DIGITAL TERRAIN MAPPING WITH STAR-1 SAR DATA

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ABSTRACT

This paper presents a description and partial results of a program to assess the capability of deriving Digital Terrain Mapping products from STAR-1 data. STAR-1 is an airborne, digital SAR. A 500 km^2 area was flown over varied terrain, and the resultant stereo images were analyzed on an analytical plotter. The DTM thus derived was used to rectify the imagery. Contour plots and an ortho-photo-like radar image were derived at a scale of 1:50,000. An error analysis was performed indicating that RMS elevation errors of less than 30 m can be achieved in a production environment.

Radargrammetry, Topographic Mapping, Digital Image Processing, Photogrammetry

1. INTRODUCTION

Airborne radar imagery (real aperture and synthetic aperture SLAR) has been utilized for several years in the production of coarse scale (1:250,000 - 1:500,000) map products over large regions. Thematic content has been the prime rationale for performing radar surveys in temperate zones. In the tropics, where clouds and haze inhibit aerial photography and satellite optical band imaging, SLAR has additionally served as a source of primary mapping information (Azevedo, 1971). While such map products are valuable, they have not addressed the requirement for medium scale (1:50,000 to 1:100,000) topographic mapping products.

In this paper we present the results of a project to examine the capability for production of digital terrain models (DTM) and associated topographic mapping products at a 1:50,000 scale using INTERA's STAR-1 synthetic aperture radar (SAR system).

The objective of the project was to determine whether a satisfactory standard for topographic mapping at the desired scale could be achieved. The approach was to collect stereo radar imagery in digital form over a representative area of about 500 km^2 for which adequate mapping control exists, to extract a DTM using an analytical plotter on strip image pairs, and to perform image rectification on the digital imagery using the derived DTM for elevation correction. Final output products include the DTM, topographic map and an ortho-photo-like image at 1:50,000 scale.

In the following sections we provide a brief description of the STAR-1 system, some considerations of the viewing geometry and description of the data acquisition and analysis. This will be followed by a presentation of the results including a summary of the associated errors and examples of the DTM products.

2. STAR-1 DESCRIPTION

STAR-1 is a fully focused, X-band SAR. It includes a real-time digital processor, and is flown in a small executive class propjet aircraft at a typical operating altitude of 10 km. It can operate in either a 'wide swath' (48 km ground swath) or 'narrow swath' (24 km ground swath) mode for which the resolution limited pixel sizes are 12 m x 6 m and 6 m x 6 m respectively. Coherent speckle is almost eliminated through a multilooking (7-look) process. Data are recorded on high density digital tape (HDDT) and may be downlinked through a broad-band data link for real-time applications. A more complete description was published by elsewhere Nichols et al. (1986).

STAR-1 was commissioned in November 1983 and has since flown land mapping projects on four continents and sea-ice surveillance missions in the Arctic (Mercer et al., 1986). Over million km^2 of imagery has been collected du this 2 1/2 year period.

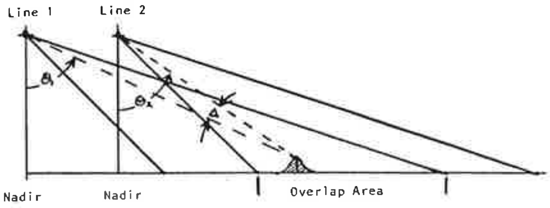

Figure 1: Representative stereo radar geometry. $\Delta = (\Theta_2 - \Theta_1)$ is the intersection angle.

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3. VIEWING GEOMETRY CONSIDERATIONS

Several authors (Pisaruck et al., 1984, Leberl et al., 1985) have commented upon the problems of optimizing viewing geometry with respect to extraction of information from SLAR stereo pairs. With reference to Figure 1 these can be summarized as follows:

1. The intersection angle $\Delta = (\theta_2 - \theta_1)$ at any ground point should be large in order to increase the stereo exaggeration factor or, equivalently, the parallax observed, thereby ultimately determining the precision with which the elevation can be determined. This is exemplified in equation 1 below.

2. The stereo pairs, from the stereo interpreter's point-of-view, should be as near identical as possible, implying that the intersection angle should be small. This is a qualitative statement, but it is clear that uncertainty in identifying the corresponding pixels in the two images will translate into uncertainty in the determination of elevation.

These are conflicting requirements, necessitating a compromise choice.

Simple geometric considerations (Leberl, 1979) provide an estimate of the limiting uncertainty, δ_h in elevation determination due to uncertainty in range determination δ_R for measurement of a single target:

$$\delta_h = ((\sin^2\theta_1 + \sin^2\theta_2)^{1/2} / \sin\Delta).\delta_R \qquad (1a)$$

For typical aircraft geometries, the denominator, $\sin\Delta$, is one of the dominant variables, while the range resolution ρ is the other, since $\delta_R \simeq \rho/2$. As a rule-of-thumb, for shallow geometries $\delta_h \; \alpha \; (\rho/2.\Delta)$, thus emphasizing the desirability of using small resolution cells and large intersection angles.

The cross-track coordinate y suffers from an uncertainty δ_R as follows:

$$\delta_y = ((\cos^2\theta_1 + \cos^2\theta_2)^{1/2}.\sin\Delta).\delta_R \qquad (1b)$$

Other considerations with respect to viewing geometry include layover and shadowing. Layover is a problem for steep angle geometries such as occur for satellites, but is generally not a problem for the relatively shallow angle geometries of aircraft. On the other hand shadowing, especially in mountainous terrain, will cause some information loss. If significant this can be compensated by flying dual direction missions.

4. DATA ACQUISITION AND PRE-PROCESSING

A test area was chosen in the Brazeau area, approximately 200 km NW of Calgary, Canada near the Rocky Mountains. The site contains a mixture of topographic relief scales, including mountains, hills and flat areas and has features of general geological and forestry interest such as wood cuts, and seismic cut lines. The area contains many cultural and natural features that serve as ground control points. The 1:50,000 national topographic series maps were used for control purposes. These maps were based upon 1966 aerial photography which was found to be out of date in many respects due to ongoing cultural activities.

Two missions were flown, both in the 'narrow swath' mode (6 m x 6 m resolution). The first (December 24, 1985) comprised three overlapping strips while the second (April 2, 1986) included five strips with substantially increased overlap. This enables a geometry with larger intersection angles in order to test the assertions of Section 3. This paper will deal only with the results of the second mission.

Each flight line was offset from its neighbour by 8 km. Because of the 24 km swath, this enables three stereo pairs to be made up by combining 8 km sections of the first and third, second and fourth, and the third and fifth strips. The intersection angles achieved with this geometry varied from 20° at the near edge to 12° at the far edge of each overlap area. Flight altitude was 9 km above mean ground level and each swath was offset 10.8 km from aircraft nadir (i.e., the flight line).

Data from HDDT were transcribed onto computer compatible tapes (CCT) and following some digital pre-processing tasks, they were written onto high precision film negatives using an MDA FIRE system. These five strips were then processed in the analytical plotter in order to derive the DTM as described in Section 5. The raw digital data from the third or central strip were used as the source data upon which the rectification process was accomplished as described in Section 5.

A segment from a representative stereo pair is shown in Figure 2. This pair is taken from the first mission (December 24, 1985) because negatives from the second mission were unavailable at the time this paper was written. Observed parallax is slightly less than in the second data set described before since overlap was 10 km rather than 8 km.

5. DATA ANALYSIS

5.1 Procedure

Processing steps deal with digital images, film versions of the images, with maps or ground control, and with flight parameters. Equipment used for the analysis encompasses a digital image processor, analytical stereo plotter, film writer and various computer graphics peripherals.

(a) Digital image pre-processing

The digital STAR-1 image data undergo a suite of image processing steps to obtain square pixels, reduce noise, reconstruct dropped lines, and to create good contrast. These new digital images are recorded onto film using a precision film writer. Typical data quantities are 4,000 x 4,000 pixels per image if the ground coverage is 24 x 24 sqkm.

(b) Ground control

Upon receipt of diapositive film images one collects ground control information. In the current case the ground control is digitized off maps at scale 1:50,000 and transformed into a

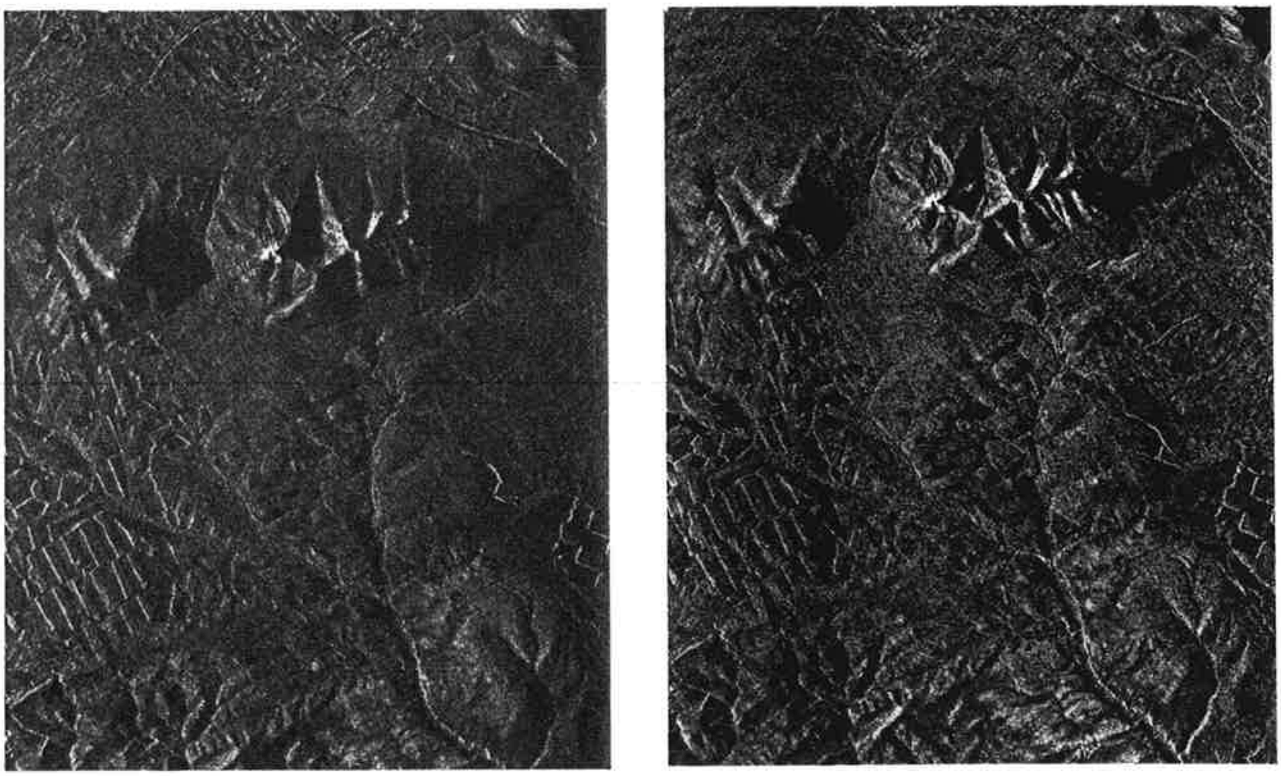

Figure 2. Segment of a STAR-1 stereo pair from December 24, 1985 mission. The area shown is about 14 km x 17.5 km.

master coordinate system. In unmapped areas ground control would need to be measured using radar identifiable ground features, either marked by corner reflectors or by well-defined man-made drainage or similar objects. The density of required control will be discussed later.

A specific type of control concerns height. Apart from full control with known XYZ or latitude, longitude and elevation one can employ also points with only known Z. Such points can be obtained from airborne profiling or barometric pressure measurements on the ground.

(c) Stereo-model set-up

The film images are used in a computer controlled analytical stereo-plotter, together with the ground control and known parameters of the image configuration, to form a stereo-model without parallaxes. This requires that preparatory measurements be taken in each image separately, that a preliminary computation be performed, then additional stereoscopic measurements are made leading to the final model set-up. The software for this step is SMART (Stereo Mapping with Radar Techniques) implemented on a Kern DSR analytical plotter.

(d) Stereo data collection

The actual data extraction follows the model set-up. An operator collects XYZ coordinates of feature boundaries (planimetric mapping) and samples terrain elevation along height contour lines, profiles, square grid points or along characteristic terrain break lines. Results consist of a planimetric map manuscript and a file of height points.

(e) Creation of a digital terrain elevation matrix (DTM)

The height measurements are entered into a software system to create a square grid elevation matrix. This matrix provides a height point for each pixel of a yet to be created rectified radar image.

(f) Creation of final contour line presentation

Either by computation from the matrix-DTM, or from the original height contours, a cartographically pleasing final "map separate" is created for height. Editing may be required of the digital file prior to its plotting on a flat-bed XY pen plotter.

(g) Creation of final planimetric presentation

The manuscript data are edited for cartographic presentation; this will include name placement, legend, coordinate grids etc. The result is plotted on a flat-bed XY pen plotter.

(h) Image rectification

The DTM, the original input digital images from step (a), and auxiliary data from the stereo model measurements are combined into a SAR rectification software system. A rectified radar image is produced by resampling of the preprocessed SAR image to (a) remove the geometric effects of scale and other artifacts and of topographic relief and (b) to tie it to the ground coordinate system. The resulting "geo-coded" ortho-radar image is written onto film.

IMAGE PAIRS STRIP I/STRIP J	NR. OF GROUND CONTROL PTS/AREA KM ^{2}	R.M.S. COORDINATE ERROR (M)		
		NORTH	EAST	HEIGHT
Model 1/3	17/200	24	30	41
Model 1/3	12/9	24	27	16
Model 2/4	21/200	23	31	28
Model 3/5	27/200	20	28	31
Theory	Equ. (1)	---	6 to 8	10 to 20

Table 1: Accuracy of STAR-1 radargrammetric coordinates. The theoretical error propagation is based on a range error of 3 m (i.e. range resolution of 6 m).

(i) Creating a composite radar image map

A reprographic reproduction process combines the rectified film image with the two map separates for height and for planimetry. The result is an image map super-imposing contour lines, planimetry, names and a coordinate grid over the rectified image.

5.2 Discussion

The individual data analysis steps have been discussed in past literature. Ground control and stereo-model set-up have been presented recently by Leberl et al. (1986) for SIR-B images. Radar stereo-photogrammetry has been studied since 1963 when the fact was established that stereoscopy was feasible with side-looking radar. Actual implementations for stereo-data extraction were attempted by Norvelle (1972), Autometric (1982) and Raggam and Leberl (1984). These implementations were all experimental in nature and performance results need to be studied with a variety of parameters.

The creation of DTMs from sampled height points is a classical task of photogrammetry and digital cartography. The problem is well understood and can rely on widely available commercial products.

Geo-coding of radar images with the help of DTMs has been discussed by Domik (1985). The problem of relating an image to an existing DTM is non-trivial if the DTM was not obtained from the image. This is not the case here. The process can therefore be organized in such a way that the DTM and SAR-image are readily matched.

The essential achievement of the current effort is the actual integration of several separate procedural and software components into a preliminary production system combining analog image analysis with digital image processing. There is considerable room for procedural improvements; the conceptual basis, however, is well established.

6. RESULTS

More than 15 ground control points per 24 km x 8 km overlap area were identified in the images and the map. These points are predominantly along drainage boundaries or man-made objects such as roads.

Table 1 summarizes the accuracies that were achieved with the data. The density of ground control was varied to find how it influences residual errors. These are of course a result of various major factors, namely:

* how well the software and control points can reduce the effects of scale and other geometric artifacts;

* stereoscopic acuity, i.e. the operator's ability to define a surface in the radar stereo model;

* point identifiability, i.e. how well symbolized map points can be found in the radar image and vice-versa;

* effects of limited map accuracy on planimetric control.

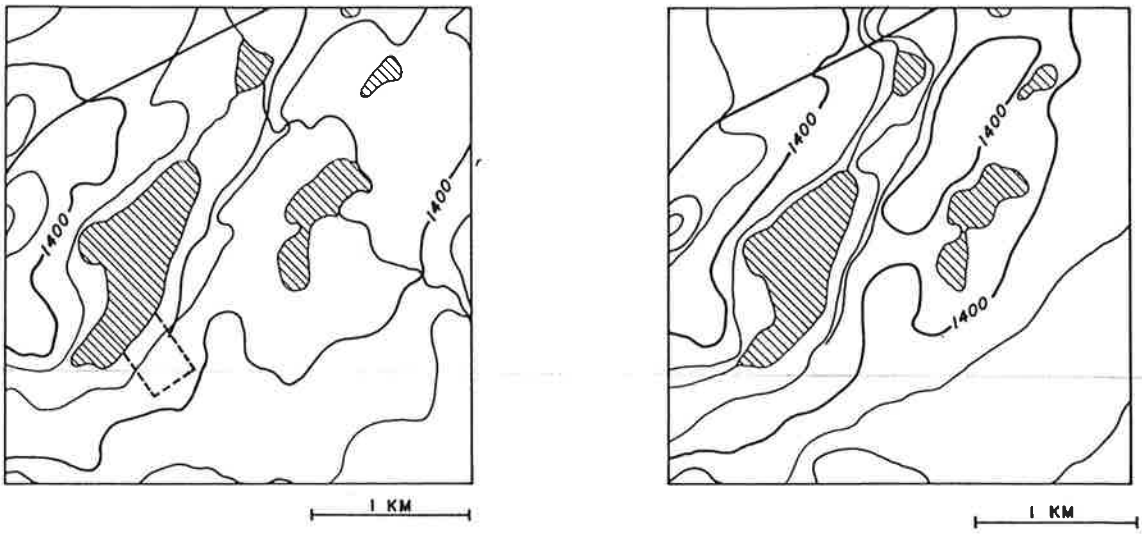

Figure 3: Segment of 3 km x 3 km of topographic map at original scale 1:50,000 (left) and the same area from the STAR-1 stereo radar (right). Note that the radargrammetric height accuracy only permits meaningful contour lines at intervals greater than 50 m.

Stereo acuity itself is affected by the radar geometry, range and azimuth resolutions, speckle and the illumination differences in the two images of a stereo pair. These differences are more pronounced when the terrain is accentuated, and are less severe in flat terrain.

The height accuracy as presented in Table 1 becomes equal to the height acuity when control point density becomes high. High control density should be equivalent to continuous precision measurements by (INS/GPS systems in areas of no control.

In the current data set, acuity is quantified by repeatedly measuring the same heights in one stereo-model. Root mean square discrepancies amount to about ± 20 meters. This confirms expectations obtained from the theoretical predictions of eqn. (1).

Point identifiability is area- and map-dependent. The currently available maps 1:50,000 appear significantly generalized regarding the transportation network. It is clear to the observer that the radar image shows significantly more transportation detail than the map. We estimate that the generalization effect on planimetry may amount to as much as ± 0.5 mm in the map or 25 m on the ground.

Elevation accuracy of map points is better. The contour interval is 20 m. This results in an expected ± 6 m height error if one disregards the effect of a planimetric error on height.

The actual output of the stereo mapping effort consists of contour and planimetric map separates. Figure 3 illustrates a contour and planimetric separate and compares this to the 1:50,000 contour map of the same area. The contour interval of the radar derived map is 100 m with computed 50 m intermediate contours, whereas the map shows 20 m contours. For the purpose of comparison we do show in Fig. 3 even 20 m radar-derived contours. The contour separate will need to be combined with planimetry and the rectified image to form the final image map.

7. CONCLUSIONS

National map accuracy standards suggest that the contour interval be not smaller than about 3 times the height accuracy of individual points. Therefore the STAR-1 system currently permits plotting of 100 m contour intervals from a height accuracy of about ± 25 m. To better describe the terrain character in rolling areas we propose to add 50 m intermediate contour lines.

The planimetric accuracy for conventional maps differs from that for more modern image maps. The STAR-1 accuracy lends itself to an image map at scale 1:50,000. With horizontal errors of about ± 25 m one needs to accept ± 0.5 mm residual errors in the map.

We find in conclusion that the STAR-1 imaging system leads to radar image maps at acceptable scales of 1:50,000 where residual errors are less than ± 0.5 mm, and where height is represented by 100 m contours and 50 m supplemental contours.

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