

## SAR Technologies for Topographic Mapping

J. BRYAN MERCER, Calgary

### ABSTRACT

Although Synthetic Aperture Radar (SAR) has been widely used in various forms of mapping for several decades, two factors have created new interest in its utilization for topographic mapping. The first is the emergence of Digital Terrain Models (DTMs) in an ever-increasing range of applications, for which digital data from remote sensing sources are becoming increasingly competitive. Secondly, the launch of SAR satellites and the development of associated technologies will provide new mapping solutions in cloud-covered areas of the world where costs and time scales are currently prohibitive. The thrust of this paper will be to summarise the status of the SAR-based technologies which are currently able to provide DTMs and associated products, or will shortly be able to do so. STARMAP, Intera's name for its process for DTM creation from airborne SAR, is now a mature, commercially successful implementation and will be described in some detail. Other technologies which will soon be available commercially will also be reviewed for their salient features, although in less detail. The systems to be addressed include satellite stereo SAR, and airborne and satellite SAR interferometry. It is concluded that a combination of the two SAR satellite technologies will be able to provide DTM extraction for much of the world at the DTED level 1 standard and better in some circumstances. Airborne interferometry on the other hand will be able to provide DTMs at a much denser grid spacing and at a considerably better vertical resolution. The technologies are complementary when coverage and cost factors are considered.

### 1. INTRODUCTION

In cloud-covered areas of the world, and particularly in the tropics, airborne SAR has been used for thematic mapping applications for more than two decades. More recently, the applications have been extended by Intera, to include topographic mapping over relatively large areas (5 000 - 100 000 km<sup>2</sup>) at typical mapping scales of 1:25 000 to 1:100 000. Products include Digital Terrain Models (DTMs), contour maps and ortho-rectified image maps in digital and analogue form. The topographic mapping process, referred to as STARMAP, utilizes digital stereo image data from Intera's STAR-1 airborne SAR. Hosted upon digital workstations, the all-digital process includes soft-copy stereo acquisition, radargrammetry, editing and output modules. Developed over a nine-year period, the process is now fully operational and several projects have now been completed. In this paper the current configuration and methodology are presented along with examples.

An alternative airborne mapping technology based upon radar interferometry has been successfully demonstrated by several groups recently. The CCRS (Canada Center for Remote Sensing) InSAR system is currently being made available for commercial operations in co-operation with Intera. The current status of the CCRS InSAR system will be summarised in this paper.

Considerable interest has also been generated by the launch of several SAR satellites including ERS-1 in 1991 and its successor, ERS-2, in May of 1995. While these have been largely used for application development, RADARSAT, the Canadian SAR satellite scheduled for launch in September 1995, has a commercial, operational mandate. The reason for the great interest in these systems is the possibility of cheaper (for the customer) data than can be provided by aircraft, along with an almost world-wide, repetitive coverage. The DTM extraction technologies associated with these satellites will be reviewed in this paper with an assessment of their virtues and limitations.

### 2. THE PROBLEM

In the context of this paper, the mapping problem to be addressed is that of elevation extraction, in the form of a DTM, and the creation of a rectified ortho-image or mosaic of ortho-images. Although not explicitly addressed here, the image interpretability, as determined by factors such as resolution,

speckle reduction, radiometric quality, and viewing geometry, is a major factor for consideration with respect to the mapping process.

In general, the mapping scales for which these technologies may be appropriate, range from 1:10 000 to 1:100 000 - that is, medium to small scale mapping applications.

It should be further noted that a particular technology may achieve the published mapping standard for a certain scale in one of the parameters (for example, image resolution) but not achieve it with another parameter (for example, vertical accuracy). Thus it may be that the customer, conscious of price and availability issues, may choose a pragmatic course wherein the traditional standards are partially ignored.

### 3. SAR (SYNTHETIC APERTURE RADAR) FOR MAPPING

The current status, with respect to operational maturity and performance (vertical accuracy) of the two technologies (stereo and interferometric SAR) and the two platforms is summarised in figure 1.

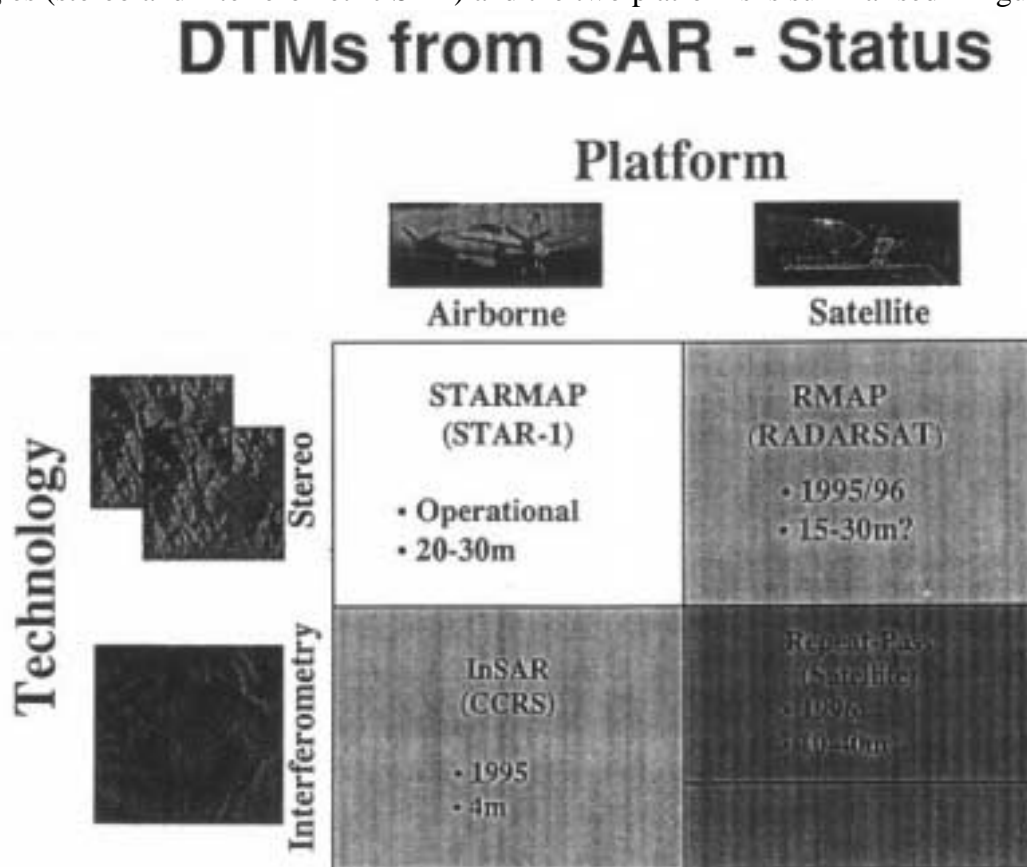


Figure 1: Status of various SAR systems for DTM creation including approximate vertical accuracy (RMS).

The airborne stereo SAR, as manifested by the Intera STARMAP process utilising STAR-1 digital data, is commercially and operationally mature. Over 300 000 kmsq of DTMs have been created in commercial projects of size ranging from 10 000 kmsq to 100,000 kmsq. As detailed later, vertical accuracies of 15-30 m (RMS) are obtained at grid spacing (postings) of 50 m. Horizontal accuracies are about 10-15 meters (RMS). Image resolution (approximately 6 meters at 7 looks), normally supports 1:50 000 products although both larger and smaller scale ortho-rectified image maps have been created for different applications.

A stereo satellite version of STARMAP, called RMAP, is expected to be available within a few months of the launch of RADARSAT (September, 1995). It is expected that vertical accuracies in the

range 10-30 meters (RMS) will be achievable, depending on terrain steepness, texture and other factors. The goal will be to achieve DTED Level 1 as a minimum (18 meters (RMS) vertical uncertainty, 3" posting). The experience that supports these expectations is reported in section 6.3. Airborne interferometry is commercially available through Intera starting in the summer of 1995. The CCRS InSAR system combines very good DTM capability (vertical accuracy 2-4 meters (RMS) at 10 meter postings, horizontal accuracy about 5 meters (RMS)), as well as excellent image quality (5 meter resolution at 4 looks).

Satellite interferometry, often referred to as 'repeat-pass interferometry', has been demonstrated under restricted conditions to provide vertical DTM accuracies at the 5-15 meter (RMS) level. To date it has utilised data from ERS-1, ERS-2 and other platforms no longer in orbit (SEASAT, SIR C). The single biggest limitation is the requirement for temporal coherence of the target pixels between successive satellite passes. To the extent that the terrain itself or the overlying vegetation changes between passes, the accuracy can be badly degraded to the point of unusability. It is intended that a commercial capability will be available based upon RADARSAT data, although the extent of the limitations are not yet well understood.

#### 4. TECHNOLOGY OVERVIEW

A very brief review of the technologies is presented in this section. More detailed accounts may be found in Leberl (1990), Mercer and Griffiths (1994), Gray and Farris-Manning (1993), Zebker and Villasenor (1992), Hagberg and Ulander (1995), and references to be found therein.

##### 4.1 Stereo SAR

The stereo approach for elevation extraction, requires as input, overlapping image pairs created from airborne or satellite platform positions which, as viewed from a common 'target' within the images, are separated in incidence angle by several degrees (optimally 10-20 degrees). This is depicted in figure 2. The extraction of the coordinates (X,Y,Z) for this individual target can be achieved through simultaneous solution of the so-called (range,doppler) equations (Leberl, (1990)). Fundamental to the process is the ability to identify or match the common target pixel in both images.

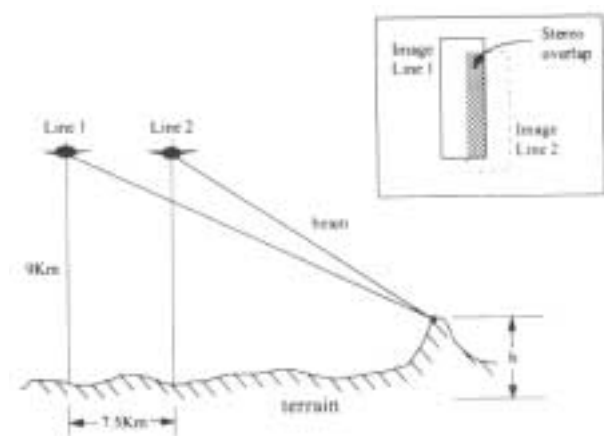


Figure 2: Stereo SAR geometry.

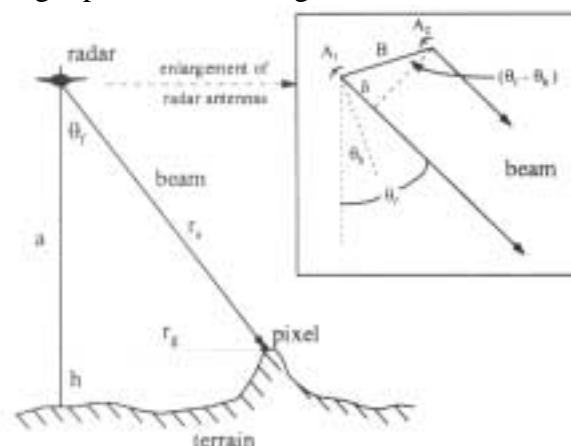


Figure 3: Interferometric SAR geometry.

Precise knowledge of the aircraft or satellite position(s) is required to locate the target in the mapping frame of interest (for example, with respect to a WGS-84 ellipsoid and UTM projection). In the case of STAR-1/STARMAP, differentially processed GPS provides aircraft track recovery at 0.5 sec intervals to a level of 1-2 meters RMS. In the absence of precise platform location (as will be the case with RADARSAT), ground control is further required.

In principle, at least, the creation of a DTM then reduces to the following steps:

- a) acquisition of an adequate sample of matched target points in 'image space' to describe the terrain surface at the level of spatial detail required (typically the sample includes a quasi-regular grid of points supplemented by breaklines and drainage lines);
- b) computation of the 'object space' (X,Y,Z) coordinates for all of these target points;
- c) interpolation of the target points into a DTM at the desired regular posting. Other practical elements include various radiometric and geometric pre-processing steps, tying the images together, possibly performing block-type adjustments to the data where multiple images are used, merging or mosaicking of overlapping DTMs over large areas or from different viewing directions, editing and QA. In the airborne case extra processing steps are required in order to correct for uncompensated aircraft motion. Contour plots are generated from the DTM and used in the editing process and ultimately output as maps. Normally the source images are ortho-rectified and mosaicked at the same time, to serve as image maps.

The major ways in which satellite stereo SAR differs from the airborne case is in the geometry (steeper and better for stereo), resolution and image quality (poorer), motion compensation (not required), track recovery (more difficult), viewing directions (limited), time between pairs (greater), cost (less), and area coverage (greater).

A more detailed description of the STARMAP process is provided in section 4 along with results of ERS-1 roll/tilt mode stereo.

#### 4.2 Interferometric SAR

The principle, depicted in figure 3, is based upon measurement of the phase difference between the backscattered wavefronts from a common target pixel, arriving at two spatially separated antennas. The phase difference is determined by the path difference between these wavefronts. Calculating the path difference from the observed phase difference, and with knowledge of the antenna separation or baseline, its orientation with respect to nadir, and the height of the platform above the reference geoid, it is then possible from simple geometry to calculate the height of the target pixel (in principle, at least). In practice, the phase is determined from an 'interferogram', which is mathematically the complex product of the complex images received from each of the two antennas. Because the phase difference can only be measured between 0 and  $2\pi$  (modulo  $2\pi$ ), there is an absolute phase ambiguity which is normally resolved with the aid of ground control and a 'phase unwrapping' technique (e. g. Goldstein et al, 1988). Thus the extraction of elevation is performed on the 'unwrapped' phase.

In the airborne case, both antennas are located on the same platform; for example, in the case of the CCRS InSAR system the main transmit/receive antenna is located under the fuselage, while the second antenna, for receive only, is located on the side of the aircraft, about 2 meters away. The prime advantage of this configuration is that it is a single-pass system. Thus the target is viewed by both antennas simultaneously.

On the other hand, satellite interferometry is currently implemented by computation of an interferogram from two passes of a satellite with time separation of at least 1 day, and 24 days in the case of RADARSAT. The orbit of the second pass must be within several hundred meters of the first in order to preserve phase coherence between the two views of the target. The exact baseline separation, beyond which phase coherence is lost, is dependent upon altitude, wavelength and spatial resolution of the system. A more serious problem is possible 'temporal de-correlation' which is the potential loss of coherence caused by the time delay between passes. Thus the quality of the DTM derived by repeat-pass interferometry will be dependent on the terrain, vegetation cover, local climate and other factors in the target area. There is considerable effort by several groups currently attempting to understand these factors. A very interesting attempt to minimize the problem of temporal

de-correlation will utilise ERS-1 and ERS-2 operating in tandem mode whereby the satellite orbits are separated by one day only. Unfortunately ERS-1 is at the end of its mission life and the tandem mission will occur only for a few months during late 1995. Another limiting factor is that these satellites do not carry tape recorders so there are practical restrictions on the areas where the technique may be applied.

## 5. IMPLEMENTATION OF STEREO SAR - STARMAP

The STARMAP Soft-Copy System (SSCS) is an all-digital stereo radar workstation and is central to the commercial extraction of DTMs from STAR-1 stereo data. It is a custom system and has been operated by Intera in development and production modes since 1991, with evolution paralleling the operational experience. A more complete description of the workstation and the associated operations is given in Mercer and Griffiths (1994). The workstation consists conceptually of three modules as summarised in the following. Although the description below is presented with respect to the airborne stereo case, a modified form was used to perform the ERS-1 stereo work described in section 5.2 below.

### 5.1 Acquisition

Pairs of image space coordinates of coincident target pixels are extracted from overlapping digital image strips in this module. This function is implemented through a digital stereo interface through which the operator perceives a stereo model. When in manual mode, an operator can lay a floating mark on the surface, corresponding to the shift in cross-track direction of one image with respect to the other, or 'removal of x parallax'.

There are a number of facilities supported in the LT module:

- The operator can quickly change from any stereo zoom level to any other, from a 1:1 presentation (each pixel displayed) down to 1:64 reduction, the levels being separated by factors of two.
- Acquired points may be depicted on the screen in stereo, enabling the operator to assess coverage and evaluate terrain description easily.
- Several different classes of point and line type may be acquired, including mass points collected in a pre-programmed grid mode, randomly acquired points, break lines, and drainage lines. The number and mix of mass points depends on the terrain type and how it may best be described.
- Individual points or clusters of points may be edited. QA at this stage is very effective, as applied to "bad" point removal, for example.
- An image correlation capability is normally enabled, both to achieve sub-pixel accuracy and for off-line densification.

### 5.2 Radargrammetry

The function of this module is to process the pairs of image coordinates (i.e., the parallax coordinates) acquired in the LT module into (X,Y,Z) object coordinates with respect to the desired map reference system. In order to achieve this, STARMAP requires as additional input, the GPS data describing the aircraft flight line history and the history of certain parameters relating to the motion compensation process.

A radargrammetric model accounts for the particular radar parameters (slant-to-ground conversion, various delays and offsets, etc.) and, in concept, intersects the spherical wavefronts transmitted from the two radar positions at the common target represented by the image coordinate pairs. Instantaneous 'squint angle' deviations associated with the aircraft velocity fluctuations are also accounted for in this process. A form of numerical adjustment, conceptually similar to a block adjustment in photogrammetry, is performed using the tie points. This process uses redundant information created by

triple overlap in portions of the imagery, and enables an internal optimization with quantifiable results that form part of the QA activities. Upon completion of the adjustment, the object coordinates for all of the mass points are computed. Depending on the terrain and other factors, there may be 50 000-100 000 such points acquired to adequately describe the terrain in a single 1:50 000 scale mapsheet-size project. More typically, the project size is considerably larger.

Since each of the acquired points now has associated with it both object coordinates and image coordinates, it is possible to create a grid transformation that will warp the input grid into the desired output grid. Through standard resampling, the grey-level information in the original images is then mapped onto the output grid. This process completes the ortho-rectification stage.

Both terrain displacement and anomalous distortions have been minimized in the process, and the images geo-coded or ortho-rectified with respect to a standard map projection (such as UTM).

### 5.3 Editing

Two functions are performed in this module: A DTM is created, along with associated contour lines, and a QA/editing activity is implemented. The (X,Y,Z) coordinates from the radargrammetry module constitute an irregular grid of points and 'feature lines'. A third-party software module transforms this irregular grid into the desired regular grid of elevation values (the DTM) at the desired spacing. Feature lines, originally acquired in LT as break lines and drainage lines, are incorporated into the process, providing a refinement to the surface description. Contour lines, at operator-selectable intervals, are created from the DTM.

In order to provide a convenient means of performing QA, the contours may be graphically displayed, inspected and digitally edited for obvious errors. More usefully, the rectified images can serve as a backdrop (monoscopically) to the contours. To the extent that some portion of the contours does not reasonably represent the terrain, a set of tools enables the operator to move, cut or otherwise modify the contours. Local changes to the contours are reflected in the DTM.

Opposite-look data may have been collected in order to fill in areas that are obscured by shadow. The opposite-look data will have been independently processed up to this point. In this module, when each of the data sets has been independently QA'd, the data are combined into a common DTM and contour set.

Subsequently, DTMs are converted to the desired output format. Contour sets are exported to a GIS where they are cut into mapsheet sizes and merged with manuscript surround data before plotting to hardcopy. Ortho-rectified strips are mosaicked using another custom Intera package and output to a high quality film plotter.

## 6. EXAMPLES

Graphical examples from three of the four technologies described above are presented in this section, along with descriptions of the associated circumstances.

### 6.1 Airborne Stereo

A 1:50 000 scale, STARMAP-derived image map and the corresponding contour map are shown in reduced form in figures 4(a) and 4(b). The image map was mosaicked from seven ortho-images. The contours are at 50 meter intervals and were created from a DTM with 50 meter postings. Check points in the general area confirmed the 20-25 meter (RMS) DTM uncertainty and the 15 meter (RMS) horizontal uncertainty of the mosaic.

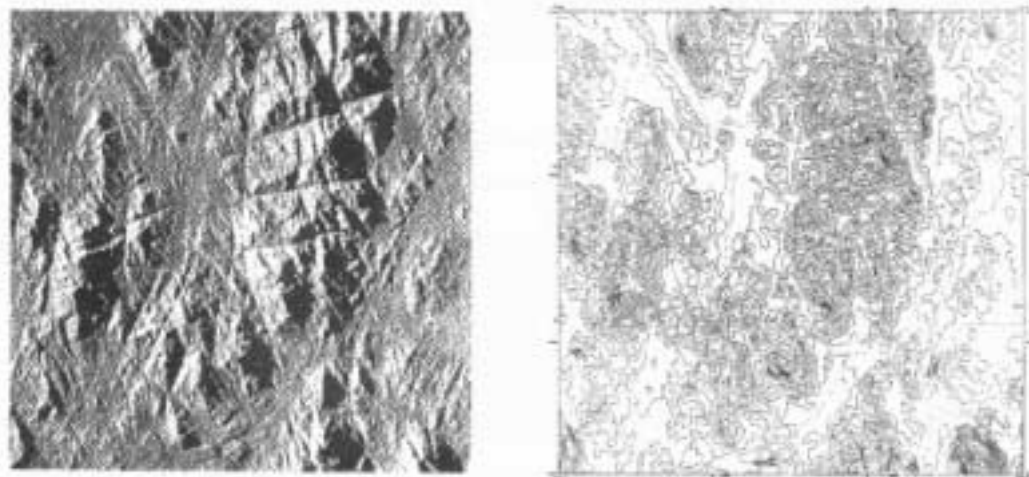


Figure 4: STARMAP hardcopy output products. Figure 4a is a Radar Image Map and Figure 4b is the corresponding contour map. The original scale of both is 1: 50 000. Normally these products are presented with full surround information and annotation. This information is not reproduced here for confidentiality reasons.

**6.2 Satellite Stereo**

Normal ERS-1 geometry is not suitable for stereo elevation extraction because the intersection angle is too small (equivalent to an inadequate base-to-height ratio in photogrammetry). However during an experimental early phase of the ERS-1 mission, the satellite was tilted upward by 12 (allowing a reasonable stereo model to be obtained. Two test sites in Canada have been addressed using a modified form of STARMAP, currently referred to as RMAP. Comparisons with 'truth' in the form of government-supplied DTMs and check points obtained from standard topographic maps were made in both cases. In areas where the topography was not too steep, vertical accuracies in the 10-15 meter range were obtained. In more rugged topography, the accuracies deteriorated as a result, we believe, of mis-match between viewing geometry and terrain. It is thought that RADARSAT's flexible beam geometry will be better suited to this type of terrain. An example of the DTM derived from one of the test sites is shown in figure 5 where it is presented as a grey-level (originally color-shaded) spatial plot and compared with the B.C. provincial government DTM. The DTMs were created at 50 meter postings. The full set of results will be submitted for publication to the Canadian Journal of Remote Sensing.

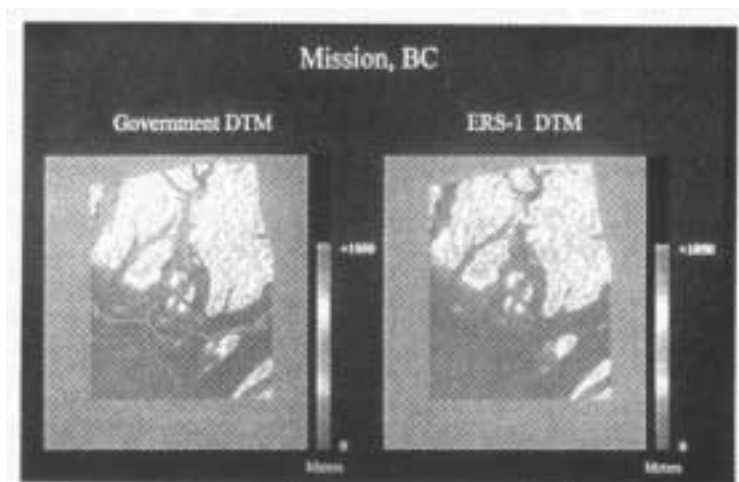


Figure 5: Gray scaled comparison of DTM's created from a) Provincial government 1:25 000 source. b) RMAP (ERS-1 satellite data) 57kmx45km. See text.

### 6.3 Airborne Interferometry

A set of airborne interferometry tests were recently conducted in the Bow Valley corridor west of Calgary, using the CCRS InSAR system. Comparison with the Alberta provincial DTM indicates vertical uncertainties at the 5 meter level. However it is thought that much of the uncertainty may lie with the 'truth'. A comparison of independently derived InSAR DTMs from opposite viewing directions shows RMS differences of 2-4 meters in areas devoid of trees. The equivalent of a few ground control points were used in achieving phase calibration (L.Gray, K.Mattar, and P.Farris-Manning, private communication). It is expected that this level of accuracy should be sustainable in commercial operations provided good differential GPS (preferably sub-meter) is available along with a few ground control points. It should be noted that 10 meter postings were used in this analysis. An example of the ortho-rectified image with color-shaded contours overlaid (reduced to grey in this presentation) is presented in figure 6. The elevation is presented using 50 meter color cycles. It is interesting to note that this presentation is similar in appearance to an interferogram except that in the latter case the color cycles are related to phase which is only indirectly related to the elevation.



Figure 6: Interferometric SAR gray scale contours (3-levels) from INSAR interferogram. Bow Valley, Alberta, just west of Calgary. Courtesy of Canada Centre for Remote Sensing.

## 7. COSTS

The unit cost of topographic map products such as DTMs or Ortho-Image maps, are dependant upon level of detail - usually quantified by scale or accuracy. Although the commercial pricing for the new technologies isn't known exactly yet, an estimate has been made for DTMs and is shown in figure 7, as a function of vertical accuracy. For comparison, standard aerial photography and SPOT-derived DTM prices are also shown.

## 8. CONCLUSIONS

It is clear that the technologies described will have increasing impact on topographic mapping on a world-wide scale, both in the production of DTMs and ortho-image maps. SAR has long had relevance in the cloud-covered areas of the world and this should continue to be the case. For example, STARMAP, the only commercial implementation of airborne stereo SAR for DTM extraction, is now operationally mature and is being adapted for satellite stereo SAR.

It should be possible, in principle at least, to create a consistent DTM data base over much of the world using stereo SAR from RADARSAT after its launch in late 1995. It is likely that this would be



supplemented by interferometric SAR although restricted to certain areas where temporal de-correlation does not present a problem. The latter might occur using RADARSAT with its 24 day repeat cycle or (for a few months in 1995) an ERS-1/ERS-2 tandem mission with its 1 day separation. The overall level of accuracy that might be achieved is approximately DTED Level 1, and better in many areas.

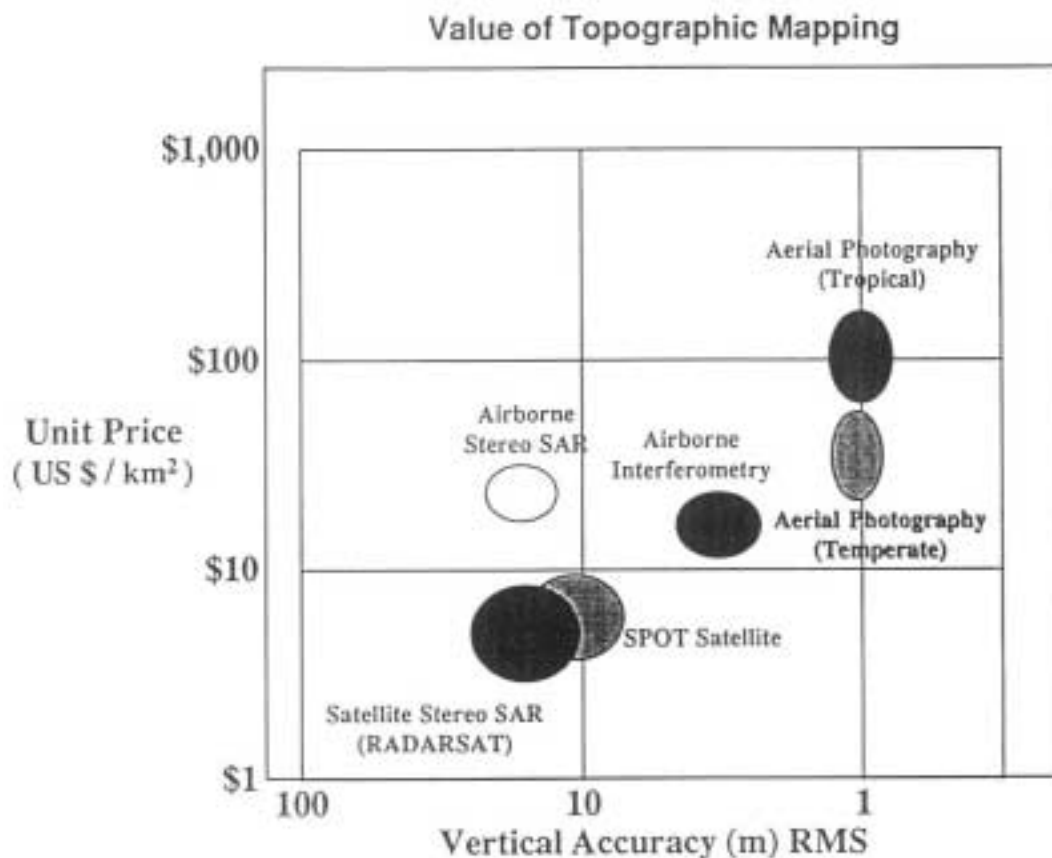


Figure 7: Estimated Cost vs. Accuracy.

Airborne interferometry on the other hand is now available to provide much better levels of detail and accuracy. DTMs can be created with vertical accuracy of a few meters, at postings of (for instance) 10 meters, and with corresponding imagery of a few meters spatial resolution. Unit costs are likely to be 2-3 times greater than can be achieved with satellite, but should be highly competitive with aerial photography in any part of the world.

**9. ACKNOWLEDGEMENTS**

The author wishes to acknowledge with gratitude, ESA/ESRIN for providing the ERS-1 stereo data under their AO program, CCRS for providing funding for the ERS-1 work under the RDDP program and RSI for providing supplementary data from the Gatineau station. We would also like to thank Dr Lawrence Gray at CCRS for providing the interferometry example used. We also thank the Provincial Government of British Columbia who donated the TRIM DTMs for test purposes.

**10. REFERENCES**

Gray, Laurence A., and P. J. Farris-Manning, (1993). Repeat-Pass Interferometry with Airborne Synthetic Aperture Radar . IEEE Transactions on Geoscience and Remote Sensing. Vol. 31: Number 1, pp 180-191.

- Goldstein, R. M., H. A. Zebker, and C. Werner, (1988). Satellite Radar Interferometry: two dimensional phase unwrapping. *Radio Sci*, Vol23: Number 4, pp 713-720
- Hagberg, J. O., and L. M. Ulander, (1995). Repeat-Pass SAR Interferometry Over Forested Terrain, *IEEE Transactions on Geoscience and Remote Sensing*. Vol. 33: Number 2, pp 331-340
- Leberl, F. (1990). *Radargrammetric Image Processing*. Artech House, Boston Mass.
- Mercer, J. B. and S. Griffiths, (1993). Operational Topographic Mapping from Airborne SAR Data (Presented at the International Symposium "Operationalization of Remote Sensing", 19-23 April 1993, ITC Enshede, The Netherlands)
- Zebker, Howard A., and J. Villasenor, (1992). Decorrelation in Interferometric Radar Echoes. *IEEE Transactions on Geoscience and Remote Sensing*, Vol 30: Number 5, pp 950-959.