Using multiple data sources to enhance photogrammetry for mapping antarctic terrain

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Extensive aerial photography cover is available for parts of the British Antarctic Territory, but the characteristics of the photography, combined with the sparsity of ground control information and rugged snow-covered terrain, make photogrammetric mapping techniques difficult to apply. This paper shows, by reference to a new 1:50,000 scale topographic map of part of the Antarctic Peninsula, how merging topographic data from various sources in a GIS environment can make photogrammetric mapping more effective. Information sources used in the map compilation include three types of aerial photography, geo-referenced satellite imagery, surveyed points in a control network and satellite image-derived control points. A shape-from-shading algorithm was used to generate contours for snowfields where absence of surface detail prevented photogrammetric contouring. A horizontal and vertical accuracy of better than ±5 m was achieved in orientation of photography covering almost all of the map area. Such errors have allowed the construction of an accurate large-scale map for an area where previous mapping had been restricted to medium and small scales.

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Introduction

Despite extensive aerial photography cover of parts of the British Antarctic Territory (BAT), rigorous photogrammetric compilation of large-scale topographic maps is precluded for many areas because of inadequate ground control. The acquisition of comprehensive new geodetic data is unlikely, even with the application of GPS survey techniques in BAT, due to the large areas to be covered, difficult access and severe climate. Furthermore, the polar terrain can make photogrammetric techniques difficult to apply. For example, problems are encountered during the construction of photogrammetric blocks across large snowfields where suitable pass-point features are absent; plotting contours on snow-covered areas is difficult because of insufficient surface detail for stereo-matching; areas of dead ground on the photographs, due to the rugged terrain and low flying heights, are common. These difficulties have hindered large-scale topographic mapping of BAT in the past, and the largest scale maps available with any extensive coverage are at 1:250,000 scale.

To enable the compilation of high quality, large-scale maps it is necessary to develop methods for more effective use of aerial photography. Regarding digital, photogrammetrically derived topographic data simply as "3-D digitising" (rather than as the principal map compilation material) allows the merging of photogrammetric map data with other remote sensing data sources within a GIS environment. In referring to the compilation of a 1:50,000 scale map of Wright Peninsula (BAS SCISTAMAP Series, sheet 1B), this paper shows how merging several data sources can enhance photogrammetric techniques and enable map compilation for an area where effective topographic mapping would not otherwise be possible. It is hoped that the techniques discussed may have wider application in other areas which present similar obstacles to large-scale topographic mapping.

Description of project

Wright Peninsula is an ice-covered peninsula on the eastern side of Adelaide Island, BAT (Figs. 1 and 2). Rothera, the main British Antarctic Survey (BAS) research station on the Antarctic Peninsula, is situated on a low, rocky promontory at the southeastern tip of Wright Peninsula. The

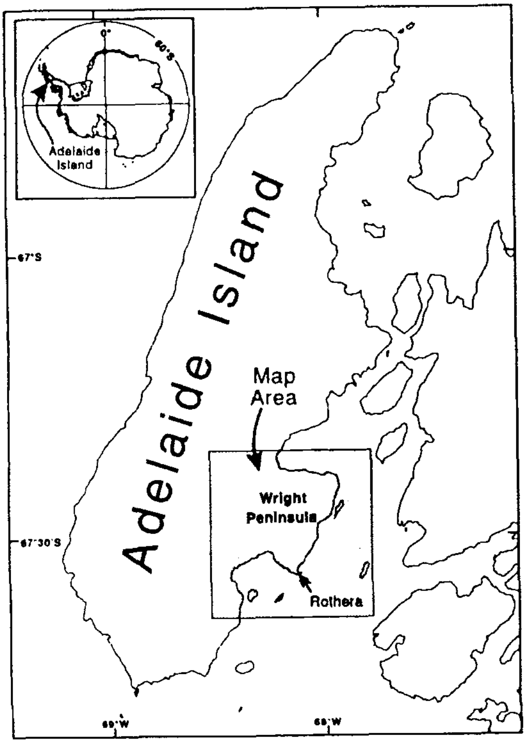

Fig. 1. Wright Peninsula on the eastern side of Adelaide Island, showing the area covered by BAS SCISTAMAP Series, sheet 1B.

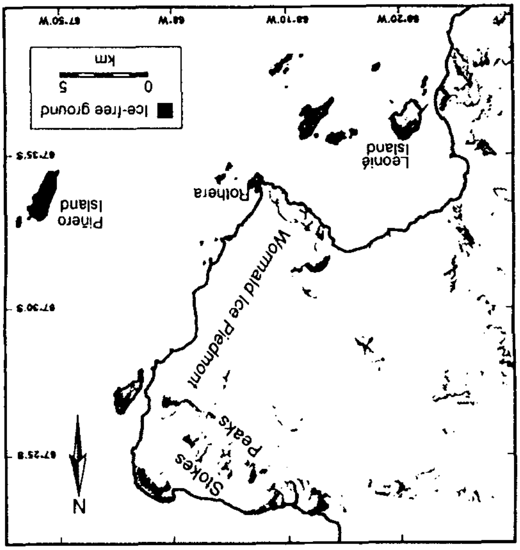

Fig. 2. Wright Peninsula, showing features within the map area.

majority of the area is open snowfield, rising from sea level to about 300 m, but isolated nunataks reach an elevation of more than 400 m. The terrain rises steeply to more than 1950 m to the west and more than 750 m to the north. There are many heavily crevassed areas.

The most detailed existing map of the area was compiled at 1:250,000 scale from hard-copy satellite imagery and is published as part of the SCAR Antarctic Digital Database (BAS, SPRI, & WCMC, 1993). A 1:50,000 scale topographic map was needed to support fieldwork on Wright Peninsula and the offshore islands, and as a travel map for safe access from Rothera research station to the rest of Adelaide Island.

Data

The data available for this map are from the following four sources:

The map area is relatively well surveyed due to the proximity of Adelaide base, an old BAS station at the southern end of Adelaide Island. The map contains eight points with both plan and height coordinates from the BAT triangulation/trilateration network. For historical reasons this survey network developed as a number of small networks local to bases operating during the 1950s and 1960s. These small networks have since been linked together by tellurometry and the whole adjusted to fit thirteen Geoceiver positions acquired in 1975/76 and 1977/78 (Renner 1982; Sturgeon & Renner 1983). The RMS residual error after this adjustment was ±11 m (Knight 1988; unpubl. rep. ES2 EW 300/38, Brit. Antarc. Surv.). GPS re-occupation of old stations (Perkins, 1993, unpubl. rep. AD6/2R/1992/L2, Brit. Antarc. Surv.) and residuals from aero-triangulation work show that local clusters surveyed together, such as the points in the Wright Peninsula area, may have a relative accuracy of ±5 m.

Small-scale aerial photographs were acquired by the Institut für Angewandte Geodäsie (IfAG), Frankfurt, as part of a collaborative project with BAS, 10–19 February 1989. The photography was flown at an altitude of 6,000 m using a Zeiss RMK camera with a super-wide-angle lens (focal length [f] = 85.5 mm), giving a nominal photo-scale of 1:70,000. The survey was flown with 80% endlap. The Wright Peninsula map area is covered by a block of 11 models (stereo-pairs) on three strips (5 + 5 + 1).

Larger-scale aerial photography was acquired in 1957 as part of the Falkland Islands and Dependencies Aerial Survey Expedition (FIDASE), and in 1991 aerial photography covering part of the area was acquired by BAS. Both these sources were flown at an altitude of 3800 m with wide-angle lens cameras (f = 153 mm), giving a nominal photo-scale of 1:25,000.

Part of a mosaic of Landsat Thematic Mapper (TM) images was block adjusted by IfAG in 1991/92 to the BAT survey network using the method described in Sievers et al. (1989). The images have also been corrected by IfAG for the effects of surface elevation, using a coarse digital elevation model (DEM) based on elevation data from the Antarctic Digital Database (Thomson & Cooper 1993). The accuracy of the block adjustment is quoted as ±75 m in x and y by Sievers (pers. commun. 1992). However the scene covering the map area was heavily weighted in the adjustment because of the Geoceiver point at Rothera; therefore the geo-referencing of this scene is more accurate than the figures quoted for the whole mosaic. Overlaying the survey points on the imagery showed a match to within one pixel on the TM scene (30 m).

Description of the problem

Established photogrammetric practice (using analytical equipment) would involve (1) formation of a block from the IfAG photography, (2) densification of the existing BAT survey network control by aero-triangulation, (3) orientation of the stereo-models to this new control and (4) compilation of topographic detail and contouring by terrain-following from the orientated models. However, because of the combination of the characteristics of the terrain and the ways in which topographic data has been collected in the past, standard procedure can rarely be applied to antarctic mapping projects. Theoretically the IfAG photography of the Wright Peninsula area should be well suited to the application of the methodology described above. The 1:70,000 photo-scale allows coverage of the area in only eleven stereo-models, the eight survey points in the area should provide acceptable initial control for aero-triangulation of the block, and compilation of topographic detail from the high quality photography should be straightforward. The surveyed control points and data sources are shown in Fig. 3.

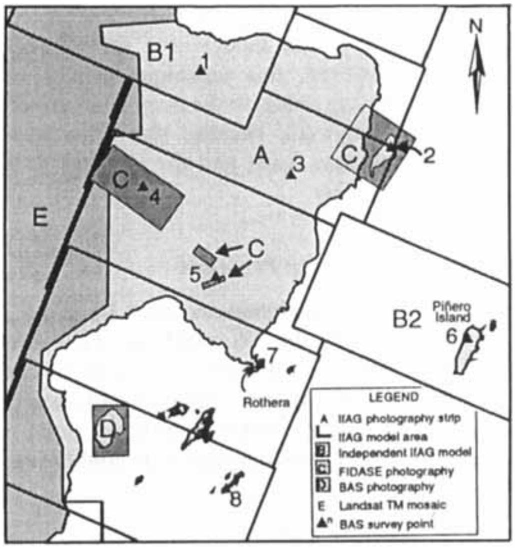

Fig. 3. Map area showing control points (1–8) and data sources used for compilation of the map.

Survey points

Historical survey points, for technical reasons, were positioned for maximum inter-visibility whilst having safe access. No consideration was given to future use as control points for photogrammetry and aero-triangulation. Thus survey points can be difficult to identify and measure on aerial photography.

Point 1 was located on a snow peak in 1964, and the shape and position of the summit cannot be assumed to have remained constant. Point 2 is too near the frame edge of the photographs to be included in the adjustment. Point 4 was positioned on a ridge with no conspicuous features nearby and cannot be reliably identified on the photography.

Furthermore the survey schemes were designed to construct only a skeleton network. As a result, survey points are often too sparse and poorly distributed for aero-triangulation; there are no control points in the western strip, where the steep terrain prevented access by survey parties.

Stereo-model (B2)

The stereo-model (B2) covering Piñero Island is almost entirely open water. Difficulties with the "relative orientation" stage of photo-restitution can be overcome by using well-distributed icebergs present in the model area for parallax removal. However, this technique cannot be applied to link the model to the main block covering Wright Peninsula because the strips were acquired nine days apart and the icebergs have drifted appreciably.

Contouring of Wright Peninsula

Wright Peninsula is dominated by a large open snowfield feeding the Wormald Ice Piedmont (Fig. 2). Whilst the photogrammetric block can be bridged across this area, using isolated, clearly identifiable crevasses as pass points, the absence of surface texture precludes accurate contouring.

Areas of dead ground

The relationship between the super-wide-angle lens (f = 85.5 mm) used for the IfAG photography, the flying height (6000 m) and the steep slopes and high relief has resulted in areas of dead ground due to lay-over effects on the photography, especially near the frame edges. Similarly, stereo-matching of the photography of the high, steep mountainous terrain covered by the western strip is difficult, even when using photography with 80% end-lap.

Methods

Data preparation

An assessment was made of the extent to which standard practice could be applied to the project in the context of the constraints described above. Successful aero-triangulation is dependent upon the quality, quantity and distribution of ground control points in the block. The characteristics of error propagation with different configurations of ground control are well established such that the theoretical minimum acceptable plan control (x and y) is one point in each of the corner models. Plan control in the block interior has little effect but extra control points around the perimeter of the block improve accuracy. A spacing of 15–20 models between perimeter control points is normal for 1:50,000 scale mapping projects with large numbers of models (Burnside 1985). Height error propagation is less favourable than that for planimetry and needs a more dense pattern of control for satisfactory block formation. In particular height control is required in the interior of the block. This is usually provided as bands of control across the block normal to the flight direction. The optimum distribution for medium-scale (1:50,000) topographic mapping is a spacing of six models between bands, with control points on alternate strip overlaps in each band (Burnside 1985).

The available photography and ground control do not meet these requirements because the distribution of the surveyed control points is inadequate for aero-triangulation of a block that includes the western strip of the IfAG photography; there are no control points in this strip. Whilst the model covering Piñero Island (B2) contains a control point and could have been included in the block whilst maintaining its geometric strength, this model cannot be linked to the other strips for the reasons discussed earlier in the section "Description of the problem". Thus a strategy was devised to maximise the available data and allow map compilation to proceed. Aero-triangulation was restricted to adjustment of the central strip, and the western strip and model B2 were treated as independent units.

Central strip. – The central strip (A on Fig. 3) was formed from three models with 60% endlap and two models with 80% endlap; the extra endlap was found to be necessary to overcome difficulties with stereo-viewing caused by the high relief of Stokes Peaks (Fig. 2). Ground control in both plan and height was available in the end models (control points 2 and 8) with points 5 and 7 as redundant control in the interior of the block. All the models in the strip contain coastline and 15 supplementary height control points, well distributed about the strip, were extracted from the shoreline and included in the adjustment. Tests on the consistency of measuring to shoreline points suggested that they could be measured to an accuracy superior to the accuracy of the surveyed points and, accordingly, they were given equal weighting. The strip adjustment was therefore better controlled in height than in plan, but for medium-scale topographic mapping a slightly lower level of accuracy in plan than height is acceptable.

Pass points were located on rock wherever possible but, in the snowfield area in the centre of the strip, a few pass points had to be located on well-defined crevasses, and the southern two models had to be linked using several pass points on floating ice. The aero-triangulation was carried out using software implementing the "independent models" method of adjustment.

Preliminary inspection of the photography in the stereo-plotter showed that the lay-over effect, discussed earlier in the section "Description of problem", would prevent the compilation of topographic detail for dead-ground areas (C and D in Fig. 3). Contouring would be impossible not only for the dead-ground areas on the photography but also for parts of the snowfield where there was complete absence of surface texture. The dead-ground problem was resolved by "patching in" topographic data from the FIDASE and BAS photography. Areas with an absence of surface texture were isolated for contouring using shape-from-shading techniques.

Dead-ground area. – Both the FIDASE and BAS photography sets at 1:25,000 scale were acquired using wide-angle lens cameras rather than the super-wide-angle lens type used for the IfAG photography. The different lens characteristics, combined with the problem areas lying by chance in favourable positions within the FIDASE and BAS photographs, eliminated the dead-ground problem experienced with the IfAG photography (C and D in Fig. 3). Both these photo-sources have a much smaller area coverage per stereo-model than the IfAG photographs, and even the aero-triangulated minor control prepared for the IfAG photography was inadequate. "Tertiary" control points were extracted directly from the IfAG stereo-models and used to supplement the existing surveyed and minor control for orientation of the FIDASE and BAS photography.

Compilation of the whole map area from the FIDASE and BAS photographs is impractical. The block of more than 40 models required could not be successfully aero-triangulated due to problems in bridging the snowfield using the larger-scale photography and inadequate control. Furthermore, currency of the data is important in this project to ensure accurate mapping of the ice-rock interface and crevasse patterns, both of which change over time (significant changes can be detected in a decade); since the recent BAS photography is restricted to the coastal strip, coverage of most of the area would be dependent on the outdated 1957 FIDASE photography.

Contouring in featureless areas. – A shape-from-shading technique was used to generate contours from the Landsat TM imagery for the sections of the snowfield where surface detail was too sparse for reliable contouring as part of the DEM. The method used is described in detail in Cooper (1994).

Cooper (1994) recognised that for many topographic surfaces important simplifications can be made to the general scattering law for illuminated surfaces. These simplifications have permitted the development of an efficient algorithm for extracting height information from digital satellite images which, given a known sun elevation and azimuth (from the image header) allows the generation of a DEM. The elevation model created by this process is arbitrarily scaled in z (height) and may have a regional tilt. Measured surface heights are needed to calibrate and level the elevation model in order to derive reliable surface elevations.

Examination of the aerial photography and satellite imagery of Wright Peninsula, and the distribution of DEM height-points derived from the IfAG photography, showed areas where features were not being adequately sampled at the photogrammetric stage of compilation, due to inadequate surface texture. These areas were abstracted from the IfAG Landsat TM mosaic and Cooper's (1994) method was used to generate elevation models from the image sub-sets. The elevation models were calibrated using photogrammetrically derived height information, based on crevasses and sastrugi, available from the spot height coverage from the IfAG photography. Contours were interpolated from the calibrated elevation models and subsequently merged with the existing photogrammetric contours.

Piñero Island. – Model B2 covering Piñero Island could not be included in the aero-triangulation of Wright Peninsula because it could not be linked to the other photography, and it has only one control point, which is insufficient to orientate the model as an independent unit. Since the IfAG satellite image mosaic has been block-adjusted to the BAT survey network rather than to independent ground control (e.g. GPS), position information derived from the mosaic is directly compatible with the existing surveyed point (excluding the adjustment error of the mosaic). Supplementary planimetric control was generated by selecting several well-distributed points on

Piñero Island, clearly identifiable on both the aerial photography and the satellite imagery. A simple GIS routine was created to measure their positions from the geo-referenced imagery, add a survey point to a map overlay and output the coordinates as a stereo-plotter control point file. Additional vertical control was easily derived from the shoreline.

Western strip. – The western strip (E on Fig. 3) was excluded from the adjustment covering the majority of Wright Peninsula for two reasons. Firstly, there are no control points in the western strip. Inclusion of the uncontrolled photography would have weakened the geometry of the block, and extrapolation from the four control points in the central strip would have been unsafe. Secondly, despite the use of photography with 80% end-lap, the combination of the extreme relief (approximately 2000 m height range within models), the flying height (6000 m) and the camera characteristics makes stereo-viewing of substantial areas of the strip difficult.

The possibility of performing a strip-adjustment of the western strip was considered. Such an adjustment could have used the satellite image mosaic, secondary control derived from the adjusted central strip in the side-lap area, and height information from the northern and southern shorelines for control. However, even if the difficulties for a strip-adjustment created by the problems with stereo-viewing could have been overcome, large areas of the map could not have been compiled photogrammetrically. In consequence, it was decided that the quality of the data would not justify the time required and the strip-adjustment was not attempted.

Topographic detail for the area was compiled monoscopically by visual interpretation of the TM data, and digitised on screen. The application of simple image-enhancement techniques aided differentiation of rock outcrop and shadow on the imagery, and the high quality IfAG aerial photography allowed compilation of sub-pixel features. Subjective "formlines" with a nominal interval of 250 m were fitted to the imagery to give a cartographic impression of relief.

Model B1. – The terrain covered by the northernmost model of the western strip (B1) is relatively low lying and acceptable stereo-viewing was possible. Inclusion of this model in the main strip-adjustment was rejected because it would have weakened the geometry of the block, but the model could be orientated as a separate unit. The model area contains no control points but has 40% overlap with the main strip. Minor control from the strip adjustment available in the overlap area and supplementary height control from floating ice (given an arbitrary height of 2 m) was sufficient to orientate the model. The poor distribution of planimetric control had to be accepted, but overlaying the map detail compiled from this model on to the satellite image mosaic in the GIS provided a check for gross scaling errors.

Map compilation and data merging

Orientation of the stereo-models from the various sources described above to the prepared control was straightforward. Surface features, including coastline, rock outcrop, moraine deposits and crevasses, were easily compiled at 1:50,000 scale from each of the data sub-sets (central strip, patched areas, B1, B2 and the western strip E).

Despite treating the dead-ground and featureless areas separately, as described above, it was clear from examination of the photography at the compilation stage that contouring by terrain-following would still be difficult to achieve to an acceptable standard in other areas where surface detail was either intermittent or indistinct. This more general problem was overcome by: (1) using photogrammetry to collect a dense array of spot-heights, (2) constructing a Digital Elevation Model (DEM) of the map area, and (3) interpolating contours from the DEM. All handling of geographic data after the photogrammetric data-capture stage was performed using the Laser-Scan Lites2 suite of programs.

For this project the DEM approach has six advantages over the normal terrain-following technique:

(1) The data compiled from the 1:70,000 photography strip would have to be merged with other data sources for the dead-ground areas and with model B1. The DEM approach allows the creation of a unified height-point dataset from which a consistent set of contours can be interpolated. This is superior to attempting to link several discrete contour sub-maps generated by terrain-following from independent sets of photography.

(2) For substantial parts of the snowfield the

density of data points that could be acquired was barely adequate; in such areas photogrammetric heighting was dependent upon surface texture provided by sastrugi fields (wind-sculpted wave forms), indistinct crevasse snow-bridge patterns, avalanche debris, etc. With the DEM method spot-heights are measured wherever such features can be identified. The DEM then generates a mathematical surface based on the spot-heights, which is taken to approximate closely the true surface (provided enough heightened points have been entered); all the available information contributes to the solution. Conversely, the terrain-following approach is restricted to measurement based on textural detail available only at the contour intervals.

(3) Height measurement with the DEM method is more accurate because each spot-height is stochastically independent. In contrast, with the terrain-following technique each point is not independently assessed but based on a decision about the terrain by the operator and influenced by the last few entries. Where surface texture is poor, thus it is easy for heighting error to be compounded over a series of point entries, causing the plotted contour to drift away from the true surface.

(4) Height information is needed to calibrate the shape-from-shading technique and can be easily extracted from the spot-height coverage already prepared for the DEM.

(5) The DEM produced as a by-product of this contouring technique is potentially useful for other projects such as glaciological modelling. A DEM derived from contours compiled by terrain-following would be of lower accuracy due to the absence of data between the contours.

(6) Contours at different intervals can be generated easily once the DEM has been prepared.

Height-point sampling for the DEM from each of the photography sub-sets was planned at different densities according to surface type, with the highest density of points in steep, complex rock areas and the lowest density of points on the low angled, smooth central snowfield. However, in practice the point density for much of the snowfield area was dictated by the poor surface texture rather than the planned sampling strategy. Analysis of the height-point data using a test sample area of 500 × 500 metres shows typical point counts of 500 on steep rock, 100–150 on the well-textured, steep ice found near the coast and 0–50 on the main snowfield area. Furthermore, the distribution of points on the main snowfield area is strongly linear because points could often only be collected along crevasses. The methodology adopted for merging the separate data-sets is summarised in Fig. 4. All the discrete sub-maps were then merged by appending the files. The "super-map" created was then stratified by feature type into coverages (layers), each covering the whole map area. In particular the height points were separated from the surface features. Great care was taken to ensure that each feature was allocated a source label. Height points were given a different graphical symbol according to source (strip adjustment, patch etc.).

The data sources were ranked according to accuracy. The strip adjustment of the IfAG photography was given the highest ranking, followed by the patched areas, then models B1 and B2, with the monoscopic satellite image interpretation at E given the least priority. The priority ranking was used to establish precedence when checking for mismatches in the overlaps between the merged data-sets.

For surface features, linework from the lower-ranked source was rationalised using the Laser-Scan map editing software to match the higher-ranked source. The height point coverage was overlaid on the satellite imagery for context and the consistency in overlap areas between the spot-heights derived from the strip-adjustment and those from the patched areas and model B1 examined in the editor. Any gross mis-matches could be re-evaluated in the stereo-plotter or extra data collected to fill in any gaps before proceeding.

Contours were derived using Laser-Scan software from the raw height-points by (1) Delaunay triangulation, (2) re-sampling to a regular grid, and (3) contour interpolation from the grid. A grid cell size of 10 m × 10 m was used which filtered any very high density areas.

One of the main reasons for using the DEM methodology is that there is less risk of measurement error by the photogrammetrist, as described above. However it was still probable that some spurious values had been collected in areas where the snow surface texture was marginal for photogrammetry. Isolated large errors in the height points cause characteristic patterns in the contour output from the DEM, such as "spikes", "pits" and "isthmuses", allowing easy detection of spurious points by overlaying the contours and height-point coverages. The contours can then be iteratively refined by re-running the DEM generation

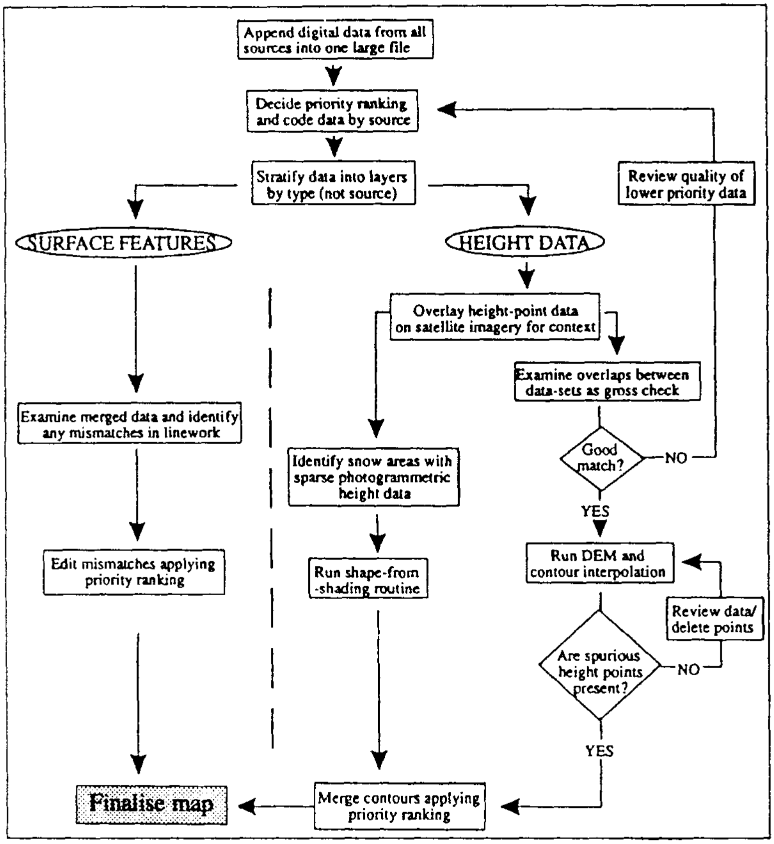

Fig. 4. Summary of the methodology adopted for merging the separate datasets.

and contour interpolation from corrected height data.

Contours generated by the shape-from-shading method for the featureless areas were then inserted into the main contour coverage and the corresponding DEM-derived contours deleted. In accordance with the priority ranking for the data sources, the less accurate shape-from-shading contours were harmonised to the photogrammetrically-derived contours in the main area. Finally the contours and the surface features were combined for the finished map.

Results

The map resulting from the method described above (Fig. 5) can be compared with an earlier map (Fig. 6) compiled at 1 : 250,000 scale, which was the most detailed existing line map of the area. Detailed compilation of surface features and accurate contouring with an interval of 50 m has been possible for the new map. On the previous map the surface features are heavily generalised and contouring is limited to the depiction of subjective "form-lines", with a nominal interval of 250 m, which give a cartographic impression of the relief.

Discussion

Strip-adjustment

The strip-adjustment yielded a photo-coordinate standard deviation equivalent to 3.2 m on the ground (Table 1). Root-mean-square (RMS) coordinate errors were 2.8 m in plan and 2.5 m in height, with the largest single residual 5 m. These coordinate errors had to be accepted, but as an error of 3 m equates to a plotting error of 0.06 mm at 1 : 50,000 scale the results are considered satisfactory for this project. The strip adjustment was based on four surveyed points with x, y and z

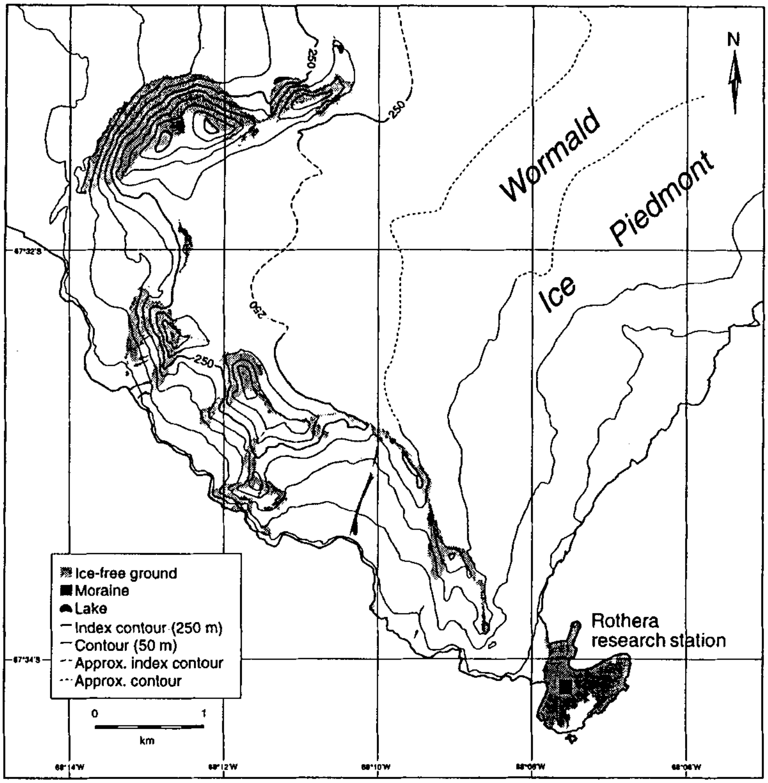

Fig. 5. Part of the completed map. The contour interval is 50 m. Ice-free ground is shaded. Crevasses are not shown.

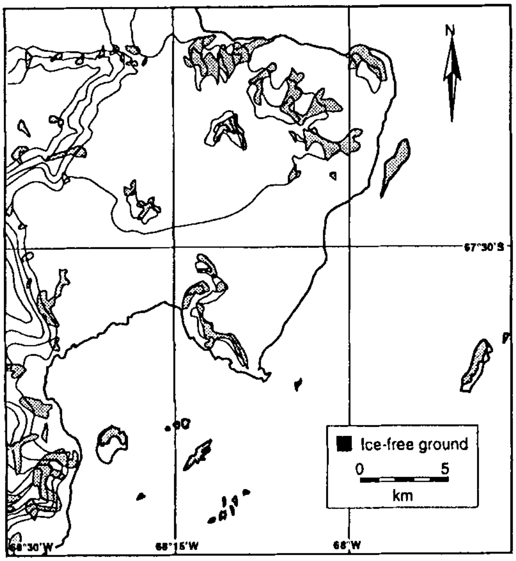

Fig. 6. An extract of the area covered by BAS SCISTAMAP 1B from the most detailed existing map of the area. This map was compiled at 1:250,000 scale from satellite imagery in 1990.

coordinates and a further 15 points with a z coordinate only (derived from the shoreline). Tests showed that a measurement consistency of about 2 m was achievable with the 1:70,000 scale photography and analytical instrument used. It is believed that the largest sources of error are the estimated ±5 m accuracy of the surveyed control points and difficulties with their identification on the photography.

Observing extra shoreline points as independent check points was considered. However the majority of the coastline of Wright Peninsula is steep ice-cliffs which is unsuitable for measuring a shoreline height. The 15 points used in the adjustment were obtained from the few sections where there was a rocky foreshore. Because of this restriction any extra points would have been located so close to the existing points that they would have been of limited value as a check. Reserving some of the 15 points as an independent check was rejected as further depleting the already limited control available for the adjust-

Table 1. Summary of results obtained using the different data sources.

Fig. 3 symbol	RMS coordinate error x,y	z	x,y at map scale	Data source for map compilation
A	2.8 m	2.5 m	0.06 mm	Strip-adjustment of IfAG photography
B1	4–5 m	4–5 m	0.1 mm	Independent orientation to control from strip-adjustment
B2	~30 m	1.9 m	0.6 mm	Independent orientation to Landsat TM derived control
C & D	4–5 m	4–5 m	0.1 mm	FIDASE and BAS photography orientated to control from IfAG strip-adjustment
E	~30 m	–	0.6 mm	Geo-referenced Landsat TM mosaic

Compilation accuracy on the map will be lower because of plotting error.

ment. Using off-shore icebergs to check the orientation of the photography was also rejected because previous experience with other projects has shown that accurately measuring the sea/ice interface on floating ice is unreliable.

Shape-from-shading contours

RMS errors in fitting the elevation models generated by Cooper's (1994) method to photogrammetrically measured calibration points were 10–20 m. Contours derived by this technique are shown as approximate on the map.

Cooper's (1994) method assumes that the scattering properties of the surface are uniform. Error was observed to be greater with larger image subsets, implying that the assumption of uniformity is invalid for this area. The snowfield is relatively low-lying (sea level to 400 m) and in a maritime environment. It is probable that there are variations in snow wetness within the snowfield which are likely to affect albedo; this factor is believed to be the major source of error. Less significant sources of error include corruption of the reflectance value of pixels in heavily crevassed areas, and the error component of the photogrammetric heights used in the calibration.

Slope is important because of the simplifications to the general case equations made by Cooper (1994). Errors arising from the assumption of negligible slope are proportional to the sine of the slope. Since the snowfield areas contoured by the shape-from-shading technique typically had slopes of less than 2°, errors from this source can be discounted.

"Patched" areas and model B1

The stereo-models for the patched areas and model B1 were both orientated to control points derived from the strip-adjustment, and from direct measurement of the stereo-models in the main strip. In practice these supplementary models could be orientated to the minor control with errors of less than 2 m (which are cumulative to the errors in the strip-adjustment). Such small errors are principally due to the difficulty of identifying points on photographs with differing states of snow-cover and direction of illumination. The patched areas are, therefore, of lower, but similar order of accuracy to the main photogrammetric compilation and are acceptable for this project.

Piñero Island

This model was orientated to one surveyed point in the BAT network, four plan control points extracted from the geo-referenced TM image mosaic and nine shoreline heightened points. RMS error in the orientation of the model was 29 m in x, 26 m in y and 1.9 m in z. The x and y values equate to a scaling error of 0.6 mm at map scale. The pixel size of the TM imagery is 30 m. The residuals from the orientation are within the nominal accuracy with which points on the images can be located and have to be accepted.

Western strip

Despite the availability of high quality aerial photography as an interpretation aid for compilation of sub-pixel detail, the 30 m resolution of the sensor constrains the accuracy of the mapping in this area. The formlines at a nominal interval of 250 m are correct in shape but essentially subjective in height and are included only to give a cartographic impression of relief.

Map compilation and data merging

Plotting accuracy on the map will be variable. Planimetric accuracy can be expected to be close to that quoted for the strip-adjustment. Heighting accuracy in ice-free or well-textured snow areas, where a dense network of spot heights could be collected, will be relatively reliable, but some degradation of accuracy is inevitable due to the approximation by the mathematical surface generated by the DEM and the contour interpolation process.

Heighting accuracy will be lower where surface texture was poor or where rugged terrain has combined with the camera lens characteristics to make stereo-viewing difficult. In areas where the measured spot heights are sparse, the DEM may be a less valid approximation of the true surface and the interpolated contours will, therefore, be less accurate.

Quantifying the quality of the height data is not possible without independent check points, but its consistency can be subjectively gauged from the complexity of the derived contours. Complex contour lines across areas known to be smooth, such as the main snowfield, indicate noisy data. However, position errors of a few metres are insignificant at map scale (5 m = 0.1 mm). Height accuracy is usually of more importance to the user of a topographic map, but, despite the difficulties of measuring the accuracy of the contours, it is considered acceptable for this project.

Conclusions

Using a GIS framework to merge the map data derived from a variety of sources by the techniques discussed has allowed the compilation of an effective 1:50,000 scale topographic map of an area previously unmapped at this scale. Standard photogrammetric techniques alone would have restricted mapping to an incomplete compilation of both topographic detail and contour information.

By close reference to the compilation of BAS SCISTAMAP 1B, this paper presents a "tool-kit" of techniques which it is hoped may find wider application in other areas presenting similar obstacles to the compilation of large-scale maps. In particular the project shows how archive survey data and photography, which was not originally planned for large-scale mapping (and at face value seems of little use), can be enhanced by complementary and more up to date data sources to allow compilation of a useful map.

The main unresolved problem with the method described is the difficulty of quantifying accuracy at both the initial data preparation stage and for the final map compilation due to inadequate primary survey information. Normal mapping practice would be to predict the accuracy possible from the available sources, and if this did not meet the required standard, to acquire better data. However, repeat data acquisition in Antarctica needs long-term planning and the constraints of the data available have to be accepted. The philosophy for mapping remote areas has to be to produce the best map from the available data, even if the accuracy of the map is less than the ideal and difficult to quantify; a slightly flawed large-scale map is preferable to either an inaccurate small-scale map or no map at all.

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