Polarforschung 67 (1/2), 53 – 63, 1997 (erschienen 2000)

A Topographical Data Set of the Glacier Region at San Martin, Marguerite Bay, Antarctic Peninsula, Generated by Digital Photogrammetry*

By Bernhard P. Wrobel[1], Henning Walter[2], Mario Friehl[1], Ulrike Hoppe[1], Martin Schlüter[1,2], and Dieter Steineck[1]

Summary: Basic cartographic data at the regional level are needed for the research on climatology, glaciology, and geomorphology of the Antarctic, i.e. in order to be able to give substantial support to specific methods of research made use of by geoscientists. We will depict hereinafter the way of stereophotogrammetric, purely digital evaluation of aerial photographs towards a high-resolution topographic data set generated largely automatically. It consists essentially of a digital photomap containing contours which, in analog (printed) form, can be used within the scale range of about 1 : 25 000 to 1 : 50 000. Two very different digital photogrammetric procedures, that were adjusted to the specific requirements of the Antarctic were employed: FACETS STEREO VISION and the software PHODIS of Carl Zeiss company. The report describes the results of evaluation obtained in the test site at the station General San Martin (Figs. 1 and 2) as well as the procedural characteristics of digital photogrammetry that could be ascertained, in particular as to which additional expenditure became necessary for work in the Antarctic.

The following sections of this contribution point out details of results obtained by present-day stereophotogrammetry. First, the aerial photographs referred to for examining the test site, and then the required steps of preprocessing are explained until image orientation. The strongly overlapping images are subsequently processed by means of the multi-temporal multi-image method of Facets Stereo Vision (= FAST Vision), and in addition by means of the PHODIS software, which must always have recourse to single stereo photo pairs. In both cases Digital Elevation Model (DEM) and digital orthophoto constitute the objectives. Finally, a digital photomap is generated which integrates all existing and produced topographic data. In all paragraphs the difficulties arising from the specific antarctic conditions are pointed out and ways how to surmount them.

In their conclusion the authors have a glance at other procedures of topographic data collection in the Antarctic; they may be feasible in future which will from today's point of view no doubt bring about quite a number of improvements, e.g. airborne GPS- and INS-supported digital photogrammetry, laser scanning, interferometric SAR as well as the new generation of high-resolution optical satellite imagery.

Zusammenfassung: Für die Forschungen zu Klimatologie, Glaziologie und Geomorphologie der Antarktis werden regionale topographische Basisdaten benötigt, um die speziellen Untersuchungsmethoden des Geowissenschaftlers wesentlich stützen zu können. In diesem Beitrag schildern wir den Weg der stereophotogrammetrischen, rein digitalen Auswertung von Luftbildern hin zu einem hochaufgelösten topographischen Datensatz, der weitgehend automatisch erzeugt wurde. Er besteht im wesentlichen aus einer digitalen Luftbildkarte mit Höhenlinien, die in ausgedruckter (analoger) Form im Maßstabsbereich von ca. 1 : 25 000 bis 1 : 50 000 verwendbar ist. Zwei sehr unterschiedliche, den Besonderheiten der Antarktis angepaßte Verfahren der digitalen Photogrammetrie werden eingesetzt: das am Photogrammetrie-Institut der TU Darmstadt entwikkelte „Facetten-Stereosehen" und die Software PHODIS der Fa. Carl Zeiss. Der Bericht schildert die im Untersuchungsgebiet an der Station General San Martin erreichten Auswerteergebnisse und die festgestellten Verfahrenseigenschaften der digitalen Photogrammetrie, insbesondere, welcher Zusatzaufwand in der Antarktis notwendig wurde.

Die folgenden Kapitel dieses Beitrages schildern näher die mit heutiger Stereophotogrammetrie erreichten Ergebnisse. Zunächst wird auf die für das Untersuchungsgebiet herangezogenen Luftbilder eingegangen und die notwendigen digitalen Vorverarbeitungsschritte erläutert bis hin zur Bildorientierung. Die sich stark überlappenden Bilder werden danach zum einen mit dem multitemporalen Mehrbildverfahren Facetten-Stereosehen verarbeitet und zum anderen mit der Software PHODIS, die stets auf einzelne Stereobildpaare zurückgreifen muß. In beiden Fällen sind DHM und digitales Orthobild das Ziel. Schließlich wird eine digitale Luftbildkarte generiert, die alle erzeugten und vorhandenen topographischen Daten integriert. In allen Abschnitten werden die durch die besonderen Verhältnisse in der Antarktis bedingten Schwierigkeiten aufgezeigt und Wege zur Überwindung beschritten.

Zum Schluss wird ein Blick auf künftig mögliche Verfahren der Topographiedatenerhebungen in der Antarktis geworfen, von denen aus heutiger Sicht eine Reihe von Verbesserungen zu erwarten sind: flugzeuggetragene, GPS- und INS-gestützte digitale Photogrammetrie, Laser-Scanning, interferometrisches SAR sowie die angekündigte neue Generation von hochaufgelösten optischen Satellitenbildern.

* This contribution is dedicated to Univ. Prof. em. Dr.-Ing. Dr.h.c. mult. Gottfried Konecny, Hannover University, in recognition of his wide range and highly efficient activities he performed in the relevant fields of photogrammetry and remote sensing.

[1] Institut für Photogrammetrie und Kartographie, Technische Universität Darmstadt, Petersenstraße 13, D-64287 Darmstadt, Germany <wrobel@gauss.phgr.verm.tu-darmstadt.de>

[2] Bundesamt für Kartographie und Geodäsie (BKG), formerly Institut für Angewandte Geodäsie (IfAG), Richard-Strauss-Allee 11, D-60598 Frankfurt am Main, Germany

Manuscript received 18 June 1999, accepted 08 December 1999

1. BASIC TOPOGRAPHIC DATA AND METHODS OF COLLECTING THEM IN THE ANTARCTIC

The generation of digital topographical data sets as such is part of the standard tasks of present-day digital photogrammetry. However, specific characteristics of the Antarctic still present a lot of difficulties, which on the one hand are due to the sheer size of this area, and on the other hand to the known very difficult accessibility which makes any photographic flight a rather demanding single-mission project from the point of view of logistics. Moreover, the ground surface presents some uncommon characteristics. There are considerable differences of brightness between snow and ice-covered areas on the one side, and the very dark uncovered rock formations, the shadow ranges, and the sea surface on the other side. Which optical sensor is ever used, its dynamic range must therefore be extraordinarily large and well resolved. Similar challenging demands are made on the geometric resolution of the sensor used, since the existing textures of the surfaces are extremely different as to their positional spectra: low-frequency monotonous fresh-fallen snow zones and very high-frequency crevasse areas, i.e. mixed zones of snow and rock, at rocky ridges, and at the rugged edges of the glaciers flowing into the sea. Thus, the sensor to be applied must fulfill requirements far above average. The topographic data set should consist of the components „Digital Elevation Model (DEM)“ and „Digital Orthopohoto (DOP)“, and also contain other topographic data obtained by expeditions as well as geographic names and occasional additions from existing maps. It is evident indeed that basic regional topographic data for glaciological problems, e.g. according to ice mass balances and their changes can supply unbiased information only if such data are part of a uniform updated geodetic reference system.

Such a universal „Reference Network Antarctica“, which is a component of the global International Terrestrial Reference Frame (ITRF), is being established in practice since about 1995 (LINDNER et al. 1999, KORTH & DIETRICH 1996). The net was designed to meet the very high accuracy requirements of plate tectonics. GPS observation instruments and marigraphs for sea level recording are of primary importance in this context. The average accuracy of better than ±2 cm for the WGS 84 coordinates X, Y, Z are by far sufficient for the needs of topographic data collection. Only the small number of points of the reference network will no doubt constitute a permanent problem. Nevertheless, photographic flights supported by high-precision GPS equipment will thus be possible in future, while at the same time requiring considerably less effort needed to measure a very limited number of reference and control points within the ground area to be covered by aerial photographs. Moreover, the results of evaluation would generally improve with costs still decreasing. It appears as if for the time being no autonomous system reliable in all aspects for the generation of topographic data sets under the described conditions of the Antarctic is available. Before explaining in the following chapters two digital stereophotographic procedures we would like to point out an interesting comparison of the procedures that competed during the period of the project 1995-1998. However, it must a-priori be clear that only large-scale recording sensors and imaging sensors are considered.

Photogrammetry was employed for covering glaciers already as early as in the 19th century, its methods still being strenuous at that time. Initially, terrestrial photographs were used, namely for the first time by the well-known Munich photogrammetrist and researcher in the field of glaciology SEBASTIAN FINSTERWALDER (1897) for his mapping of the Vernagtferner (glacier) situated in the Ötz Valley (Austria). To cover the Arctic regions aircraft is required. Photogrammetric activities of this type were already performed as early as 1931 within the scope of the dirigible's „Graf Zeppelin“ voyage to the Arctic, as e.g. in Franz-Josef-Land (KOSTKA 1997). With respect to the Antarctic, the first survey flight can be traced back to the British expedition in the years 1934-37 under Rymill (cf. SCHMIDT-FALKENBERG 1990) whereas Germany launched in 1938/39 an airborne photographic flight campaign to Neuschwabenland, the material of which was evaluated cartographically by O. VON GRUBER (1942). However, photogrammetry was widely used in the glacier areas of the USA, Canada, and Europe not earlier than about the sixties (KONECNY 1966, 1972) when the technique had been developed further (aircraft, cameras, films, plotting instruments) since approximately the sixties until to the recent past (WELSCH et al. 1997). In the Antarctic, too, systematically arranged photogrammetric photographic flights were carried out. Until to the end of the mid-seventies aerial photographs of most of the Antarctic mountainous and coastal regions were available, which were used above all for the production of topographic maps at the scale 1 : 250 000. For detailed plots at a scale of 1 : 50 000 and larger the BKG conducted several photoflight campaigns in the Antarctic with the polar aircraft of the Alfred-Wegener-Institut for Polar and Marine Research (AWI) subsequently to the Antarctic expedition of 1983/84 (SIEVERS & WALTER 1984, BRUNK 1992). The photographic flight routes and further data on the airphotos have been documented. Further information is given by the BKG via Internet under http://www.ifag.de.

Two technological inventions during the last years have rendered possible considerable progress in photogrammetry, namely the aforementioned integration of NAVSTAR position observation system GPS, and of an Inertial Navigation System (INS) into the photographic flight as well as digital photogrammetry, which has now been made operational. The importance of the GPS method for photogrammetric coverage of Antarctic regions cannot be estimated high enough: given that smaller numbers of image and control points than hitherto are required owing to an appropriate choice of camera, image overlaps, and scale it is now possible to meet in a flexible manner the glaciologist's requirements, i.e. up to detailed plots at the scale 1 : 50 000. Apart from the photographic flight also the subsequent digital-photogrammetric evaluation profits by GPS; it entails a high degree of automation of all working stages and discharges the photogrammetric operator to a large extent of tiring routine work - an effect that is very welcome considering the vast regions covered monotonously by ice and snow of the Antarctic.

The applicational range of photogrammetry described so far proves in itself its acceptance with regard to the polar regions - which applies also to its future possibilities, as has been demonstrated above. However, the specific weaknesses of this technique must also be mentioned: dependency on weather conditions and sunshine (clouds / low solar latitudes, polar night) as well as unsatisfying accuracies of the stereoscopic method of measurement in the case of unstructured snow and ice surfaces. For the test site near Marguerite Bay described herein (Figs. 1 and 2) aerial photographs were taken in 1989 which at that time could be covered using ground control points, that is without support from photo flight GPS data. So, the orientation of the images had to be based only on ground control points. Nevertheless, the pertinent evaluations were preferably performed already with the help of digital photogrammetry, which will be treated in the following chapters.

With the launch of the first LANDSAT remote sensing satellite by NASA in 1972 the new phase of optical remote sensing was started also for large parts of Antarctica. Great areal performances (output per area unit) and multi-channel spectral image data with low resolution though, do nevertheless increase the state of knowledge about Antarctica considerably, while supplying the user with image material in a cost-saving manner. The Earth Reconnaissance Program has since then

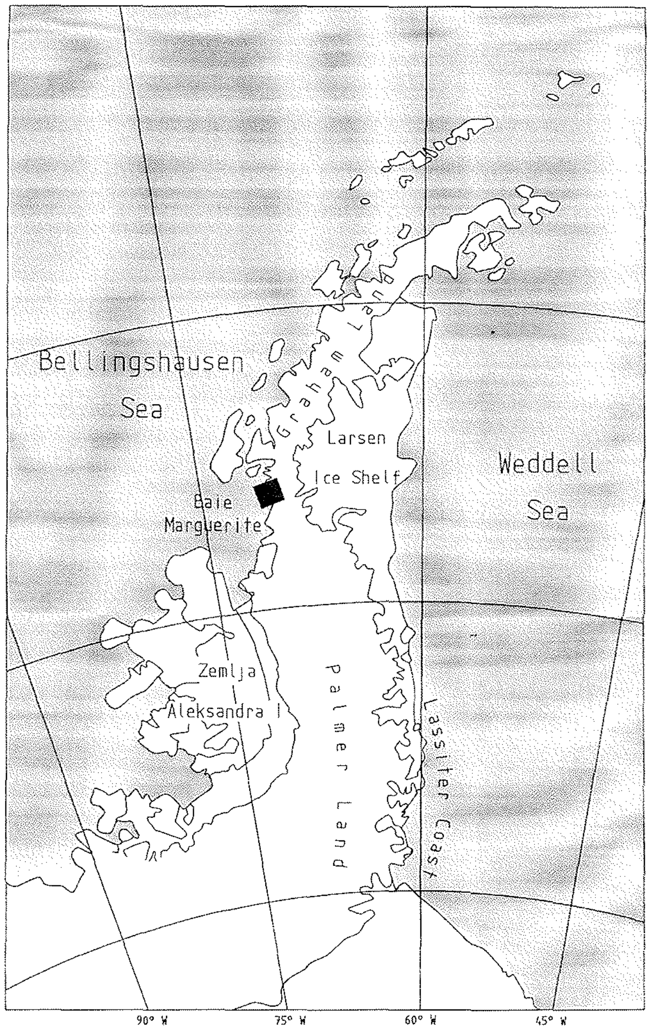

Fig. 1: Location of the test site on the Antarctic Peninsula.

Abb. 1: Lage des Untersuchungsgebietes auf der Antarktischen Halbinsel

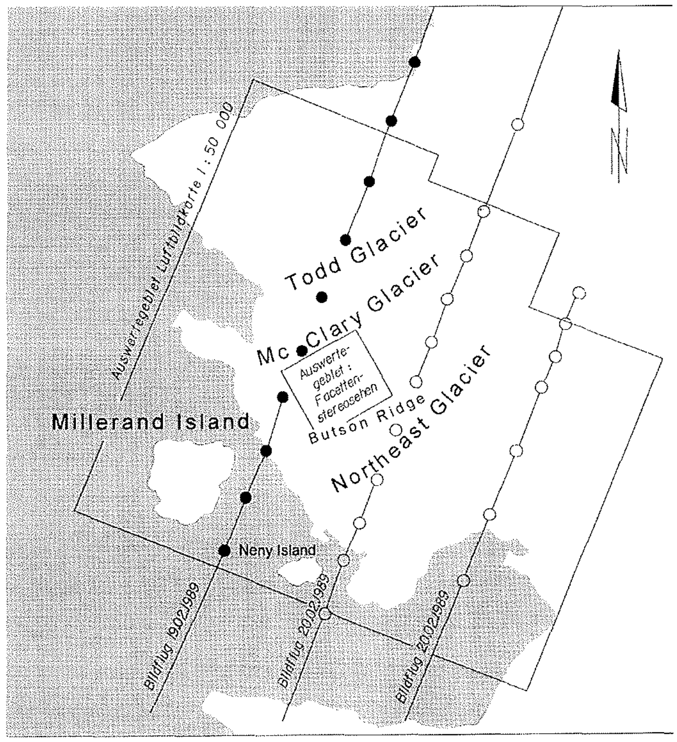

Fig. 2: Test site near the station General San Martin, Marguerite Bay.

Abb. 2: Untersuchungsgebiet bei der Station San Martin, Marguerite Bay, Maßstab 1 : 500 000

been continuously extended by a steady increase of new satellites, providing with the French satellites SPOT and the photographic satellite imagery of the Russian research centre PRIRODA images that can be evaluated stereoscopically, which are suited for the production of topographic maps by means of DEM. However, all relevant evaluations are restricted to the smaller scale-range 1 : 100 000. As compared with aerial photographs satellite remote sensing constitutes a completion of the Antarctic large-scale and small-scale stock of data. A feature common to both techniques is their dependency on sun light and weather.

The latter characteristics of the passive optical sensors considered above were overcome through the active SAR scanning system in the microwave range of the spectrum on board the ERS satellites of ESA. The information capacity of the SAR technology (MERCER et al. 1998, METZIG et al. 2000, WUNDERLE & SCHMIDT 2000, MÜLLER et al. 2000, RAU et al. 2000) which as a whole is of extraordinary importance for Antarctic research - must nevertheless be considered as compensatory as to its characteristics, and as complementary with regard to the data supplied by aerial photogrammetry (BRANDSTÄTTER & SHAROV 1998). This becomes clearly evident, e.g. in the DEM computations. The SAR interferograms constitute altitude differences of unsurpassed high relative accuracy, but their integration into a DEM within a fixed reference system is seriously disturbed or avoided due to problems of unambiguousness on rough surfaces (flanks of glaciers in the transitional zone of unmoved ice, crevassed areas, rocks) as well as by layover and signal noise, whereas the smooth, texture-free regions - the only ones that present difficulties to stereophotogrammetry - cause no problems. This fact tends to favour a combined use of both sensors instead of single-sensor use.

2. PREPROCESSING OF AERIAL PHOTOGRAPHS OF THE SURROUNDINGS OF THE STATION SAN MARTIN

The glaciers situated in the surroundings of the Argentine station San Martin (Fig. 2) are part of the long-term subject of research of the Institute for Physical Geography of Freiburg University. The common test site agreed-upon for the purpose of topographic data collection covers an area of approx. 30 x 20 km^2, presenting a maximal altitude difference of 1800 m between the sea and the ridge of the Antarctic Peninsula, which poses no problem with respect to the evaluation procedures. However, the terrain characteristics mentioned above make specific requirements: the abundance of forms and the high brightness contrast. The smaller inland area of 4.5 x 4.5 km^2 was selected for testing the more universal evaluation method FAST Vision. It is situated at the Butson Ridge, covers parts of the McClary glacier, and also includes the elevation „Schauinsland“

(see Figs. 2 and 3).

The choice of aerial photographs referred to for the test sites has been made from the flight campaign 1988/89 by the BKG. A very good photographic image quality was achieved, the large overlap realized presenting advantages for evaluation in the Antarctic. In the table below the most essential parameters of the aerial photographs have been compiled.

Aerial photo coverage: 19.02.1989, 22:05 GMT or 13:30 local solar time, sun's altitude ca. 15° 20.02.1989, 15:40 - 16:20 GMT or 11:12 - 11:52 lo cal solar time, sun's altitude 33° flight altitude 6100 m above ground image scale 1 : 70 000 image overlaps: in the direction of flight 66-88 %, laterally ca. 60 % 28 images For more detailed information cf. flight survey index map 1 : 500 000 Adelaide Island, Grandidier Channel, Antarctic Expedition 1988/89, Institut für Angewandte Geodäsie, now BKG, Frankfurt a. M. Camera: Super wide-angle camera Zeiss RMK A 8,5/23, image format 23 x 23 cm^2, D filter, 13 % transmission of centres Film material: Black-and-white Agfa-Gevaert AVIPHOT PAN200, rel. speed 24,5 DIN Exposure: 19.02.89: 1/250s, aperture 8; 20.02.89: 1/250s, aperture 22 Processing: Agfa PAKOTONE, G74c, Gradation 1,84 Digitization: Precision scanner Zeiss SCAI Grey values 8 bit after transfer of internal 12 bit with adjusted transfer function, Pixel size in the image 14 x 14 mm^2 Pixel size on the ground ca. 1 x 1 m^2 Position accuracy of the pixel: ±2 µm Data volume per picture: 270 Mbyte Data volume of all 28 pictures: 7,6 Gbyte Control points: Five 3D points and 13 spot elevations in the Lambert projection, derived from WGS72 (SIEVERS & BENNAT 1989)

Tab. 1: Technical data on the aerial photos and control points used of the region adjacent to the station General San Martin.

Tab. 1: Technische Daten über die benutzten Luftbilder und Passpunkte der Region an der Station General San Martin

The image scale 1 : 70 000 allows reliable evaluations of maps of up to maximally ca. 1 : 25 000. Thus, many research activities in the Antarctic can be supported, but not interpreted and detected with all details of glaciological relevance as to elements of form and shape, for which purpose the scale 1 : 10 000 commonly used in glaciology would be suited, as is illustrated by the thorough investigations of BRUNNER (1977, 1980). Nevertheless, for the DEM result the requirements of 30 m grid width and ±15 m altimetric accuracy can be easily met with some exceptions. With these characteristics SAR interferometric DEM and velocity computations of the glaciers, too, can be supported. Many elements of form, which are of interest to the glaciologist, are reproduced very finely by the image scale 1 : 70 000. Therefore, the pixel size had to be chosen very small with 14 x 14 mm^2 for digitization, but which nowadays no longer poses a serious problem of storage.

The extremely high differences of brightness as given in the Antarctic require particular care in the case of photographic flight (SIEVERS & WALTER 1984) as well as with the digitization of the images. According to our experiences both steps of acquisition entail losses with are due to present-day technology. Optical density measurements in black-and-white negatives yielded a density range of negative of up to 2.8 D. The limited dynamic range of the scanned values of the scanner of 1 : 256 (= 2.4 D) does not suffice for this purpose. Moreover, inertia of the CCD elements and the very high scanning speed, which could not be reduced by the user, caused that dark terrain surfaces could no longer be resolved radiometrically in a differentiated manner and that strong grey value edges were smeared over many pixels. Normally, digitization of the analog aerial photographs could be performed „free from losses", if the internal grey value resolution of 12 bit (= density range of negative of more than 3 density values) was freely accessible to the user. The transfer of 12-bit-grey values into 8-bit-grey values could then be combined with a local, signal-adjusted image filtering (of the high-pass type with correction for shadows and shore edges). 8-bit-grey values are normally sufficient for most photogrammetric evaluation processes since these are principally not based on the full grey values, but on the gradients of the latter which, however, suffer no damage by high-pass filtering. A corresponding image transfer (also called „digital dodging") was (not yet) feasible within the project under discussion. We only were able to reduce the problems of high contrasts to a suboptimal extent by use of a transfer function derived from the histograms of the images. As a result of the investigations it must be retained that in the Antarctic grey values of the image with 12 bits should be referred to. According to the product information given by the manufacturers of precision scanners these are in future to be provided with a 12-bit output. Interestingly enough, the new generation of highly resolved optical satellite images with 11-bit-grey-values meets a-priori these requirements.

Pre-processing of the aerial photographs includes above all the computation of data as precise as possible of the interior and exterior orientation of the airphotos, which is a prerequisite for any kind of photogrammetric work (KRAUS 1993). Whereas the interior orientation can be performed without any difficulties using the PHODIS software, the specific peculiarities of the Antarctic become evident when determining the exterior orientation by means of the bundle block adjustment method. The task of the bundle block adjustment consists in determining commonly the data of the exterior orientation of all images and to improve the data of interior orientation by means of calibration functions (= bundle block adjustment with self-calibration). The critical working stage of bundle block formation consists in assigning unambiguously and measuring of corresponding points in the images (= point transfer). One has to have recourse to characteristically natural image details that should be measurable as precisely as possible. Such details can be found less often in images taken in the Antarctic - as compared to regions found in Germany. This task has been assumed by the BKG, which entails many risks. Considering the very large aperture angle of ca. 110 gon of the super wide-angle camera used here, and also the fact that photoflights were carried out on two different days (shadows differing considerably!) this task is by no means an easy one. The BKG accomplished the point transfers successfully using the digital photogrammetric workstation DPW 770 of LEICA company.

The photogrammetric-geodetic point field (consisting of 141 object points including the given control points) was then definitively determined by means of the data set represented in Table 1 through bundle block adjustment (program BUND, ETH Zürich). Self-calibration yielded only one single significant parameter k of a radially symmetric deformation k x r^3, which covers the considerable influence of refraction existing with super wide-angle images. The exterior accuracy achieved of the object points (σ_x = 3.5 m, σ_y = 2.2 m, σ_z = 2.7 m) reflects primarily the uncertainty of re-identifying the control points in the aerial photographs according to the surveyors' descriptive sketches; the non-linear shares of distortion of the Lambert projection in the coordinates X, Y, Z are much smaller. The interior accuracy (precision) of the object points was with ± 0.50 m on an average clearly better, the standard deviation σ_0 of unit weight amounting to σ_0 = 8.5 (m in the image = 0.57 pixel. These results can be labeled as good. The fact that they were achieved despite of a relatively small number of tie points per image can be clearly reduced to very good overlap conditions of the image block. With a size of σ_0 = 8.5 µm in the image, and of 0.60 m on the ground as average quality of the intersections of rays in the bundle block a limit is practically set for the following surface reconstructions which cannot be further reduced. It is interesting to see that this figure can be interpreted as the average surface roughness of glaciers, see Fox & Nuttal 1997. Eventually, the comparison of interior with exterior accuracy reveals that approx. a fourfold increase in accuracy would be possible if the photographic flight had been supported by GPS.

3. APPLICATION OF THE MULTI-TEMPORAL MULTI-IMAGE METHOD OF FACETS STEREO VISION

The present software packages offered by the various manufacturers for computing digital elevation models from digital aerial photographs have not been designed to the specific needs of the Antarctic. The richly textured surfaces typical of other regions are the precondition; they must be covered by (at best low-growth) vegetation or have other features rich in contrast with sufficient areal density, as e.g. rock formations, but not fine sand, snow, etc. From the existing approaches of digital photogrammetry for DEM computations only the one based on intensity has to be considered. In this method the image grey values (corresponding to image brightness or intensity, however, in essence only gradients being really important) are directly related to the object surface. This allows any grey value gradient, which occur rather seldom in the Antarctic, and even the smallest one to be optimally used for DEM computation. This would not be feasible following the other approaches (feature-based and relational approach). Optimal use of the gradients was pursued with FAST Vision, principally with the following measures:

(i) Processing not only the minimum of two images at the same time, but a greater number , i.e. in principle as many images as are required (multi-image method). This leads to a reduction of a number of error influences and strengthens the geometric configuration of the imaging rays for the purpose of surface reconstruction. The test site marked in Fig. 2 has been covered by two flight strips in altogether six images, which are all processed in the computing process of FAST Vision.

(ii) Unfortunately, these images were recorded on two days at times differing by ca. five hours (Tab. 1). Azimuths and altitudes of the sun (15° or 33°) differ very strongly and, as a consequence, also the overlapping aerial photographs, cf. Figs. 3a with 3b. Therefore, the FAST Vision approach had to be adapted to the generation of two digital orthophotos (DOP) (one each for the dates 19.02 and 20.02.1989), but at the same time to only one single common DEM. Since FAST Vision includes in any case both components, i.e. DEM and DOP, in one approach, no fundamental difficulties arise from extending the procedure to multi-temporal image processing. Integration of multi-temporal image data in one working step (least squares adjustment of all image data) is of considerable advantage: reduction of the image noise in general, parts of objects located in hard shadows of one strip become evaluable, provided that they appear in sufficient brightness in the other one - and, finally- an increase of accuracy can be obtained (Wrobel & Schlüter 1997).

(iii) The two object space models given in the FAST Vision approach, DEM and DOP, are in this case represented each by quadratic meshes (facets) and bilinear interpolation functions. The sizes of facets must meet the need for regularization of this method as well as the projects requirements formulated together with Freiburg University. With the given pixel sizes on the ground of ca. 1 x 1 m^2 and with the textures of Central Europe a DTM resolution with grid widths of ca. 8 x 8 m^2 could in principle be achieved (Schlüter & Wrobel 1998), even to 2 x 2 m^2 (Tsay 1996) when using wavelets. The less favourable textures must be taken into account for the Antarctic, which means also to ensure higher redundancy. The following facet ratios were selected after a series of experiments:

1 DEM facet = 8 x 8 DOP facets = 16 x 16 pixels
= 30 x 30 m^2 in resolution stage 2
= 15 x 15 m^2 in resolution stage 1.

The weights of the so-called „curvature equations" are closely related to these parameters, which contribute considerably to the stabilization of FAST Vision bridging texture-free areas within the problem zones mentioned above. The weights, too, had to be determined empirically.

More detailed information on the mathematics and numerical procedures of FAST Vision is given in WROBEL (1987), WEISENSEE (1992), TSAY (1996) and SCHLÜTER (1999).

The test site in the centre of Figure 2 contains nearly all aforementioned surface characteristics of the Antarctic. We performed in this site a series of tests with FAST Vision and also with measurements in the analog aerial photographs carried out by an operator. As we already mentioned, these are of a better quality than the digitized images. The test results can be summarized and evaluated as follows:

• At all places with good textures prevailing (strong grey value gradients), height accuracies of ±0.50 m are obtained or ±0.08 ‰ of the flight altitude, which is a very good value even under Mid-European conditions. With the number of ±0.50 m the lowest bound possible at all is reached, which was defined by the accuracy of image orientation (cf. preceding chapter). Moreover, the standard deviations of the heights are realistic here.
• In the other places (with the exception of problem areas) where weaker grey values gradients are present, accuracies of better than ±1 m up to± 5 m were achieved.
• In the problem areas (either too dark or too bright) both factors, DEM values and their standard deviations, are clearly less certain: ±10 m, at places even more, or no solution at all is achieved. This must be expected since there the picture signals - as mentioned above - are strongly disturbed and no longer realistic.
• The success of multi-temporal multi-image processing by FAST Vision becomes clearly visible when comparing Figure 3a with 3b:
  – The contours of the evaluation on the basis of six images, Fig. 3b, are locally smoother (i.e. more precise), glacier areas and other fine structures appear in the orthophoto sharper - which in the case of FAST Vision is an unambiguous evidence for a better DEM result. Beyond that, the shadow regions present here a more differentiated and more plausible morphology.
  – The areas presenting themselves very smoothly on top left in Figures. 3a and 3b differ only little from each other - which proves that already with three pictures each good results can be achieved, provided that they were acquired only with undisturbed image signals. It shall also be mentioned in this context that the results were generated fully automatically without being supported by operators' measurements nor editions.

Let us record that: FAST Vision has proved an optimal method of digital photogrammetry for applications in the Antarctic. However, the restriction must be added that the software presently available does not comprise the operationability: Easy handling of the many gigabytes of the image data and direct interactive inference of the operator in case of problems or

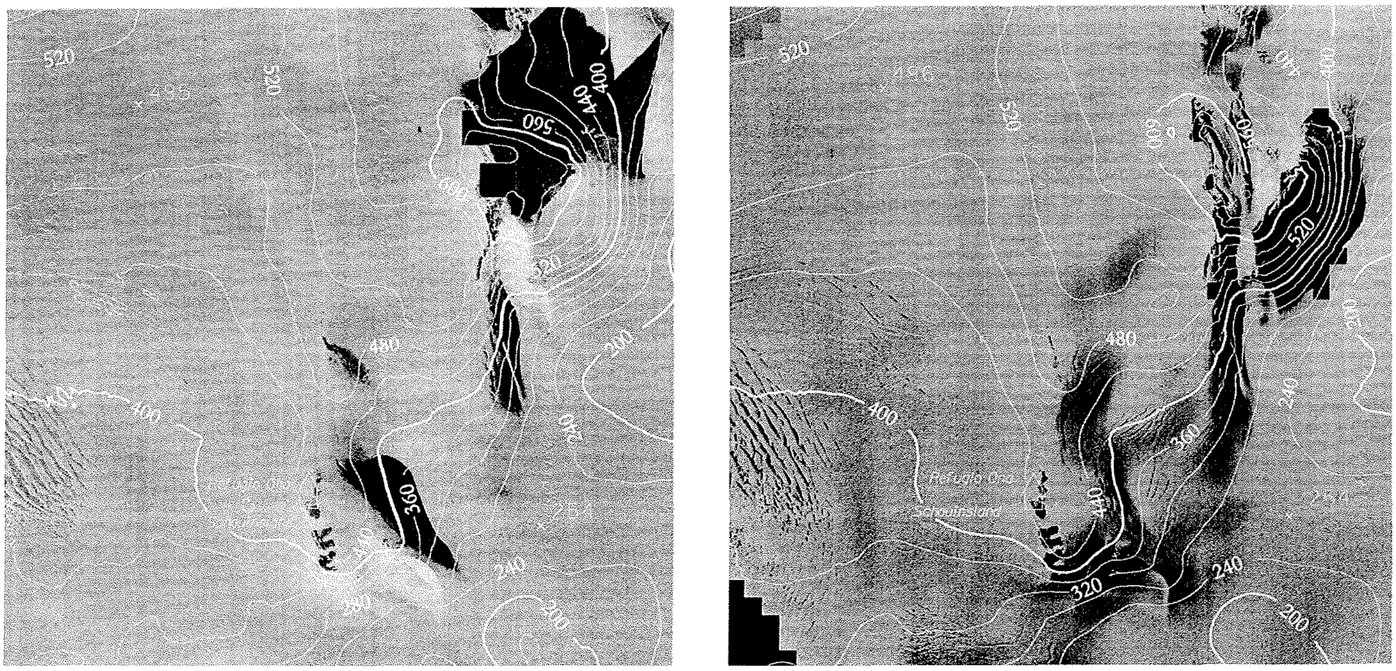

Fig. 3: Reconstruction of the surface and orthoimage of the area near Butson Ridge, scale 1 : 50 000, generated by Facets Stereo Vision. **(a):** Unitemporal result of reconstruction with the three images of 19/02/1989, t = 22:05 GMT. The reconstruction at top right is strongly disturbed. Equidistance of the contours: 40 m. **(b):** Common DTM reconstruction with the six images of 19 and 20/02/1989. The orthoimage has been derived from the images of 20/02/1989, t = 15:50 GTM. Equidistance of the contours 40 m.

Abb. 3: Oberflächenrekonstruktion und Orthobild des Gebietes am Butson Ridge, Maßstab 1 : 50 000, erzeugt mit dem Facetten-Stereosehen. **(a):** Unitemporales Rekonstruktionsergebnis mit den drei Bildern vom 19.02.1989, t = 22:05 GMT. Die Rekonstruktion rechts oben ist stark gestört. Äquidistanz der Höhenlinien 40 m. **(b):** Gemeinsame DTM-Rekonstruktion mit den sechs Bildern vom 19. und 20.02.1989. Das Orthobild stammt aus den Bildern vom 20.02.1989, t = 15:50 GMT. Äquidistanz der Höhenlinien 40 m.

doubt, as is generally the case with commercial systems, are lacking. Integration of FAST Vision into one of the commercial systems would remedy this restriction.

4. PRODUCTION OF A TOPOGRAPHIC DATA SET WITH THE SOFTWARE PACKAGE PHODIS

Production of the topographic data set up to the photomap 1 : 50 000 for the area according to Figure 2 was performed by means of the software PHODIS of ZEISS company. Some modules from the package MICROSTATION of BENTLEY company were also used. Both packages are sufficiently well known; they are a typical sort of commercial software for digital photogrammetry.

The work is based on 28 oriented image data sets (cf. preceding chapters). However, instead of a multi-image evaluation it was now necessary to carry out the evaluation with single stereo pairs. 18 stereo pairs with relatively large mutual overlaps were appropriately selected from the 28 stereo pairs, processed and integrated into an adjusted topographic data set. This was done by the following sequence of work:

A) Stereoscopic measurement of skeleton, edge, and lines of greatest slope as well as of form points, cut off areas, etc. by an operator. The measurements cover the strongly curved typical morphological elements of the region, such as fault edges of the ice towards the sea, the mountain ridges and terrain ridges, narrow furrows and single points detectable in the monotonous, low-texture snow areas. The coordinates acquired by the operator of these elements enter the subsequent automatic DEM computations quasi as set values, thus supporting the process - per se automatic - only in those stages where experience had shown the necessity of interference. The manual work of the operator is clearly higher under Antarctic than Mid-European conditions.

B) Automatic DEM generation for the selected 30 m grid and computation of contours.

C) Check of the contours by means of direct stereoscopic viewing of terrain and contours in the stereo model. If necessary, correction measurements and computations on A and B will follow.

D) Combination of the DEM results of the individual stereo models into a final DEM of the region. Because of the existing overlaps of the stereomodels further checks and corrections are possible.

The accuracy of the DEM depends completely on the local textures. On the basis of comparison measurements and the height differences in the overlaps of adjacent stereomodels we obtain the following classes of accuracy:
±3-10 m: mountain ranges, rock areas, snow-free zones;
±10-20 m: crevasses, ice faults, structured, snow-covered terrain;
±50 m or more: monotonous snow-covered areas without structures.

The accuracies obtained here are evidently lower than they were before with FAST Vision. The DEM exists in the 30 m grid, ASCII format with X,Y and elevation Z.

E) Orthophoto computations of the region under discussion by means of the previously computed DEM. The super-wide angle images present overlaps in steep slopes to a higher extent than with other aerial photographs, especially when situated near the image margins. This problem could be solved by cutting out the central zone of the images and by integration into one final ortho image. We realized a pixel size of 600 dpi so that it can be printed in good quality at another scale range.

F) In the last stage of work the digital photomap was created after the integration of further topographic information into the data sets D and E. Topographic details such as location and geographical names of stations, mountain peaks, etc. were supplied to us by participants who had taken part in expeditions of the Department of Physical Geography of Freiburg University as well as from existing small-scale maps, and from HATTERSLEY-SMITH (1991). As another source of information complementary to aerial photographs we had recourse to nautical charts of the British admiralty dating from the years 1960 and 1982. They were useful in two respects; on the one hand there were true gaps along the coasts in the aerial photographs. On the other hand small and smallest islands or cliffs can be identified as such in aerial photographs only with great difficulty and can hardly be distinguished from drifting ice floes. Therefore, with regard to the sea area the photomap presents the quality of the aforementioned nautical charts including its own limiting characteristics. Moreover, it should be mentioned that due to planimetric differences that could be ascertained between nautical charts and oriented aerial photographs, information from nautical charts was always transferred to the photomap with local affine transformations. The finished digital map is multicoloured and provided with a margin and a detailed legend in German, English, and Spanish. It is available as a file in the data format of the software MICROSTATION 95 (BENTLEY Co.). The topographic data set, which consists of DEM (cf. D) and digital photomap (cf. F), can be ordered on request.

Figure 4 gives an impression of the visual quality of the map. In our opinion this example shows the still unequalled resolution of the images of optical sensors and their „of course“ easily interpretable reproduction of the terrain. The digital form of such geodata generally facilitates further processing in the subsequent software packages of the geoscientist, even though at an initial stage only for the purpose of more detailed 3D vision of single areas that are of particular interest.

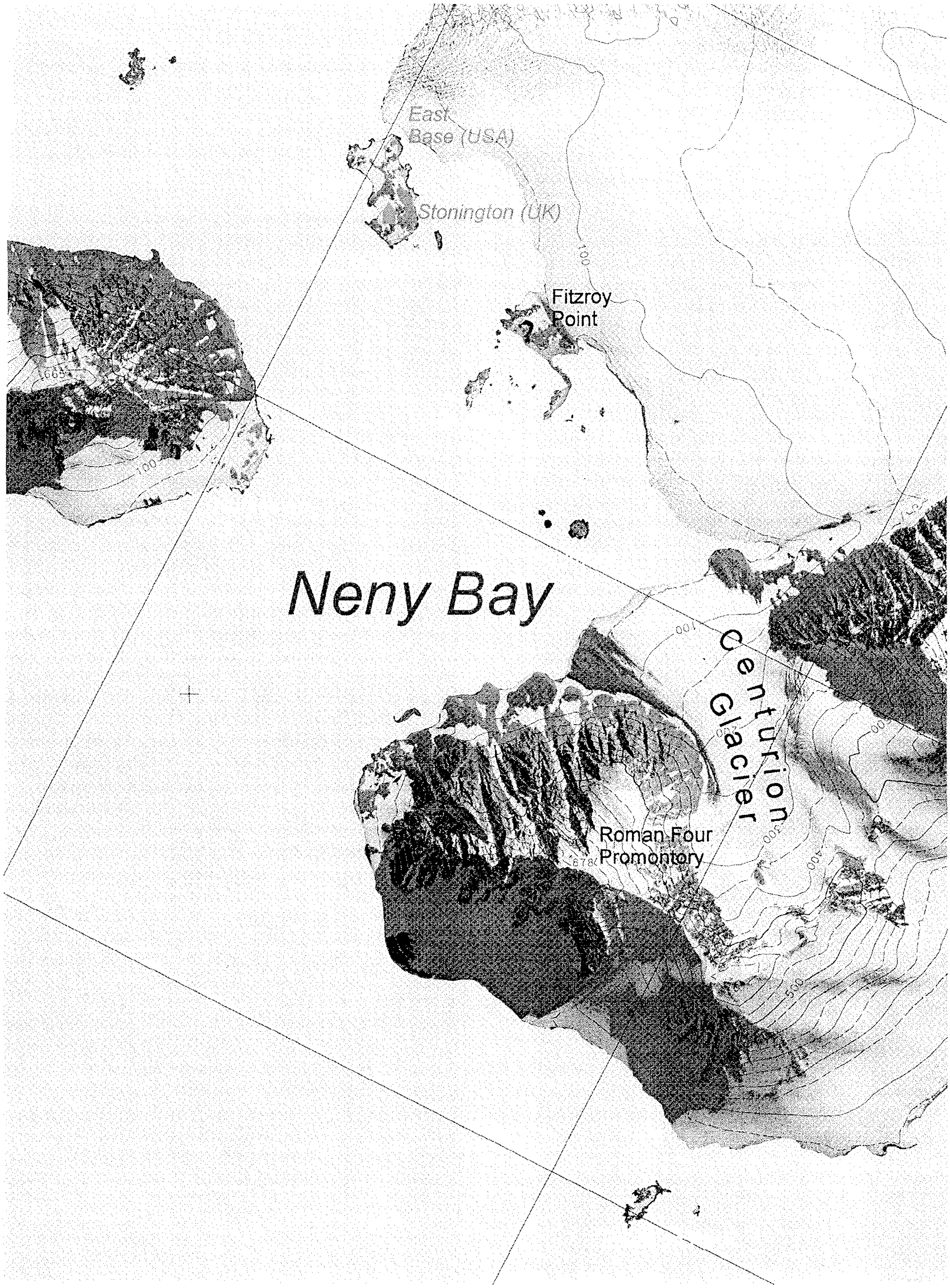

Fig. 4: Extract at 1 : 35 000 scale from the photomap Base General San Martin, Baie Marguerite.

Abb. 4: Ausschnitt im Maßstab 1 : 35 000 aus der Luftbildkarte Base General San Martin, Baie Marguerite

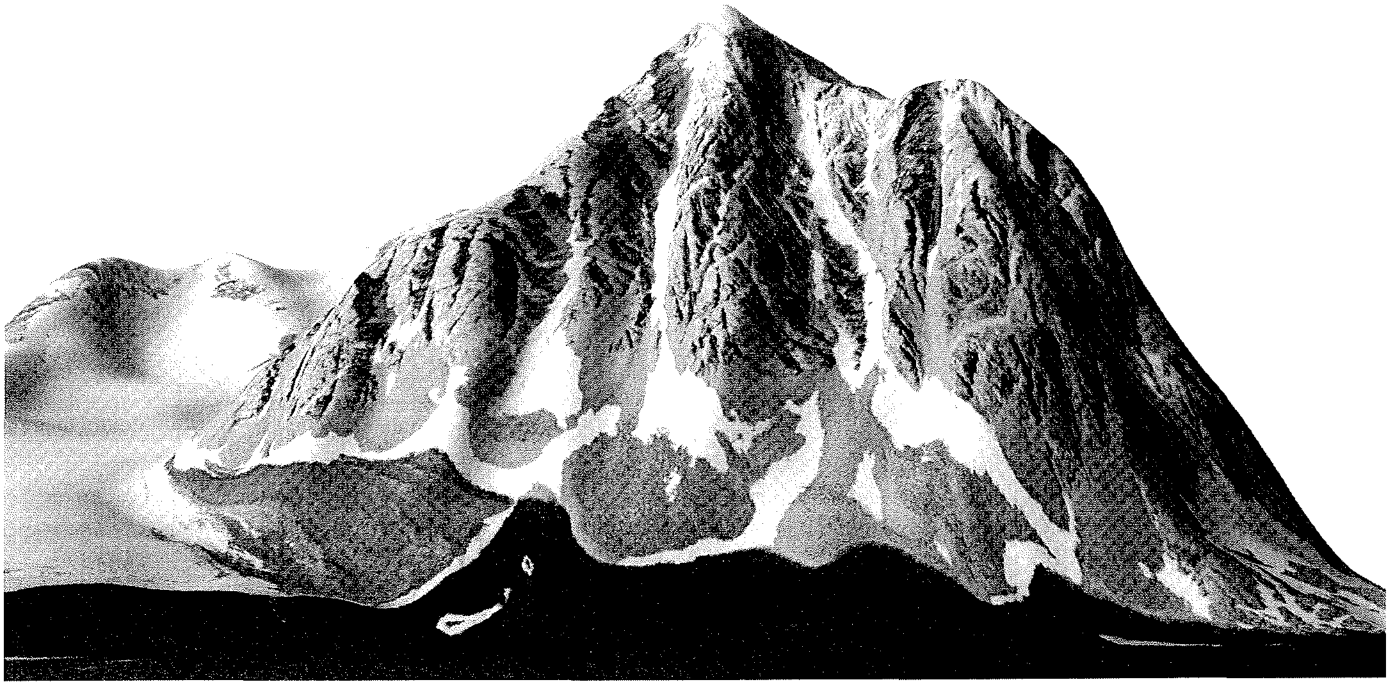

Fig. 5: Perspective view of the 3D reconstruction of glacier Centurion and Roman Four Promontory, 1.5 times exaggerated, cf. Fig. 4.

Abb. 5: Perspektivblick auf die 3D-Rekonstruktion von Gletscher Centurion und Roman Four Promontory, 1,5-fach überhöht, vgl. Abb. 4.

5. CONCLUSIONS AND OUTLOOK

In the surroundings of General San Martin Station a digital topographic data set was generated from aerial photographs of the year 1989 through two very different stereophotogrammetric techniques (FAST Vision and the PHODIS software package of C. ZEISS Co.). From the results obtained we have come to the following conclusions:

• Both methods suffer from the fact that the image signals contained in the photographic aerial images can be digitized only with losses because of the too large contrast - which is a feature of the present scanner generation, but which in principle could be avoided.

• Topographic data sets meeting the specific requirements can be generated successfully by both methods. Information acquisition by means of FAST Vision can be considered as an optimum (very precise and safe, high degree of automation) since this procedure is capable of processing all existing images simultaneously, which applies also to multi-temporal images. The PHODIS software is primarily (as well as commercial software from other companies, e.g. LEICA HELAVA SYSTEMS) conceived for stereopairs and therefore needs relatively strong support by an operator when applied in the Antarctic - despite of all automation. Beyond that, it nevertheless offers many conveniences to the user and also modules, which are required for the production of a complete high-resolution photomap.

• The digital-photogrammetric technique of evaluation can thus be employed with success in the Antarctic. The photoflight material obtained from the many photoflights that were already carried out will in future be evaluated in accordance with up-to-date and fastened procedures.

It has been described more in detail at the beginning of this paper, that aerial photographs as source of information referring to Arctic and Antarctic terrain have without doubt played an important role ever since aircraft were available. Moreover, in the recent part optical images and SAR images from satellite remote sensing have followed. A short outlook will in the following illustrate that during the last years a number of promising developments have been initiated which should clearly improve the possibilities of acquiring topographic data sets in the Antarctic. These aspects shall in short be documented with the main features seeming to us to be of importance. Again we begin with airborne sensors:

• As has already been pointed out digital photogrammetry as employed in the area near Marguerite Bay would lead to a substantial increase in accuracy and efficiency if for future photoflights GPS and INS support (i.e. in-flight measurement of camera position and attitude) would permanently be ensured. A further quality increase can be expected if one of the new digital multiple-line cameras (cf. the contributions in FRITSCH & STILLER 1999) would be applied instead of a classical aerial camera. Both camera types have in many respects the same characteristics, but the digital line cameras have the striking advantage of direct digital image signal acquisition with 12 bit resolution, whereby, e.g. the problem of signal degradations can easily be solved which are caused by the very large contrast of the Antarctic surfaces. Cameras of this type have been developed by

„Deutsches Zentrum für Luft- und Raumfahrt" (DLR). The High Resolution Stereo Camera-Airborne (HRSC-A), with five lines for panchromatic stereo images and four lines for multispectral channels, has already proven its high practical performance in many campaigns (WEWEL et al. 1998). It can be rented for every project. Another, three-line digital camera is presently in the testing stage and shall be put on the market in the year 2000 by LEICA HELAVA SYSTEMS (SANDAU et al. 1999).

• In the practical sector of German surveying the GPS and INS-supported laser-scanning system, which is also an airborne system, has been very quickly accepted by the users. The laser scanner belongs to the active sensors; it opens an economy-priced, direct access to the very precise (ca. ±2 dm) and highly resolved DEMs (ca. 1 elevation value per 1-4 m^2), even in wooded areas (cf. the contributions in WEHR & LOHR1999). Its application in the Antarctic could be quite conceivable, provided that the laser wave-length is selected appropriately. However, the areal performance per flight strip is rather low as compared to that of the camera; moreover, additional normal aerial photographs are needed for the purpose of terrain interpretation or for preparing a picture map.

• The airborne interferometric SAR technique presents very good areal performances (output per area unit) owing to a greater width of flight strips and the very high flying speeds of up to 750 km/h!. It is superior to the known satellite SAR, as e.g. with the ERS 1/2 or RADARSAT, which is due to the single-way principle employing two receiver antennas fixed to the aircraft, and the much greater signal-to-noise ratios of the image signals that are caused by the lower flying height. Several companies offer meanwhile their services at an international level such as, e.g. Aero-Sensing-Radar Systems, Dornier Satellite Systems, Intermap Technologies, cf. references. According to the manufacturers' specifications these systems present extraordinarily good performances. Production of terrain imagery for all current image scales of ca. 1 : 5 000 to 1 : 100 000 is feasible with corresponding accuracies and resolutions for DEM. MERCER et al. (1998) report on comparative tests with height accuracies of ±3 m in a grid of, e.g. 5 x 5 m and a flight strip width of 10 km. Employment of one of these systems in the Antarctic verified by appropriate tests has not come to our knowledge as yet; we rate very high the prospects of success in the light of the system being largely independent of weather conditions and position of the sun. It remains to be noted that these radar techniques are based on backscattering of a coherent microwave radiation in the surface layer of the terrain, and not on reflexion at its surface. Hence, these images convey an impression that is often far away from the natural impression given by the terrain - contrary to the impression given by aerial photographs; the insufficient resolution of the imagery is a disturbing factor, too. The general acceptance of radar image maps remains questionable.

• Finally, let us have a look at the future importance of image data from satellite-borne sensors for research in the Antarctic. As has already been pointed out they generally offer to the geoscientist a considerable cost reduction while presenting a high areal performance (output per area unit). For this reason alone - apart from others - this data source will always be of importance. Apart from the SAR images that will also in future constitute a basis (of the very sucessful Shuttle Radar Topography Mission in February 2000) a new generation of optical, very highly resolved images has been announced with pixels on the ground of up to 1 m^2 (FRITZ 1997, FRASER 1999). Control of the image recording is very flexible, so that nearly synchronous stereo-pairs with overlaps in the direction of the orbit can be detected - which means a configuration (base to height ratio 1 : 1!) and a resolution quite similar to those aerial photograph configurations which we evaluated at Marguerite Bay. We are therefore facing the exciting question as to whether by means of the SAR images and optical images just mentioned the principal need for geobase data of the Antarctic can be met.

All in all, we take the view that access to geobase data of the Antarctic will more and more be favourable in the foreseeable future. „White spots" in topographic data sets or in maps of the Antarctic might in future apply exclusively to the attribute „fresh-snow areas".

6. ACKNOWLEDGEMENTS

Our sincere thanks are to Prof. Armin Grün, ETH Zürich, for his cooperation in joint bundle block adjustments with his BUND software. This paper reports about the results of research work within the DYPAG group, supported by the German Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie. Responsibility for the content is with the authors.

References

Brandstätter, G. & Sharov, A. (1998): Environmental monitoring in the high Arctic using different types of high resolution satellite imagery.- Intern. Archives Photogrammetry and Remote Sensing 32, 7: 201-210, Budapest.

Brunk, K. (1992): Zur Kartierung und geographischen Namengebung in der Antarktis.- Nachrichten aus dem Karten- u. Vermessungswesen, 107: 55-66

Brunner, K. (1977): Darstellung alpiner Gletscher in großmaßstäblichen Karten – Diss. Techn. Universität München.

Brunner, K. (1980): Zur heutigen Bedeutung von Orthophotokarten unter Berücksichtigung von Orthophotokarten vergletscherter Gebiete.- Bildmessung und Luftbildwesen, 48: 151-157.

Finsterwalder, S. (1897): Der Vernagtferner, seine Geschichte und seine Vermessung in den Jahren 1888 und 1889.- Ergänzende Zeitschrift des Deutschen und Österreich. Alpenvereins, 1. Band, Graz.

Fox, A.J. & Nuttal, A.-M. (1997): Photogrammetry as a research tool for glaciology.- Photogrammetric Record, 15 (89): 725-737.

Fraser, C. (1999): Status of high-resolution satellite imaging - In: D. FRITSCH & R.H. SPILLER (eds.), Photogrammetric Week '99, H. Wichmann Verlag, Heidelberg.

Fritsch, D. (ed. 1998): Workshop: Automatische Rekonstruktion von Stadtlandschaften mittels Laser-Scanning - Institut für Photogrammetrie, Universität Stuttgart.

Fritsch, D. & SPILLER, R.H. (eds. 1999):Photogrammetric Week '99.- H. Wichmann Verlag, Heidelberg.

Fritz, L.W. (1997): August 1997 status of new commercial earth observation satellite systems. - In: G. KONECNY (ed.), Sensors and mapping from space, Workshop of the Intern. Soc. Photogrammetry and Remote Sensing, Hanover, vol. 17, proceedings, Institute for Photogrammetry and Engineering Surveys, University of Hanover, Germany.

Gruber, O., von (1942): Das Wohltat-Massiv im Kartenbild.- In: A. RITSCHER (Hrsg.), Wissenschaftliche und fliegerische Ergebnisse der Deutschen Antarktischen Expedition 1938/39, Bd. I, 157-230, Tafeln 29-48 und Karten 1-3, Verlag Koehler u. Amelang, Leipzig.

Hattersley-Smith, G. (1991): The history of place-names in the British Antarctic Territory.- The British Antarctic Survey, Scient. Rep., Cambridge.

Konecny, G. (1966): Applications of photogrammetry to studies of Arctic and mountain glaciers of North America.- Canadian J. Earth Sci., 3/ 6: 183-198.

Konecny, G. (1972): Gletscherphotogrammetrie. - In: JORDAN, EGGERT & KNEISSL (Hrsg.), Handbuch der Vermessungskunde.- Band III a/2, S. 1428-1470, J.B. Metzlersche Verlagsbuchhandlung, Stuttgart.

Korth, W. & Dietrich, R. (1996): Ergebnisse geodätischer Arbeiten im Gebiet der Schirmacheroase, Antarktika 1988-1993 - Deutsche Geodätische Kommission, Reihe B, Heft 301, München.

Kostka, R. (1997): Franz Josef Land - Studien zur Kartographie des nördlichsten Archipels Europas.- Mitteil. Österreich. Geograph. Ges., 139: 313-326, Wien.

Kraus, K. (1993): Photogrammetry. Fundamentals and Standard Processes.- Vol. 1, 4th ed., Dümmler Verlag Bonn

Lindner, K., Mayer, M., Heck, B. & Kutterer, H. (1999): Das geodätische Referenznetz Antarktis.- In: G. CHESI (ed.), X. Internationale Geodätische Woche, Obergurgl, Heft 18 Mitteilungen des Geodät. Instituts, Universität Innsbruck.

Mercer, J.B., Thornton, S. & Tennat, K. (1998): Operational DEM production from airborne interferometry and from RADARSAT stereo technologies - ASPRS-RTI Annual Conference, Tampa.

Metzig, R., Dietrich, R., Korth, W., Perlt, J., Hartmann, R. & Winzer, W. (2000): Horizontal ice velocity estimation and grounding zone detection by SAR interferometry near to Schirmacheroase, Antarctica.- Polarforschung 67: 7-14

Müller, U., Sandhäger, H., Sievers, J. & Blindow, N. (2000): Glacio-kinematic analysis of ERS-1/2 SAR data of the Antarctic ice shelf Ekströmisen and the adjoining inland ice sheet.- Polarforschung 67: 15-26

Rau, F., Braun, M., Saurer, H., Goßmann, H., Kothe, G., Weber, F., Ebel, M. & Beppler, D. (2000): Monitoring multi-year snow cover dynamics on the Antarctic Peninsula using radar imagery.- Polarforschung 67: 27-40

Sandau R, Fricker, P. & Walker, A.S. (1999): Digital photogrammetric cameras - possibilities and problems.- In: D. FRITSCH & R.H. SPILLER (eds.), Photogrammetric Week ´99, H. Wichmann Verlag, Heidelberg.

Schlüter, M. (1999): Von der 2 1/2D- zur 3D-Flächenmodellierung für die photogrammetrische Rekonstruktion im Objektraum - Deutsche Geodätische Kommission, Reihe C, Nr. 506, München.

Schlüter, M. & Wrobel, B.P. (1998): Das Dezimeter-DGM durch photogrammetrische Oberflächenrekonstruktion mit dem Facetten-Stereosehen.- Allgemeine Vermessungsnachrichten, Heft 8-9: 295-303.

Schmidt-Falkenberg, H. (1990): Der Einsatz von Photogrammetrie und Fernerkundung in der Antarktisforschung.- In: Festschrift G. KONECNY zum 60. Geburtstag, Wisenschaftl. Arbeiten Fachrichtung Vermessungswesen, Universität Hannover, Heft 13: 231-242.

Sievers, J. & Walter, W. (1984): Photogrammetrie 1983/84 im westlichen Neuschwabenland.- Berichte Polarforsch. 19: 146-164.

Sievers, J. & Bennat, H. (1989): Reference systems of maps and geographic information systems of Antarctica.- Antarctic Science 1(4): 351-362.

Tsay, J.-R. (1996): Wavelets für das Facetten-Stereosehen.- Deutsche Geodätische Kommission, Reihe C, Nr. 454, München.

Wehr, A. & Lohr, U. (eds. 1999): Airborne laser scanning. Theme issue of ISPRS Journal of Photogrammetry and Remote Sensing, 54: 63-214.

Weisensee, M. (1992): Modelle und Algorithmen für das Facetten-Stereosehen.- Deutsche Geodätische Kommission, Reihe C, No. 374, München.

Welsch, W.M., Lang, M. & Miller, M., eds. (1997): Geodetic activities: Juneau Icefield, Alaska, 1981-1996 - Schriftenreihe Studiengang Vermessungswesen, Heft 50, Universität Bundeswehr München.

Wewel, F., Scholten, F., Neukum, G. & Albertz, J. (1998): Digitale Luftbildaufnahme mit der HRSC - Ein Schritt in die Zukunft der Photogrammetrie.- Photogrammetrie, Fernerkundung, Geoinformation (6): 337-348.

Wrobel, B.P. (1987): Digital image matching by facets using objects space models.- In: A. OOSTERLINCK & A.G. TESCHER (eds.), Advances in image processing, pp. 325-334, proceedings SPIE 804, The Hague.

Wrobel, B.P. & Schlüter, M. (1997): Digital terrain model generation in the Antarctic - a challenging task for digital photogrammetry.- In: M.O. ALTAN & L. GRÜNDIG (eds.), Proceedings of the 2nd Turkish-German Geodetic Days, 28th-30th May, 407-416, Berlin.

Wunderle, S. & Schmidt, J. (1999): Estimation of glacier velocities by ERS-1/2 SAR interferometry in the area of San Martin, Marguerite Bay, Antarctic Peninsula.- Polarforschung 67: 41-51