DIGITAL 3D-DATA ACQUISITION WITH THE HIGH RESOLUTION STEREO CAMERA-AIRBORNE (HRSC-A)

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KEY WORDS: Camera, Scanner, High-resolution, Multi-spectral, Automation, Image Matching, DEM, Orthophoto.

ABSTRACT

The consequent way to complete the digital line in photogrammetric processing is to perform digital data acquisition. Since digital frame cameras for photogrammetric purposes will not be available within the next years, digital line scanners will not only fill this gap, they have several advantages, as there is the permanent nadir viewing geometry. At the Institute of Planetary Exploration of the German Aerospace Center (DLR) the High Resolution Stereo Camera (HRSC) has been designed for international missions to planet Mars. During the past three years an airborne version of this camera, the HRSC-A, has been successfully applied in many flight campaigns. The HRSC-A, fulfilling all requirements of a photogrammetric sensor, is based on the along-track triple-stereo principle. It combines 3D-capabilities and high resolution with multispectral data acquisition. A high-end GPS/INS system yields precise and high-frequent orientation data for the acquired image lines. In order to handle these data, a completely automated photogrammetric processing system, developed in cooperation between the Technical University of Berlin and the DLR, is used to generate impressive multispectral 3D-image products of HRSC-A data combined with accuracies in planimetry and height of better than 0.1 ‰ of the flight altitude.

1 INTRODUCTION

At the DLR the HRSC was developed as a multispectral multi-stereo scanner system for the exploration of Mars (Neukum & Tarnopolsky, 1990; Albertz et al., 1992; Neukum et al., 1995) and will be flown onboard the European Mars Express mission in 2003 (Neukum et al., 1999). A modified version has been established for airborne applications, the HRSC-A. It fulfils all radiometric and geometric requirements of a photogrammetric camera system and is equipped with a completely automated photogrammetric processing system, yielding high-accurate images and 3D-products (Wewel et al., 1998). The special properties of the HRSC-A and the photogrammetric products have been proven during accuracy tests and many applications.

2 DATA ACQUISITION WITH THE HRSC-A

The High Resolution Stereo Camera (HRSC) is a multiple line pushbroom instrument. Nine superimposed image tracks are acquired simultaneously (along-track) by nine CCD line sensors mounted in parallel and behind one single optics (see Figure 1).

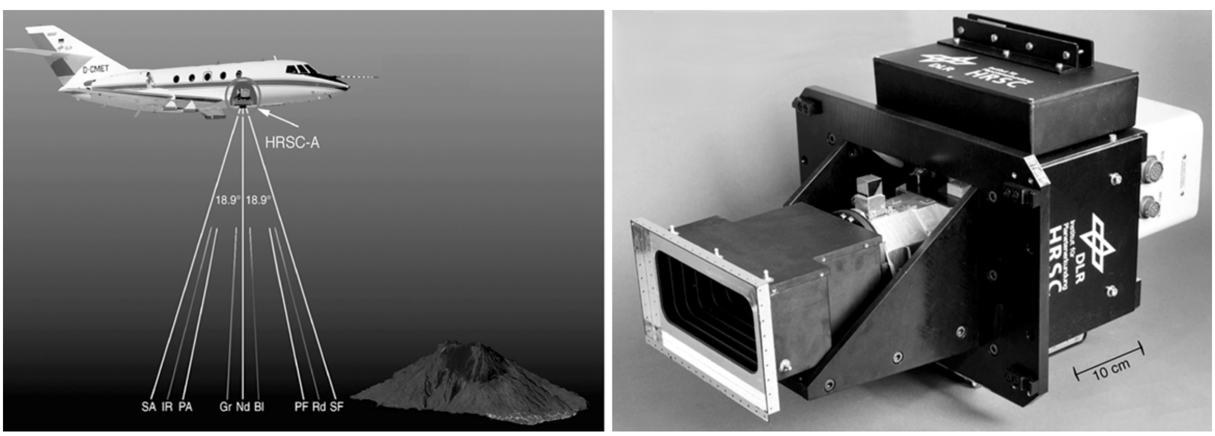

Figure 1. The HRSC-A: Imaging Principle and Design

Five of these sensors are panchromatic sensors arranged at specific viewing angles and provide the multiple-stereo and photometric capabilities of the instrument. Four of the nine CCD lines are covered with different filters for the acquisition of multispectral images. According to its development for space missions, the camera has small dimensions, low mass, low power consumption and a robust design. A slightly modified version of the instrument has been adapted for operation in terrestrial airborne remote sensing. To optimize image radiometry, the recording levels of the individual channels are controlled separately by adjustable gain factors. The HRSC-A (see Figure 1 and Table 1) is identical in its main structural features to the original HRSC system and includes its original optics. Some additional electronics have been added to meet specific airborne requirements. During image acquisition, data rates of 10 MByte/s provided by four parallel signal chains can be stored on a high-speed tape recorder. The camera is mounted on a stabilized platform (ZEISS T-AS) in order to damp mechanical vibrations and to enforce near-nadir viewing. Position and orientation during the flight are measured continuously by means of Differential-GPS and INS.

Focal Length:	175 mm
Total Field of View:	37.8° x 11.8°
Number of CCD Lines:	9
Stereo Angles:	±18.9° and ±12.8°
Pixels per CCD Line:	5184 (active)
Pixel Size:	7 µm
Radiometric Resolution:	10 bit reduced to 8 bit
Scan Rate:	max. 450 lines/s
Mass:	camera 12 kg (32 kg incl. subsystems)

Table 1. HRSC-A Technical Data

3 GPS/INS DATA PROCESSING

For the position and attitude determination of the HRSC-A camera the integrated GPS/INS system APPLANIX POS/DG (Hutton & Lithopoulos, 1998) is used. The Position and Orientation System (POS) consists of two components, the self-contained and separeted Inertial Measurement Unit (IMU) and the POS Computer System (PCS). The IMU consists of a high-performance Litton LR-86. It contains Litton A4 navigation grade accelerometers and Litton G7 dry-tuned gyros (DTG). The IMU is directly mounted on the top of a HRSC-A frame for precise measurements of camera motions. It provides data of incremental velocities and angular rates with an output data rate of 200 Hz. The POS also houses a GPS receiver L1/L2 Novatel Millenium Card. The GPS antenna is mounted directly above the HRSC-A camera. The POS provides logging of raw IMU data and of raw GPS data to the 8 mm tape of the PCS for further use in GPS/INS post-processing. After the GPS/INS post-processing the HRSC-A camera position is available with accuracies of ±2-3 cm, while the angular accuracy of the sensor orientation is ±0,004° (roll and pitch) and ±0,008° (heading) with a data rate of 200 Hz. These orientation data are synchronized with the HRSC-A image data and the orientation of each image line is interpolated.

4. DIGITAL PHOTOGRAMMETRIC PROCESSING

The digital photogrammetric processing system was developed in cooperation with the Technical University of Berlin for the Mars96 mission. An automated procedural software system has been derived for airborne application (Figure 2). It makes use of a set of systematically preprocessed image, orientation and calibration data. The automated photogrammetric process basically consists of the following steps:

- computation of HRSC-A/IMU boresight offset,
- pre-correction of the data for image matching,
- digital multi-image matching,
- derivation of raster DEMs,
- generation of (color) orthoimages of single strips and (color) mosaicing of orthoimage strips

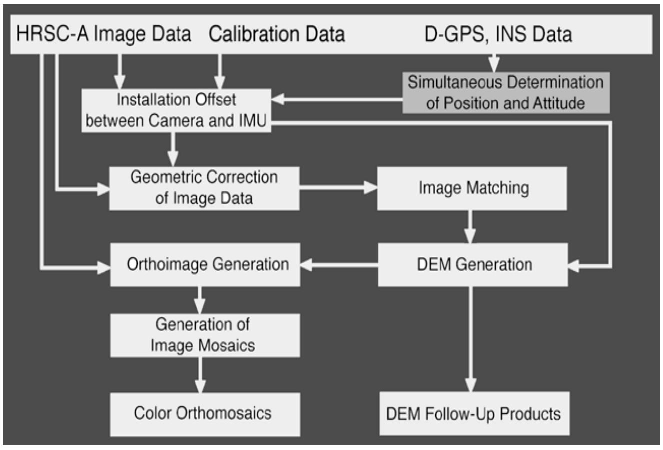

Figure 2. HRSC-A Photogrammetric Processing Line

4.1 Computation of the Boresight Offset between the HRSC-A and the IMU

The Inertial Measurement Unit (IMU) cannot be mounted exactly parallel to the HRSC-A camera axes. Therefore the offset between both systems has to be computed and must be added to the measurements of the IMU. This computation can be done without any additional ground control information, since the HRSC-A provides multi-stereo information. Within an iterative process a set of image coordinates of identical points, measured in adjacent strips, is used to determine those angular offsets, which yield the best ray intersection of these conjugate points. The resulting rotation matrix is applied to the original post-processed attitude data.

4.2 Pre-correction of Original HRSC-A Data

Image data of a pushbroom system like the HRSC-A are influenced by the permanenently changing exterior orientation. Applying image matching techniques to the original image data would result in failures, since the matching algorithm would match not only textures but also flight motion effects, especially when they appear periodically. To avoid these failures, the HRSC-A data of all five stereo sensors are pre-corrected by rectifying them to a mean terrain level and applying the data of the exterior orientation. Thus, height differences in the pre-corrected stereo data only appear as parallaxes in flight direction. When processing data of rough terrain, an additional reduction of the size of search areas during the matching process can be achieved by introducing a pre-calculated rough terrain model. It is also necessary, to store information about the pre-corrected data sets, which describes their position in the original data, since only for this data level orientation information is unique. Doing this pixelwise, it would give an additional amount of data of eight times the pre-corrected data itself (line/sample history in 8 Byte/pixel). Therefore a run-length encoding compression algorithm is applied, which makes use of the nearly homogenous distribution of the pre-corrected pixels. The compression yields a data reduction from 800% to less than 20%, with a maximum error of a tenth of a pixel.

Figure 3 shows the potential of the rectification process and the quality of the GPS/INS data, even under the extreme conditions during a flight maneuver. The flight movement corrected data set already defines a first product level which can be used for interpretation purposes, but it still contains dislocations due to the shape of the terrain.

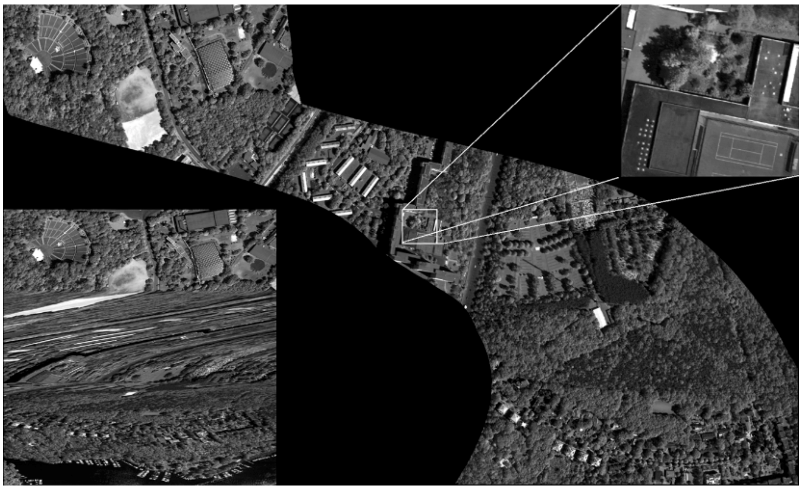

Figure 3. Effectiveness of Geometric Correction under Extreme Conditions, Original HRSC-A Data (lower left), Pre-Rectified Image Data (center and upper right), Flight Altitude 3000 m, Ground Resolution 15 cm

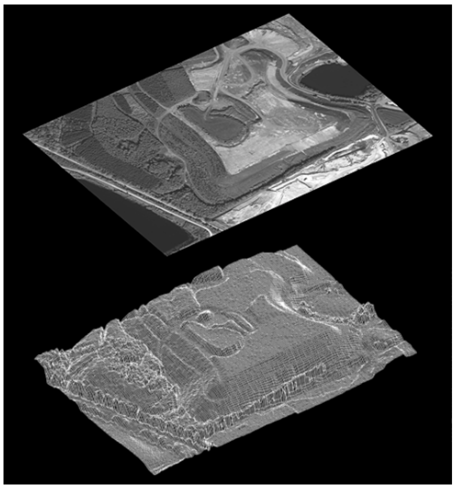

Figure 4. Pre-Rectified HRSC-A Image of a Hillside and Perspective View of the DEM Grid

4.3 Digital Multi-Image Matching

There are several possible matching strategies to use the multi-stereo information of HRSC-A, e.g. seperated matching of each two-image combination or using a dedicated image as a master image and the other stereo data sets as matching partners. Nevertheless, the chosen matching strategy should take the basic optimization aspects into account:

- the quality (accuracy) of the result,
- the quantity (completeness) of the result,
- the robustness (need for automation) of the process,
- the afford (time restrictions) of the process.

Following the goal to derive DEMs with 3D-accuracies of about ± 0.2 m, the matching grid size should be about 0.5-1 m in order to map the terrain variations. The original image data are pre-corrected to a resolution of 0.3-0.5 m and a 1-2 pixel raster width is used within the matching process. Matching tests showed that for common terrain shapes a denser grid would not significantly improve the accuracy, but would increase computation time drastically. To optimize the matching accuracy, image matching is applied during a hierachical (pyramidal) procedure, where cross correlation is applied to reduced data sets and least-squares-matching is used for the high-resolution pyramid level, where finally accuracies of 0.1-0.2 pixel can be achieved. The permanent nadir viewing geometry of the HRSC-A makes the nadir channel to be the most appropriate master image. It guarantees the best possible coverage (completeness) because of the reduction of hidden areas. In order to reduce the influence of matching failures and to introduce redundancies, the nadir grid points should not be matched with only one partner but with all (four) possible stereo partners. Thus, the multi-stereo capability of HRSC-A gives the unique chance to determine points with up to five observations.

4.4 The Derivation of Raster DEMs

Together with information about the interior and exterior orientation each set of image coordinates of a match point includes up to five rays. The intersection of these rays and the quality of intersection is computed within a least-squares adjustment process. Points, which are defined by less than three rays, are eliminated due to the lack of redundancy. They could intersect perfectly but might be a result of a matching failure. The intersection accuracy gives another chance of defining a quality criteria and to eliminate blunders.

The remaining set of object points is defined in the GPS/INS reference system (WGS84) and can be transformed to other geodetic datums, depending on the intended cartographic representation of the final raster DEM. The DEM, finally represented in any requested map projection, can now be interpolated from the set of object points. The DEM defines the next type of product. It can be used for the extraction of profiles, contour lines or other DEM follow-up products (see Figure 4). Finally, it is the basic prerequisite for the following generation of orthoimages.

4.5 Generation of Orthoimages and Orthoimage Mosaics

During orthoimage generation, rays, defined by the calibration and the orientation data of each pixel, are intersected with the surface described by the DEM. The grid of intersections is used for indirect resampling of the orthoimage. The final step within the photogrammetric data processing is the generation of orthoimage mosaics using orthoimages of adjacent strips. The result is a homogeneous image mosaic for each spectral band (see Figures 5 and 7). The color bands can be combined with the generally higher resolution of the panchromatic nadir channel by means of IHS color transformation, thus yielding color mosaics including the high geometric resolution of the panchromatic data.

5 GEOMETRIC VALIDATION OF THE HRSC-A-SYSTEM

In the past years several flight campaigns have been performed in order to validate the HRSC-A system. In spring 1998 detailed tests have been done in two test-fields with over one hundred check points. The intention was to test the entire system, comprising the HRSC-A and its combination with the APPLANIX GPS/INS system, as well as the test of the complete software system. Besides the accuracy the tests should investigate the stability and robustness of the results as well as its usefulness and operational aspects.

A test-field near Bedburg (close to Cologne/Germany) covering 1,5 x 6,0 km^2 was prepared. Additionally, the test-field Vaihingen/Enz of the Institute for Photogrammetry at the University of Stuttgart (IFP) was flown. The camera was mounted on a Cessna 208 Caravan. The aircraft has two hatches, so a conventional photogrammetric camera (RMK-TOP15) could still be operated in parallel to the HRSC-A. The IMU block of the APPLANIX system is separated from the control electronics of the INS system. Since the IMU block is small, it could be positioned directly on top of the camera body. The GPS antenna used by the navigation system was mounted vertically above the HRSC-A and the IMU sensors. The positions of the system components were determined precisely by using geodetic measurements. The eccentricity of the camera axis to the GPS antenna was less than 1 cm in the horizontal direction. Because of using a stabilizing platform (ZEISS TAS), the camera and the INS on the one hand and the GPS antenna on the other hand were not in a static system. Therefore the eccentricity should be always as small as possible. In order to minimize the effects of the eccentricity the rotation angle of the three platform axes were stored and calculated afterwards. The data of the different sensors were synchronized via GPS time signal.

In the Bedburg test-field 109 signalized ground control/check points (white plates of 45 x 45 cm^2) were placed. 29 of these points were measured directly by means of DGPS. The remaining points were determined by an aerotriangulation at the IFP. The obtained accuracy was 4 cm for the horizontal and 9 cm for the vertical coordinates. The test-field was flown at an altitude of about 3000 m with a flight speed of approximately 72 m/s. This yields ground pixel resolutions of 12 cm across-track and 16 cm along-track for the nadir channel (integration time 2.24 ms) and 32 cm for the stereo channels (4.48 ms). The test-field was covered by three image strips with 50% overlap. Additional two cross strips were flown. As a result of this configuration all check points could be observed in at least two of the image strips. The Bedburg test flight took 2.5 h from the initialization of the INS on the ground up to the landing. During this time a GPS reference station was operated in the test area.

For the total flight time the camera positions were derived in planemetry and height with an accuracy of ±1.6 cm by an integrated GPS/INS processing (Hutton & Lithopoulos, 1998). The rotation angles were estimated with rms errors of ±0.2' for roll and pitch angles as well as ±0.5' for the azimuth. The comparison of this values with the field of view of a HRSC-A pixel (0.14') shows the importance of the accuracy of the attitude measurements with respect to the error budget of the point determination.

The boresight offset between the HRSC-A and the IMU was computed by using three ground control points and approximately 250 identical points, measured in the five stereo images of a single strip respectively in the images of adjacent image strips. Besides the boresight angles shift vectors in the local coordinate system of the flight direction were estimated. There was a shift of 78 cm in flight direction. The offset could be interpreted as a result of a synchronisation error of 5 ms between the image and the navigation data. The error could also be verified at straight lines in the images. The offsets were applied to the position and attitude data.

The object points were determined by spatial intersection of the rays of the conjugate points in the five HRSC-A stereo images. The image coordinates were measured manually in the original images. The mean absolute deviation of the object points to the given check point coordinates are shown in Table 2.

Image Strip	Check Points	Mean Deviation [m]			
		mx	my	mz	mp
1	47	0,10 (*)	0,07	0,16	0,20
2	52	0,10 (*)	0,06	0,21	0,24
3	38	0,08 (*)	0,06	0,14	0,17
4	8	0,07	0,15 (*)	0,19	0,25
5	11	0,06	0,08 (*)	0,07	0,12
1-5	156	0,09	0,07	0,17	0,21

Table 2: Mean Absolute Check Point Deviations, Test-Field Bedburg, (*) = flight direction

The mean deviation of all points is ±12 cm (0.04‰ of the flight altitude) for planimetry and ±17 cm (0.06‰) for height. The image strips were acquired within one hour. Within this time frame no systematic drift effects of the INS system accured. Quite similar results have been derived from the Vaihingen/Enz test-field evaluation and from other operational applications. Even if the project area size exceeds some hundred km^2 and the flight time is several hours, the same excellent accuracy and robustness of the products can be obtained. The tests demonstrate that the reliability and the geometric accuracy of photogrammetric products derived from this type of line scanner is at least as high as those of conventional aerial cameras.

6 APPLICATIONS

Since the first airborne experiments (May 1997), the HRSC-A system has been used for many different applications. Simultaneous high resolution multispectral orthoimages and DEM data have been acquired for applications as different as volcano monitoring (Gwinner et al., 1999), mapping of urban areas, open coal mines, flood hazards, and coastal zones.

The derivation of morphological characteristics such as slopes, volumes, or drainage patterns through the analysis of DEMs is an essential step for many geoscientific and environmental applications. DEM analysis frequently is combined with the analysis of remote sensing imagery, for example to classify and measure topographic changes related to volcanic activity (see Figure 5), landslides or avalanches.

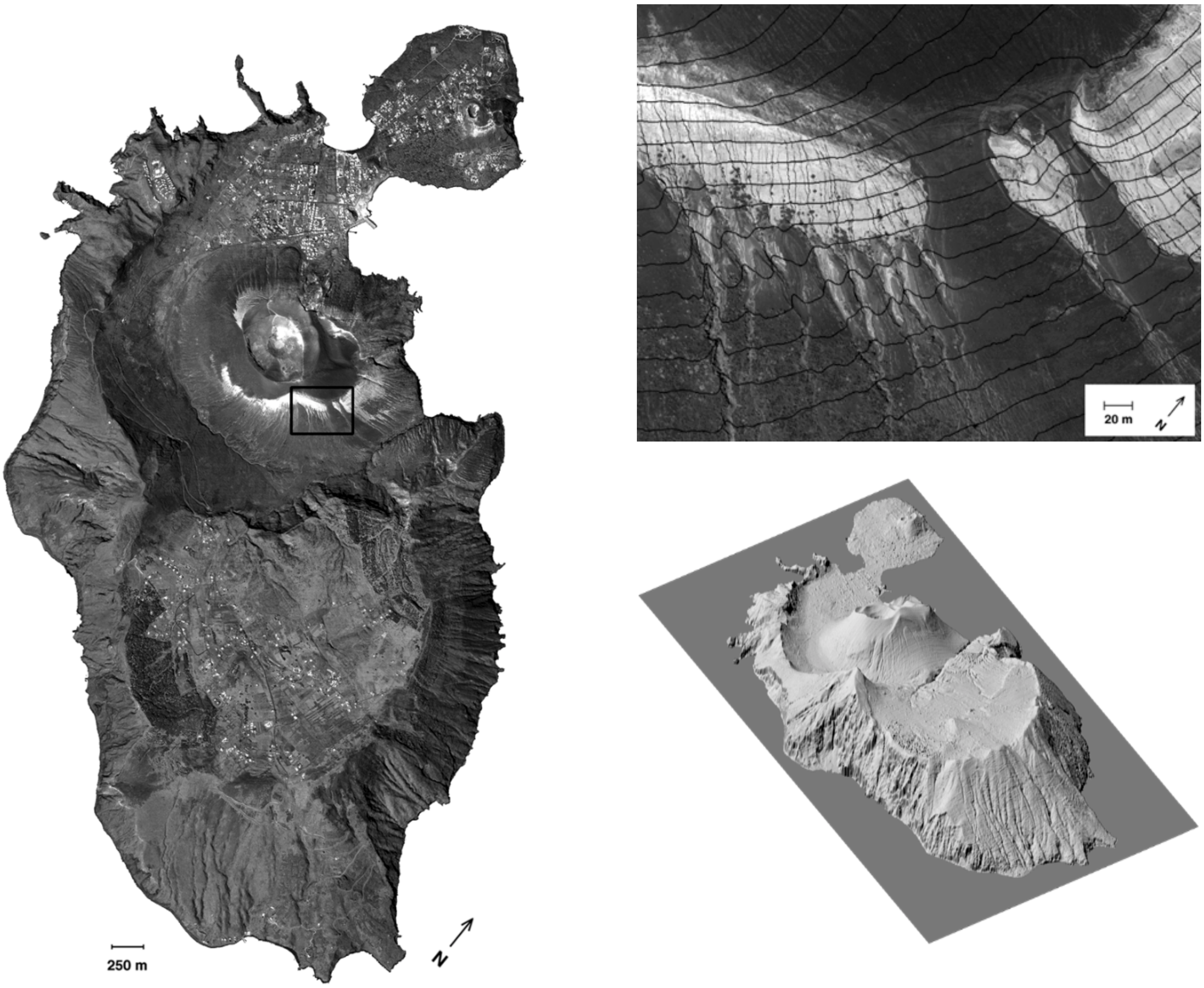

Figure 5. Left: Orthoimage Mosaic of Vulcano Island based on 7 HRSC-A Image strips, (original in color).
Upper right: Detail of Orthoimage Mosaic with Contour Lines (equidistance 10 m),
Lower right Shaded Perspective View of HRSC-A DEM of Vulcano Island
(Flight campaign at the Aeolian Islands, Italy, 1997)

Planning requirements for urban areas increasingly involve GIS technology, e.g. using 3D models for the needs of the mobile phone service in the telecommunication industry. The potential of the HRSC-A system for photogrammetric surveys in urban areas has been shown in its operational use at several European cities (see Figure 6) during a joint ISTAR/DLR project on European cities for HRSC-A application in the telecommunication market (Renouard & Lehmann, 1999).

The need for both high resolution multispectral images and DEM data can be addressed by airborne digital imaging with the HRSC-A.

Figure 6. Portion of a Shaded DEM of Lisbon (Portugal), processed by ISTAR (France) using HRSC-A Data

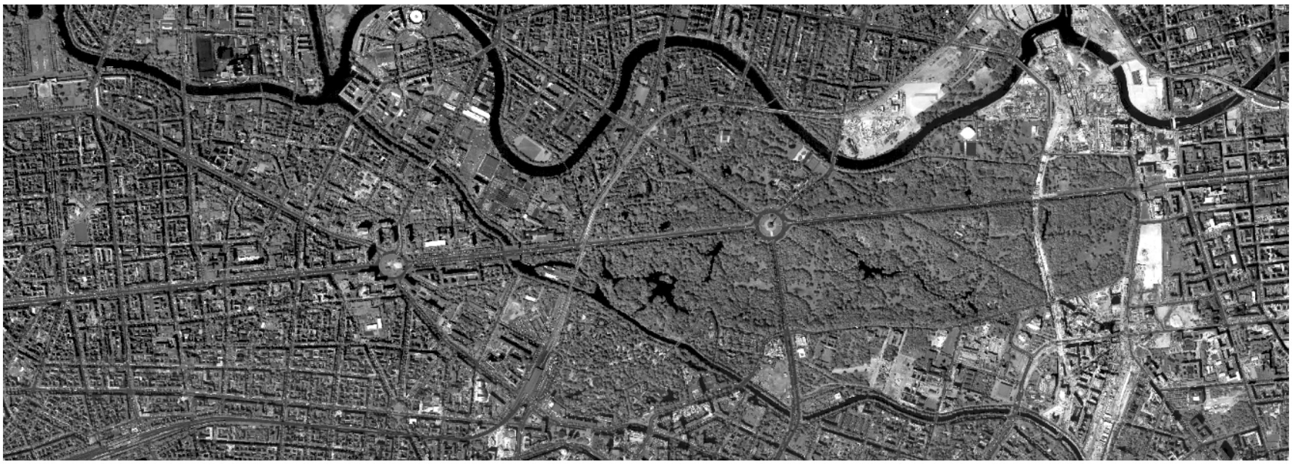

Figure 7: Flight campaigns over Berlin, (1998, 1999).

The orthoimage mosaic (top) is based on seven image tracks acquired from a flight altitude of 3000 m and with a maximal ground resolution of 15 cm. Below, a greyvalue-coded visualization of the central Berlin DEM is shown. The dark patches in the DEM, arranged in north-south oriented bands, are open construction sites for subground infrastructure.

Figure 8 shows a series of magnification steps and the HRSC-A capabilities of imaging large areas in high resolution. It enables the generation of digital image maps in scales of up to 1:500.

Figure 8. Different magnifications of Figure 7 (Brandenburger Tor, Berlin), Flight altitude 3000 m

7 CONCLUSIONS

The HRSC-A has demonstrated its unique potential in digital image acquisition within years of operation. The achieved accuracies show that the combination of a high-resolution multispectral digital line scanner and a comprehensive processing system yields high accurate data products for large regions. More than this, the digital techniques enables new fields of geoscientific, environmental and cartographic applications while minimizing analogue to digital data transition and cost intensive manual interactions.

ACKNOWLEDGEMENTS

We would like to acknowledge the scientific and operational contributions of all persons of the DLR, which are involved in the HRSC-A developments and flight campaigns.

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