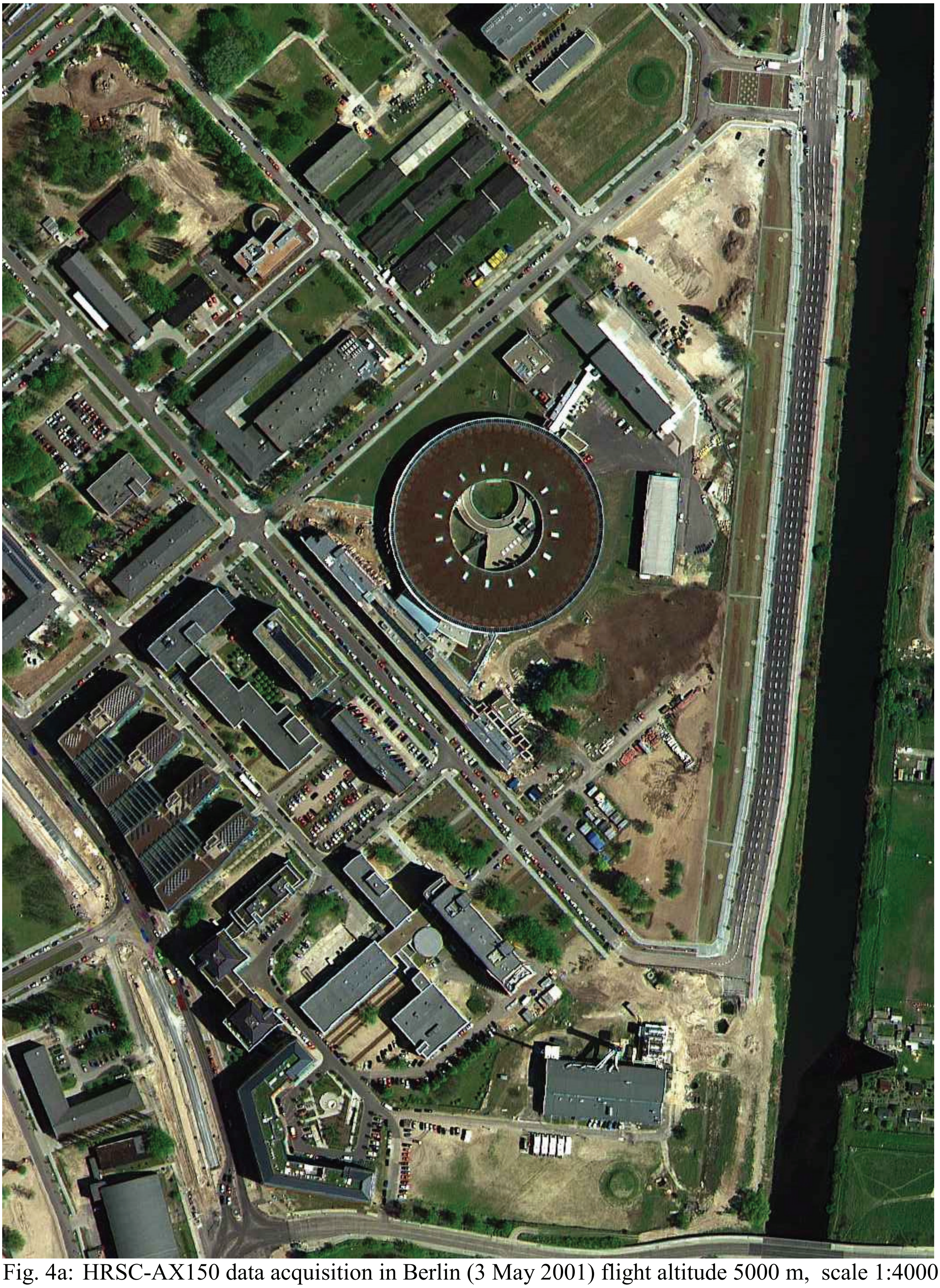

Fig. 4a: HRSC-AX150 data acquisition in Berlin (3 May 2001) flight altitude 5000 m, scale 1:4000

Fig. 4b: HRSC-AX150 data acquisition in Berlin (3 May 2001)
flight altitude 5000 m, scale 1:10000

Fig. 5: HRSC-AX150 data acquisition near Berlin (25 April 2001) flight altitude 3000 m, DOM and RGB images

Fig. 6: HRSC-AX150 data acquisition near Berlin (10 Apr il2001) flight altitude 1000 m, RGB and IGB images