THE HRSC-AX MT. ETNA PROJECT: HIGH-RESOLUTION ORTHOIMAGES AND 1 M DEM AT REGIONAL SCALE

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ABSTRACT:

Digital photogrammetric sensor systems that have become available during the last years provide a high potential for generating high-resolution digital elevation models (DEM) and orthoimages for large areas. We report on results from a digital photogrammetric mapping project at Mt. Etna, Italy, applying the airborne HRSC-AX sensor and photogrammetric processing system. The survey parameters have been defined by taking typical requirements of natural hazard areas into consideration, where timely needs for up-to-date topography represent an important operational constraint, in addition to geometric quality. The selected survey parameters allowed us to cover the entire area of Mt. Etna within 3 successive campaign days, while the point accuracy achieved by stereophotogrammetric processing is about 30 cm on average, according to over-determined intersections. Accuracy has been examined with respect to variations of ground sampling distance and terrain type and is found to attain values better than 20 cm in the summit area of Mt. Etna. A DEM at 1 m spatial resolution, as well as orthoimages at 25 cm/pixel have been derived. We conclude that airborne digital photogrammetric surveys that enable the production of high-resolution DEM and orthoimages can be performed effectively under such demanding constraints as are imposed by applications in hazard mitigation, and we discuss the requirements and time-scales associated with timely generation of higher level photogrammetric data products for this purpose.

1. INTRODUCTION

During the last years the general availability of airborne digital photogrammetric data has been increasing gradually after the introduction of a number of new sensor systems, of which some are commercially available. While the imaging characteristics of these sensor systems are generally documented in great detail, the number of published reports on the performance of what can be considered one of their most important potential strengths is still quite limited: enabling the (almost) automatic generation of high-resolution DEM and orthoimages for large areas. We present recent experimental results related to this application which we obtained using the airborne High-Resolution Stereo Camera (HRSC-AX) sensor and photogrammetric processing system (Wewel et al., 2000; Scholten and Gwinner, 2004). We will focus on the properties of the DEM result, which in turn forms the basis of the derived orthoimages.

As compared to the large extent of the Mt. Etna area (> 1500 km^2), previous experiments using airborne HRSC data on volcanic terrain (Gwinner et al., 1999; Gwinner et al., 2000) have been limited to smaller areas. A photogrammmetric survey of Mt. Etna, which is among the large and most active volcanoes of the world, can be considered both a highly demanding and very instructive task. Among the more demanding target properties are the large elevation range (more than 3300 m), very rugged topography, as well as large areas with low contrast and texture. In addition, strong overall brightness contrasts between the dark volcanic deposits (on the upper flanks and near the summit) and the inhabited zone (on the lower flanks and the periphery) are present within individual flight tracks. The survey parameters have been defined by taking typical requirements of natural hazard areas into consideration. In these areas, strong and timely needs for up-to-date topography data do regularly arise after periods of increased activity. Time efficiency of the survey configuration under operational conditions is, therefore, in addition to geometric quality, among the most relevant performance parameters here.

Mt. Etna is a quite well suited target area for testing performance characteristics due to the good availability of reference data and the presence of inhabited, well-textured and well-accessible terrain along all parts of the lower flanks of the cone. After presenting the survey characteristics and data processing aspects we will discuss the performance based on internal quality measures related to point accuracy. Feasibility issues under operational aspects will also be discussed.

2. SENSOR SYSTEM AND PROCESSING METHODOLOGY

HRSC is an experimental multi-line pushbroom camera system developed at DLR (Neukum et al., 2001). It features 5 panchromatic stereo channels and 4 color channels. HRSC-AX (Table 1) is a derivative of the sensor system currently operated in Mars orbit onboard the ESA mission Mars Express (Neukum et al., 2004). Among the modifications for airborne operation are the integration of a GPS/INS inertial navigation sensor system and the re-design of the focal plate unit, including near-nadir pointed color channels. Digital image acquisition with the HRSC-AX is based on the multi-line pushbroom principle. 9 CCD lines, each with 12,000 pixels, are placed in the focal plane behind one single optics (150 mm focal length). The ground sampling distance (GSD) across-track depends on the IFOV (0.043 mrad) and the altitude above ground. At 3,500 m altitude the across-track GSD is approx. 15 cm. The along-track GSD depends on scan rate and ground speed. At approx. 70 m/s ground speed the along-track GSD is also 15 cm.

HRSC-AX150 Technical Parameters	
Focal length	151 mm
Field of view	41 x 29 deg
CCD lines	9 (5 for stereo, 4 for color)
Stereo angles	± 20.5 and ±12 deg
Number of active pixels	12,000/line
CCD pixel size	6,5 micron
Radiometric resolution	12 bit
Spectral bands	stereo & nadir 520-760 nm
	blue 450-510 nm
	green 530-576 nm
	red 642-682 nm
	near infrared 770-814 nm
Scan line frequency	Max. 450 lines/s
Dimension: WxHxD	390 mm x 410 mm x 430 mm
Mass	Camera 45 kg, Adapter 40 kg
Stabilization	ZEISS T-AS- platform

Table 1. HRSC-AX Technical Parameters

Exterior orientation data for HRSC-AX are acquired simultaneously with a high-end DGPS/INS system (APPLANIX POS/DG 510). The Inertial Measurement Unit (IMU) is directly mounted on top of the camera. GPS position using a L2-antenna is recorded with 2 Hz while angular variations and accelerations are provided at a sampling rate of 200 Hz. Improved position and attitude data are derived with the help of combined differential GPS and INS post-processing techniques based on GPS reference data recorded on ground (Lithopoulos, 1999; Scholten et al., 2003). The camera is mounted on a ZEISS T-AS stabilized platform during operation.

Photogrammetric processing of HRSC-AX data (Wewel et al., 2000; Scholten et al., 2002; Scholten and Gwinner, 2004) is based on laboratory and in-flight geometric calibration, and includes an optimization of the GPS/INS-solution. 3D point determination is done in along-track stereo mode based on area-based automatic image correlation. Object point calculation is performed by over-determined forward ray intersection for at least 3 stereo observations per object point. The points are integrated into a regular DSM grid by raster interpolation techniques.

3. MEASUREMENT CAMPAIGN

In our survey planning, we gave consideration to the typical time constraints of applications for hazard mitigation purposes by aiming at a parameter setting that minimizes the survey efforts while still allowing for the generation of a 1m DEM for the entire area. In particular, we avoided any accompanying ground measurements (including ground control points), except for the GPS reference data from existing permanent stations. As compared to standard HRSC-AX surveys (about 3000 m flight altitude and track lengths of up to 30 km), we also chose an unusually high flight altitude (6000 m) as well as relatively long track lengths, which are near the limits of stable GPS/INS solutions. Different back-up flight plans were made for the case of partial cloud cover.

The chosen survey parameters allowed for covering the entire area of Mt. Etna within 3 successive campaign days (about 18 flight hours). The flights took place in July 2005. Due to the considerable height variation on ground (0 to 3330 m a.s.l.), the constant flight altitude of 6000 m results in a variation of ground distance between 2700 m and 6000 m and a ground resolution of 14-22 cm/pixel in the nadir channel (28-44 cm/pixel in the remaining 4 stereo channels due to macro-pixel formation). In addition to 49 regular flight tracks, flown in E-W direction with alternating heading, data have been acquired on several N-S oriented cross-tracks crossing the summit area of Mt. Etna. To insure a side overlap of at least 40%, the track spacing has been reduced on tracks containing areas higher than 2000 m a.s.l. The length of the tracks varies between 25 km and 40 km, the width of the target area is more than 40 km in N-S direction. For the post-processing of the GPS/INS data, reference data from different permanent ground GPS stations of the ground deformation monitoring network of Mt. Etna operated by Istituto Nazionale di Geofisica e Vulcanologia (INGV) have been used.

4. DATA PROCESSING

From the nearly 1 Tbyte of radiometrically calibrated imagery, we first derived a preliminary DEM at 5 m spatial resolution, which was then used for the generation of the rectified stereo imagery at 30 cm/pixel resolution used for precise image matching. Fig. 1 shows an example of an image sequence with unusually strong distortions for demonstration of the effectiveness of the geometric image correction involved. Finally, a DEM at 1 m spatial resolution has been derived as well as orthoimages at the scale of 25 cm/pixel. For both data products the UTM (Zone 33) projection in combination with the WGS84 ellipsoid has been used.

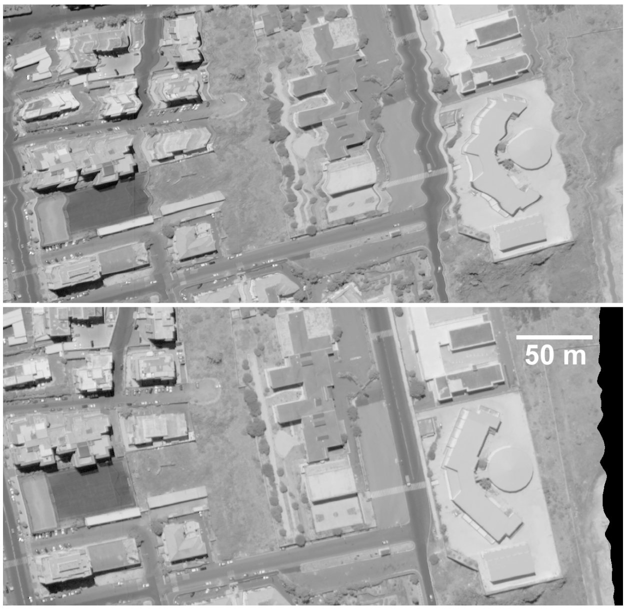

Figure 1. Top: example of unusually strong geometric distortions in the raw nadir image caused by roll angle variations. Bottom: result of geometric image correction.

The photogrammetric improvements for the GPS/INS solution include a boresight correction, timeline refinement and correction of constant positional offsets. These corrections are reflected in the reduction of the intersection error for manually measured identical points (Table 2). Note that no ground control points have been used to achieve these improvements.

Day	# Within-track identical points	# Across-track tie points	# Ground control points	Initial 3D error within-track	Initial 3D error across-track	Final 3D error within-track	Final 3D error across-track
1	27	10	0	35.3	92.0	35.5	30.4
2	53	23	0	35.8	56.9	30.6	30.7
3	39	16	0	40.3	45.1	33.1	26.0

Table 2. Photogrammetric improvement of post-processed GPS/INS orientation data

Processing step	Net processing time	Processing Mode	Output data volume
Systematic processing, radiometric calibration and pre-processing	2-2.5 d per day of survey	sequential	930 GByte
GPS/INS postprocessing	0.5-1 d per day of survey	sequential	1.5 GByte
Prematching and generation of 5m-DEM	7 h (entire project)	parallel	55 GByte
Optimization of orientation data	0.5 d per day of survey	sequential	--
Generation of matching images and matching	~7.5 d per image track	parallel	~38 GByte per track (~ 1.95 TByte total)
Object point calculation	0.5 d per image track	parallel	~ 1.05 TByte
DEM generation	9 d (entire project)	sequential	3 GByte

Table 3. Net processing times and associated data volumes for individual processing steps. Processing times refer to a 1.4 GHz CPU.

Table 3 lists the net processing times for individual processing steps during DEM generation, together with the approximate data volume generated during each step. Note that the data volume of the calibrated raw data is already nearly 1 TByte and that, during fully parallel processing, an additional data volume of about three times the raw data volume has to be stored temporarily. For example, the number of object points derived from each image track amounts to about 230 millions. Thus, the total number of individual point measurements included in the final DEM is larger than 10^{10}.

These numbers demonstrate that aspects of process management and data handling are important factors, in addition to com-puting speed. Assuming no limitation by data transfer and storage capacity, the generation of the 1m DEM for the whole area could be accomplished within ca. 3 weeks, while the preliminary 5 m DEM can be available already after 3-4 days.

A further consequence of the very large data volume is the requirement to reduce the need for interactive components to a minimum, e.g. through the use of numeric quality parameters that can be applied automatically. In particular, no interactive DEM editing has been applied in this work.

5. QUALITY ASSESSMENT

At the time of writing, the final DEM integration is still ongoing since a small fraction of the image tracks has not been fully processed yet. The 1m DEM results already achieved, covering more than 1000 km^2 and the full height range present in the area, do however allow first statements on the quality of the DEM based on the distribution of intersection errors and visual inspection.

The intersection error associated with an object point provides a measure for its relative 3D accuracy (1σ) and has proven very useful for estimating DEM quality based on internal information (Gwinner et al., 2005). The intersection error is derived from the improvements of the orientation data that result from achieving an optimal intersection of the conjugate rays in terms of least-squares adjustment. As a 3D error, it provides a measure of 3D position uncertainty and thus includes the error of both the height and the lateral components.

We mapped the intersection error of all object points entering the DEM on a test area of about 117 km^2 that includes 6 image tracks which span the entire DEM area from East to West and cover the summit area of Mt. Etna. Fig. 2 shows the corresponding frequency distribution. The mode of 28.6 cm is in good agreement with the 3D errors obtained during the manual optimization of the GPS/INS solution and is well below the chosen DEM grid spacing of 1m.

Two major effects can be considered to explain the dispersion of the error distribution (Fig. 2): 1) the local image resolution and 2) the surface type. The effect of terrain type is examined for two sub-areas of the test area, which are both located at an intermediate altitude range (1000-1700m, Fig. 3). The first one is a rather rough surface free of vegetation inside Valle del Bove. It is covered with young lava flows (area 5.5 km^2). The intersection error here has a mode of 22.7 cm and nearly all errors fall below 0.5 m. The second area is located in a distance of about 2 km. It has the same extent, but the rocky surfaces are mostly covered by vegetation (trees and shrubs) and by loose ashes in this area. Fig. 3 shows that the intersection accuracy is clearly reduced here, which can be primarily related to the highly discontinuous character of the vegetation surface. However, both the mode (29.5 cm) and the overall distribution of the intersection errors are still appropriate for a 1m DEM grid also in this case. Since the range of terrain heights in the survey area is large compared to the chosen flight altitude, measurement accuracy can be expected to be significantly influenced by variations of local image resolution. Note that the

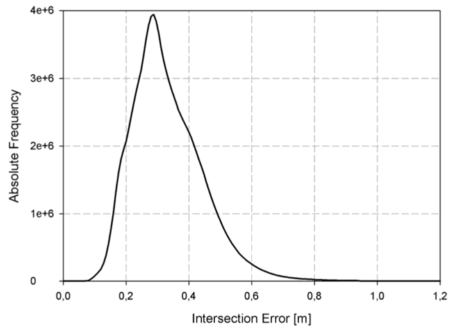

Figure 2. Histogram of intersection error for test area (117 km^2) covering 6 image tracks over the full width of the survey area.

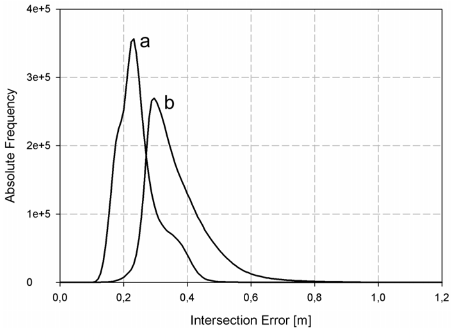

Figure 3. Histogram of intersection error for two sub-areas at intermediate altitude. a) without b) with vegetation cover.

flight altitude above ground is more than twice as large near the coast (6000 m) than over the summit area (2700 m). When comparing the intersection accuracy to local heights (Fig. 4), an inverse correlation between intersection error and true ground distance is clearly discernible. It is, however, evident from Fig. 4 that the impact of other parameters than ground resolution is significant as well (such as surface type, see above). The average intersection error at intermediate heights (1000-1500m) is about 30 cm and is in good agreement with the results obtained using manually measured points (Tab. 2) and with the mode of 28.6 cm of the intersection error obtained for the complete test area of 117 km^2 (Fig. 2). In the summit area, i.e. at maximum ground resolution, the relative precision attains values of better than 20 cm.

Two examples of shaded relief maps demonstrate the level to which small surface features are resolved in the 1 m DEM. In Fig. 5, small irregularities of lava surfaces to the East and North-East can be traced. They display height differences of few decimetres to meters. In Fig. 6, the small arrows point to engineering constructs which correspond to steps in the river bed approximately one meter high which show up cleary in the shaded relief map.

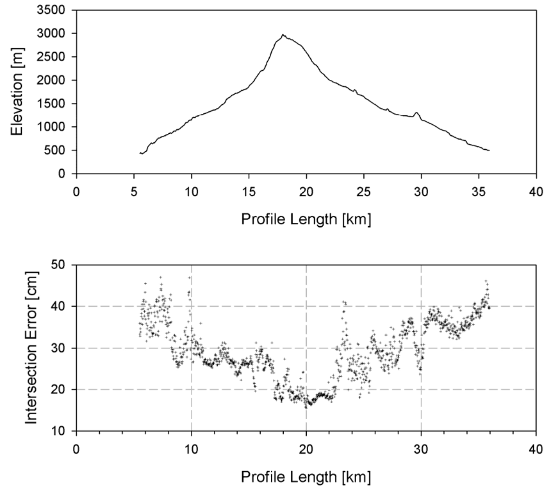

Figure 4 Top: Vertical section crossing the summit area of Mt. Etna in E-W direction. Bottom: Mean intersection error along the section, calculated in 25x25 m grid cells. The significance of local ground resolution is indicated by the inverse correlation between the intersection error and true ground distance.

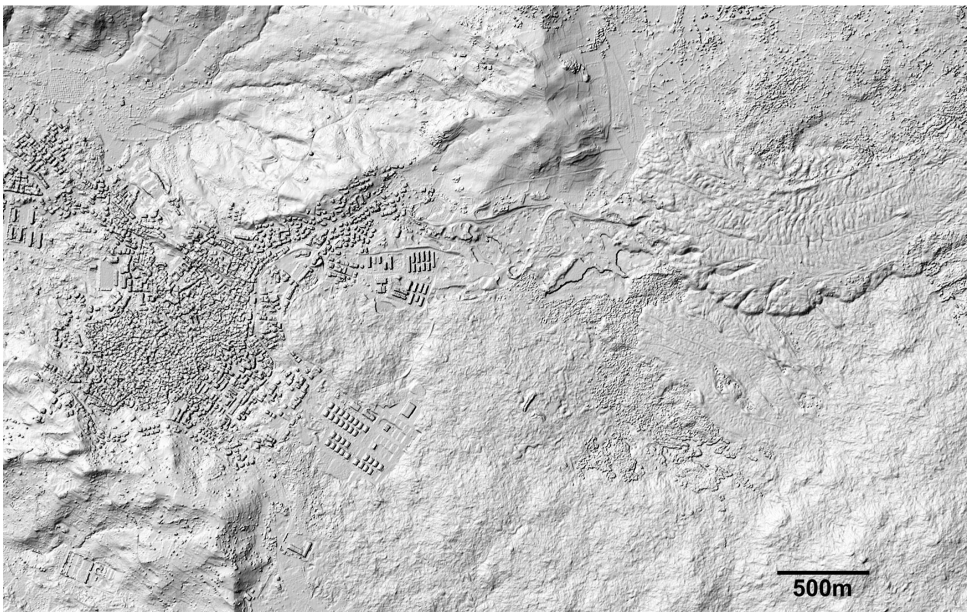

Figure 5. Shaded relief map of the area of Bronte showing detailed lava flow morphology.

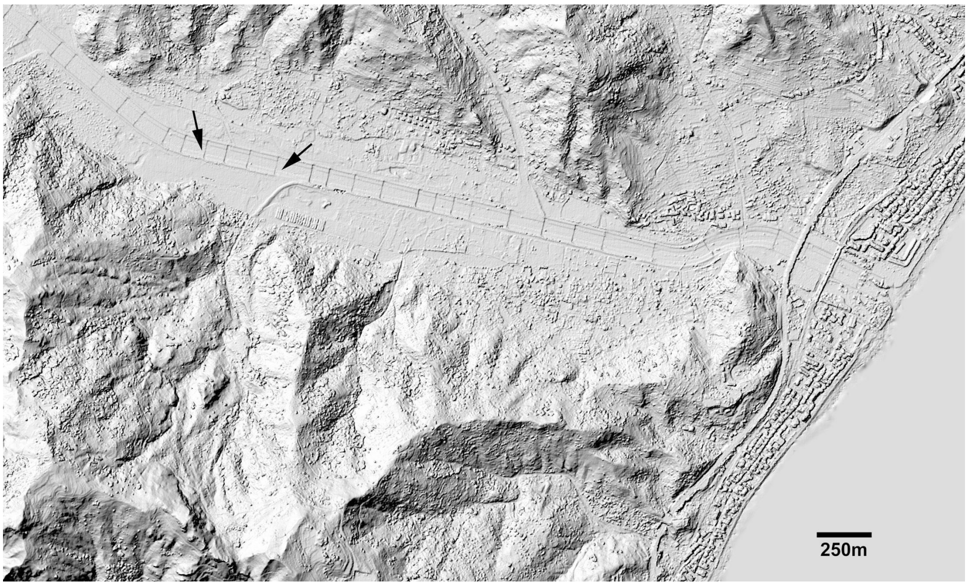

Figure 6. Shaded relief map of a costal area near Taormina. The small arrows point to engineering constructs which correspond to steps in the river bed approximately one meter high.

6. CONCLUSIONS

We reported on the generation of high-resolution DEM (1 m) and orthoimages (25 cm/pixel) for a large project area by means of airborne stereophotogrammetric mapping. In addition to the need for high geometric quality, timeliness is of high relevance for hazard mitigation, which is a major requirement in the area of Mt. Etna. Time efficiency under operational conditions has therefore been given specific consideration, particularly in the planning of the airborne survey. The point accuracy achieved by stereophotogrammetric processing of the data is about 30 cm on average, according to over-determined intersections. Geometric accuracy has been examined with respect to variations of the local ground sampling distance and the terrain type and is found to attain values better than 20 cm in the summit area of Mt. Etna.

Considering the geometric quality achieved and the fact that the data acquisition for the entire project area could be accomplished within only three days, we conclude that airborne digital photogrammetric surveys that enable the production of high-resolution DEM and orthoimages can be performed effectively under the demanding constraints of applications in hazard mitigation. Of particular importance is the possibility to avoid the use of ground control points.

Concerning data processing, a high degree of automation enables at least the generation of DEM with reduced spatial resolution (e.g. 5 m) within few days. Presuming the availability of the necessary hardware resources, the minimum time needed to achieve full quality results as considered in this paper is estimated to be about 3 weeks. As our summary of the large data volumes associated with different processing levels demonstrates, the available capacity for data handling can be a major limiting factor for processing time. While algorithms allowing for automated processing with low requirements for interactive tasks can be considered as a primary prerequisite, due consideration has therefore to be given also to the important aspect of data management when operational applications are envisaged.

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