Operational DEM Production from Airborne Interferometry and from RADARSAT Stereo Technologies

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ABSTRACT

In this paper we report upon the advances achieved over the past year in the creation of Digital Elevation Models (DEMs) on an operational, commercial basis, using data from two very different radar platforms. STAR3i is an airborne interferometric Synthetic Aperture Radar (SAR), capable of achieving DEMs at a level of detail and accuracy suitable for map scales as large as 1:10,000. A less detailed, but correspondingly less expensive product is achieved using TOPOSAR™ technology to create DEMs from RADARSAT stereo image pairs.

This new capability is timely because DEMs are being used increasingly in a host of applications ranging from GIS-based topographic data bases to tower-siting in the telecommunications industry. SAR, because of its cloud-penetrating capability, allows data acquisition in large parts of the world where imaging with conventional optical systems has previously been problematic and expensive. Moreover, this technology enables users to obtain DEMs with delivery times that are much shorter than those which the mapping community traditionally experiences.

The STAR3i (formerly IFSARE) radar, flown in a Lear Jet, has been operated commercially by Intermap Technologies since January 1997 and has created DEMs for projects in SE Asia, South America, Africa, Europe and North America. The system achieves vertical accuracies under operational conditions, at the 2 - 3 meter (1 σ) level with postings of 2.5 - 10 meters as required. The ortho-rectified images created simultaneously, have resolution approximately matched to the 2.5 meter pixel spacing.

The DEMs created from TOPOSAR , and using optimum RADARSAT standard beam pairs, can achieve 10-20 meter (1 σ) vertical accuracies at 50 meter postings; using fine beam pairs, similar accuracies can be obtained, but at a finer posting. Early results indicate DTED level 2 accuracies can be achieved in the latter mode, at least for some terrain types. In the absence of ground control - that is, using only the supplied orbital data for control purposes - the DEM may be offset by up to 35 meters; however the same relative accuracies are achieved. This is an important capability when faced with DEM acquisition over remote areas. DEM production using this technology has been underway since late 1996.

In this paper we describe the two systems and present recent test results and examples. The cost/performance trade-offs are also discussed and are compared compared to other technologies. Lastly, 'Global Terrain', a new approach to making the DEM data more widely available will be presented.

1. Introduction

Despite wide recognition of the need for creation of spatial data-basesin support of resource and infra-structure development, parts of the world remain poorly mapped at scales of 1:100,000 and larger (U.N. Cartographic Conference, Beijing, 1994). In cloud-covered areas of the world this is particularly problematic, because aerial photography is expensive and the ground is often obscured from the view of optical satellites. Because of its cloud penetration capability, radar has been used for image mapping at small scales for several decades. This technology has been evolving and in the the early 1990's, Intermap Technologies Ltd (at that time, Intera Technologies) applied its STARMAP stereo technology on data from the STAR-1 airborne system to create DEMs of about 300,000kmsq in various parts of the world (Mercer and Griffiths, 1993).

Intermap has replaced the STARMAP technology and STAR-1, with two related technologies, which at the time of submission of this paper, had been in commercial service for about eleven months. The stereo technology has been migrated to create DEMs from RADARSAT stereo data using a new process called TOPOSAR. On the other hand, STAR3i is a new airborne interferometric SAR from which DEMs are created at about a factor of 10 times greater detail. The two systems are complementary, in terms of accuracy/detail tradeoffs against price/availability arguments.

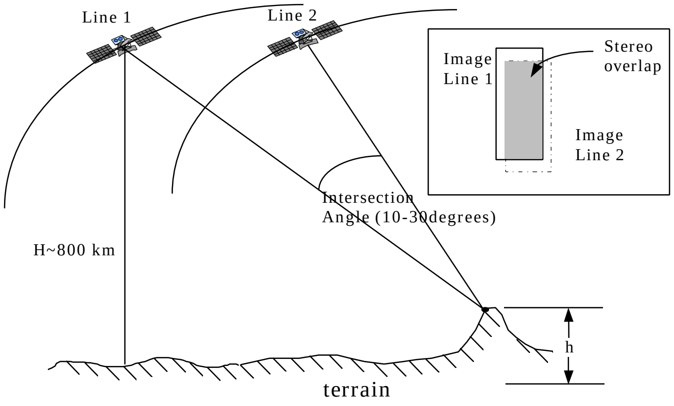
In this paper we review each of the technologies, and provide specifications of mapping interest along with the results of accuracy tests, performance details and a summary of project work undertaken to date. For most users, price and accuracy is an issue and we provide a comparison of the price of DEMs for these and competing technologies over a range of accuracies. Lastly we introduce 'Global Terrain' **-** a different approach for making Intermap's DEMs more widely available.

2. TOPOSAR: DEMs from RADARSAT Stereo

2.1 Background and Current Implementation

The principles associated with elevation derivation from stereo radar images has been widely reviewed (in particular, Leberl, 1990). The implementation described in this paper has evolved out of the STARMAP system summarised in Mercer and Griffiths, 1993. STARMAP utilised stereo radar images from the STAR-1 airborne SAR and successfully created DEMs of about 20-25 m (RMS) vertical accuracy in several major commercial programs.

The basis for stero radar elevation is depicted in figure 1. In this simplified two-dimensional geometrical representation, the height of an object with respect to a reference surface can be deduced from the parallax difference as perceived from two different points of view, provided the slant range distances (satellite to common target) and the satellite locations are known. In actuality, the rigorous determination of the object location is through solution of the range-doppler equations (eg Leberl, 1990) which allows for a three-dimensional generalization of the foregoing simplification. These equations describe the simultaneous intersection at the object, of range spheres and doppler cones originating from the two satellite positions. In the case of RADARSAT (abbreviated RSAT in the following), the input images would typically be standard- or fine-mode beams with different angular separations (referred to as the 'intersection angle'). For instance, an S2/S7 stereo pair would have an intersection angle of about 19.5 degrees. The slant range resolution (nominally 25 meters and 10 meters for standard and fine modes, respectively) and the geometry (mainly the intersection angle) are, in principle, responsible for defining the achievable relative vertical accuracy. The spatial position of RSAT can be determined from the ephemeris data with or without the assistance of externally supplied ground control points.



Stereo SAR Geometry

Figure 1: Schematic of the RSAT Stereo Geometry

The creation of a DEM is the result of the acquisition and interpolation, of an adequate sample of object points to represent the terrain. For example a 100 meter DEM grid of coordinates covering a standard RSAT stereo pair (assuming an 80km x 80km overlap), would entail acquisition of about 640,000 points. In order to identify the common objects viewed in each image, automated matching is normally performed, usually with the assistance of a stereo viewer to allow operator intervention and QA. The automated matching is analogous to that performed in Digital Photogrammetry applications but because of the specific issues associated with radar images (speckle, shadow, layover etc) has its own particularities. Additionally, in the case of mountainous terrain, breaklines are optionally acquired (in the TOPOSAR implementation) to supplement the automatically acquired grid points.

Theoretically (Leberl, 1990), the slant range resolution and the geometry (mainly the intersection angle) are the determining factors related to the achievable vertical accuracy; in practise, however, the success of the auto-matching process, with respect to sub-pixel matching accuracy, is also a major determinant of the vertical accuracy that can be obtained. This appears to be due to two factors. The first is that the basic process of auto-matching, irrespective of the particular algorithm, uses multiple local points (in effect, an averaging process), in contrast to the single point statistics referenced in the theoretical treatment. The second factor, is the nature of the terrain itself, in that the smaller the intersection angle, the more similar the two sub-scenes to be matched will appear. This is in opposition to the theoretical argument in which increasing intersection angle reduces vertical uncertainty. The terrain itself thus factors into the ultimate quality of the DEM through its impact on the matching success.

TOPOSAR is curently hosted on a UNIX Workstation with stereo interface. It has been designed as a production workstation driven by three factors: throughput, accuracy and ease of use. Throughput and accuracy are addressed in sections 2.2 and 2.3 respectively. In addition to these factors, it is required that TOPOSAR be able to use GCPs if they are available but derive a solution without them, in order to make the process more global in application.

The major stages of the process are:

- Image Ingestion (image pair input, epi-polar resampling)
- Point Acquisition (set-up, automated hierarchical matching of mass points, break-line generation, stereo visualization)
- Radargrammetry (coordinate computation, DEM generation, image ortho-rectification)
- Initial Editing (blunder removal)
- Final Editing (cartographic editing of derived contours/DEM in monoscopic environment)
- Final Product Generation

A stereo visualization window is presented to the operator for the point acquisition process. At any stage, the contours derived from the DEM can be re-projected back into image space and shown overlaid upon the stereo image pair. This is normally a final form of QA insofar as it enables the operator to visualize the degree to which the contours (and hence the underlying DEM) represent the terrain.

2.2 Performance

Typical throughput times of the sub-processes for a single RSAT stereo pair of a scene with moderate terrain, are shown in table 1 below, for a project hosted on a 200 Mhz Ultra SPARC II workstation. The times shown presume there are no input data problems.

Process	**Operator**	**Machine**
Image Preparation	5 min	15 min
Seeding	30 min	30 min
Image Matching	0 min	5 hours
Radargrammetry	1 hour	2 hours
Initial Edits	1 hour	1 hour
ORI Generation	1 hour	2 hours
Final Edits	6 hours	6 hours
Total	9 hours 35 min	16 hours 45 min

Table 1: Typical TOPOSAR Process Times

The most operator intensive portion of the process is the final (cartographic) editing stage. The nature of the terrain tends to make this number somewhat variable. The terrain type will also impact the point acquisition stage to some degree. For example, steeply mountainous terrain may require operator intervention to collect supplementary break-lines.

2.3 Accuracy Tests

A number of data sets have now been processed for which there are GCPs or other truth data with which the TOPOSAR DEMs may be compared. In table 2, these are listed. They include a variety of RSAT beam mode combinations, and include both standard and fine mode data. The terrain types included are flat to hilly. No GCPs were used in derivation of the solutions in any of the tests.

The sources of the 'truth data' are listed and include DEMs of various quality, GCPs and and points extracted from maps. Ideally, the 'truth' would be of a higher level of quality, such that its own errors would be insignificant compared to those of the TOPOSAR DEMs. In reality, this was not always the case. Thus the TOPOSAR errors in some cases are overstated. Typically the TOPOSAR DEM was differenced from the 'truth' DEM and the mean vertical difference and standard deviation of the difference reported. In order to determine the horizontal differences in Easting and Northing, recognizable features on the ORIs (Ortho-Rectified Images) were compared to GCPs or maps. Of course part of the difference is attributable to difficulty in precisely co-locating these features.

In the six test cases reported, the standard deviation in the vertical varied from 8 to 16 meters for grids (that is, sample spacing or 'postings') of 30 to 50 meters. Offsets ranged from zero to 41 meters. If these results represent the typical situation, then it can be concluded that in the absence of ground control, one would expect to observe relative uncertainty in the vertical of 8-16 meters RMS deviation with respect to some offset which is generally less than 30 meters (90% confidence). If a few GCPs are available, then the offset can be largely removed.

It should be noted that the situation for steep mountainous terrain is quite different. Because of the severe terrain displacement and layover that can be encountered, there may be large areas for which there are no recoverable data points in which case interpolation would be required and accuracy would suffer. Thus accuracy will be terrain dependent. The pragmatic response to these situations is to reduce the effect by utilizing shallower beam angles. This necessitates using smaller intersection angles and foregoing the associated theoretical geometry gain. However the loss is generally compensated by an ability to obtain a processable stereo-pair.

Test #	Project Name	Terrain Type	Area (km x km)	RSAT Mode	Output Posting	'Truth' Data	Source	Points Tested
1	Ottawa	Flat + Hilly	50 x 50	S2/S7	50 m	OBM	Prov Govt	49924
2	Ottawa	Flat + Hilly	50 x 50	S2/S7	50 m	NTS Map	Fed Govt	20
3	Ottawa	Flat + Hilly	50 x 50	S3/S7	50 m	OBM	Prov Govt	45628
4	Argentina	Flat + Hilly	28 x 63	S3/S7	50 m	GCPs	Client	160
5	Tuzla, Boz	Rolling Hills	36 x 46	F1/F5	30 m	IFSARE	ERIM	1364
6	Cholame,	Hilly	6 x 19	S2/S7	50 m	IFSARE	ERIM	45628
7	Congo, Afr	Flat	50 x 50	F1/F5	50 m	GCPs	Client	7

Test	Project	Vertical			Northing		Easting	
#	Name	('RSAT - Truth')			('RSAT - Truth')		('RSAT - Truth')	
		Mean	1 s		Mean	1 s	Mean	1 s
1	Ottawa	41.1	13.5					
2	Ottawa				44.7	20.5	41.7	18.1
3	Ottawa	-12.9	16.1					
4	Argentina	-0.3	7.8		0.1	9.5	0.2	12.7
5	Tuzla, Boz	0.7	15.6					
6	Cholame,	-8.6	13.6					
7	Congo, Afr	26.5	13.2		15.3	26.7	-42.8	32.4

Table 2(a) and (b): Vertical and horizontal difference statistics for TOPOSAR DEMs and ORIs derived from RSAT stereo pairs. Table 2(a) provides test details, table 2(b) provides the corresponding results.

2.4 Implementation Experience

TOPOSAR-derived DEMs have been created on a commercial basis from RSAT stereo pairs since early 1997. In the eleven months since then, about a dozen commercial projects totalling almost 300,000kmsq have been completed. Individual projects ranged in size from a minimum of 500 kmsq (Heard Island in the South Indian Ocean) to a maximum size of 160,000 kmsq in Indonesia. Projects have been undertaken in SE Asia, South America, Africa, Japan and the USA.

In parallel with these commercial activities, several projects have been and are continuing to be undertaken for research or for marketing/demonstration purposes. This includes a project to better understand the effect of steep terrain slope on performance and on beam mode optimization.

In figure 2 we present an example of a DEM created of a remote region in Papua New Guinea. This visualization is in the form of a perspective view with the corresponding radar image draped upon it and is color-coded with respect to elevation using a standard IHS technique. The area shown is about 15km x 16km and the elevation rises from 250 meters to 1,400 meters. No ground control points were available for this DEM. It was, however, possible to assess the accuracies achieved, by creating the DEM twice, once from each of two independant stereo pairs obtained from opposite viewing directions (that is, from ascending and descending passes). Comparison of the resulting DEMs in the common valley areas implied accuracies similar to those reported in table 1.

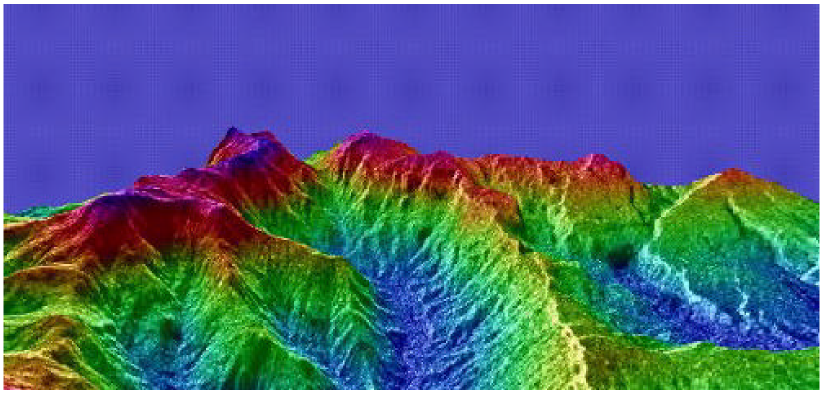
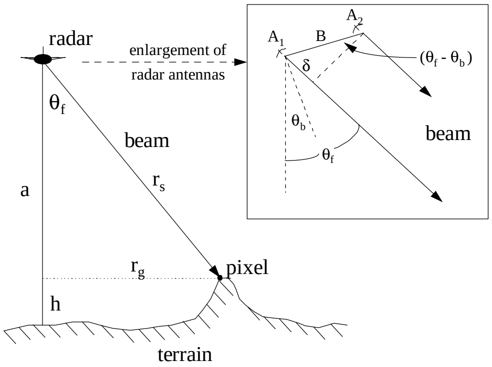


Figure 2: TOPOSAR-derived, image-draped perspective view of 15x16 km RSAT scene in Papua New Guinea. The scene is IHS color-coded with respect to elevation.

3. STAR3i - DEMs from IFSARE

3.1 Background

The interferometric process has been widely discussed in the literature, particularly for the case of repeat pass interferometry (e.g. Zebkor and Villsenor (1992), Goldstein (et. al., 1988). Some of the general issues associated with airborne interferometry have been discussed, for example, in Gray and Farris-Manning (1993).



Interferometric Airborne SAR Geometry

Figure 3: Schematic of Airborne IFSARE Geometry

The principle, depicted in Figure3, is based upon measurement of the phase difference between the backscattered wave fronts from a common target pixel, arriving at two spatially separated antennas. The phase difference is proportional to the path difference between these wave fronts. Calculating the path difference from the observed phase difference, and with knowledge of the antenna separation or basellin*e*, 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 “intergerogram”, 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 2π (modulo 2π), 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. The prime advantage of this configuration is that it is a single-pass system. Thus the target is viewed by both antennas simultaneously. (This is in contrast to the situation for repeat-pass interferometry for which scene and atmospheric changes between satellite passes can limit the practical application for DEM production over many of the geographical areas of interest).

Intermap Technologies, through agreements with ERIM and DARPA (Defense Advanced Projects Agency), have obtained exclusive rights to market and operate the IFSARE airborne SAR system developed by ERIM. The system has been re-named STAR-3*i.* The IFSARE system was described by Sos, et. al. (1994), and is briefly summarized from an operational point of view in the following paragraphs. The first commercial operations of STAR-3*i* commenced in December, 1996. In the ensuing 12 months of operation, commercial projects in the USA, Europe, Africa and SE Asia have been flown by Intermap , creating DEMs for a total area in excess of 250,000 kmsq.

3.2 System Specifications and Performance

The radar, an X-band, interferometric SAR, is carried in a LearJet 36 and is capable, under ideal circumstances, of imaging 30,000 km^2 in a single operational day. Positioning and motion compensation are achieved through use of a laser inertial reference platform and GPS which is differentially post-processed. Its normal operational mission mode would be performed at 40,000’ (12.2 km) ASL and in this mode would collect 2.5 meter pixels across a 10 km ground swath. The DEM created from the interferometric data is post-processed, and an ortho-rectified image (ORI) is simultaneously produced.

Because of its altitude capability, it is able to operate over mountainous terrain. The intermediate viewing geometry (approximately 45^{o}) reduces the problems of layover, although not eliminating it in steep mountain regimes. Because of the 400 knot cruising speed, and 5 hour flying range, the LearJet can be rapidly deployed world-wide, subject mainly to local permit issuing schedules.

Processing is currently performed on a local network of Ultra SPARC II workstations with rather large amounts of disk and memory. Work currently under-way will result in a new processor which will enable field processing and quasi-real time throughput performance. The main system parameters are summarised in table 3. The specifications are presented with respect to two limiting operating altitudes (with respect to ground level). At lower altitudes, the signal-to-noise ratio is larger and thus the height noise is lower (Zebker and Villasenor, 1992) thereby improving relative accuracy; however, swath width is reduced.

Parameter	**Operating Altitude**	
	40,000ft	**20,000ft**
Operational Speed	750 km/hr	750 km/hr
Depression Angles (nom.)	35 - 55 deg.	35 - 55 deg.
Swath Width (ground plane)	10 km	5 km
Nominal Resolution	3 m	3 m
Pixel Spacing	2.5 m	2.5 m
DEM Sample Spacing	2.5, 5, 10 m	2.5, 5, 10 m
DEM Vertical Accuracy		
Absolute*	3.0 m	1.5 m
Relative	< 2m	< 1 m
DEM Horizontal Accuracy**	3 m	3 m
Collection Rates***		
Maximum (kmsq/hr)	7,500	3,750
Typical (kmsq/hr)	2,000	1,000

* GPS base station within 200km

** Based on the accuracy of the accompanying ORI

*** Typical rates account for line lengths, turns, overlap, etc

Table 3: Summary of STAR3i System Specifications

3.3 Test Results

Two major independent test analyses were performed on data sets collected by STAR3i (called IFSARE at that time) in the Chalome Hills and Camp Roberts areas of California and reported in Carlisle, 1996 and Norvelle, 1996 as part of the DARPA-sponsored GEOSAR project. Radar DEMs for the two areas, each about 10 km x 16 km in size, were compared against truth in the form of air-photo derived DEMs of specified 0.5 meter (1σ) vertical accuracy and 5 meter postings. The results reported in the two analyses and with respect to the two areas were similar: the difference between the STAR3i DEM and the 'truth' DEM was about 1.5 meters (1σ) with respect to a mean offset or bias of about 1.5 meters. This offset can be removed by GCPs if available. Although this was flown under test conditions, operational experience with the system confirms this level of performance. The platform for these tests was flown at an altitude of about 40,000 ft. In separate tests flown at 20,000ft, the relative uncertainty has been observed to be at the sub-meter (1σ) level owing to improved signal-to-noise ratio and other factors.

It should be remarked that these results are were achieved in areas devoid of vegetation (vegetated areas were masked out in the analyses, about 6% of the total). Where vegetation exists, the resulting DEM will represent a volume scattering region within the vegetation layer. It should also be noted that in mountainous areas with extreme terrain shadow or layover may occur. In such areas, no data exist, and the resulting DEM may be interpolated from surrounding regions.

An example of a STAR3i DEM created in the Freiburg area of Germany is presented in figure 4.

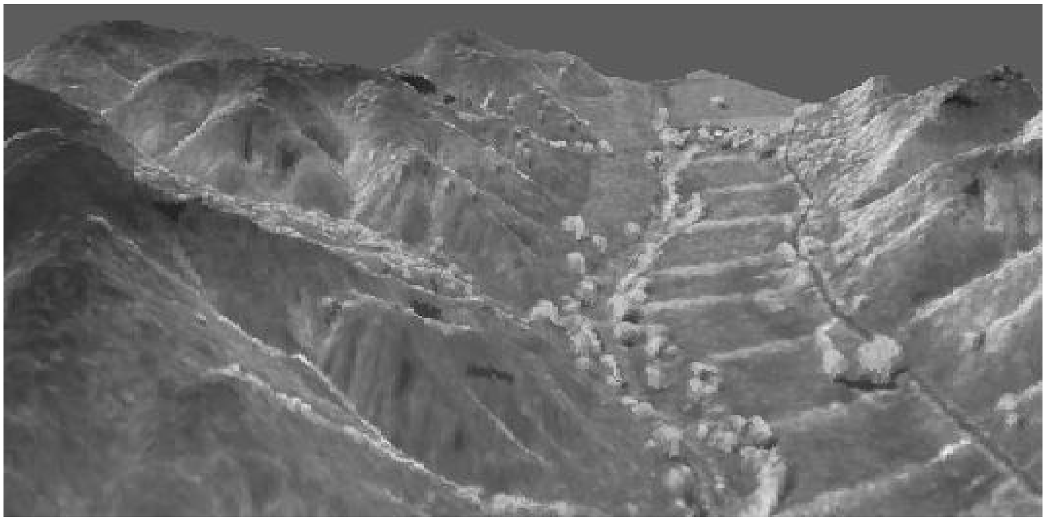


Figure 4: STAR3i-derived, image-draped perspective view of area of Chalome Hills in California. Original color-coded with respect to elevation. Terraced relief with individual trees noted on right-hand side.

4. Price Issues

In general, prices for mapping products, including DEMs, reflect the degree of detail they incorporate. In the case of DEMs, this is illustrated in figure 5, by plotting the approximate unit price (US$/kmsq) to the user, as a function of vertical accuracy (1σ) for a number of technologies, both satellite-based and airborne. The price shown includes the cost of data and processing. Several points may be noted from this graph:

1. DEMs created from RSAT are competitive in detail and in price with those derived from SPOT. The virtue of the RSAT-derived DEMs emerges in cloud-covered areas because of the cloud-penetration capability of radar.

2. In the 1-3 meter accuracy range, STAR3i -derived DEMs are very cost competitive with photogrammetrically-derived DEMs not only in the cloud-covered areas of the tropics but in other regions as well.

3. Laser-scanning systems are becoming a competitive threat to photogrametrically-derived DEMs in the sub-meter domain.

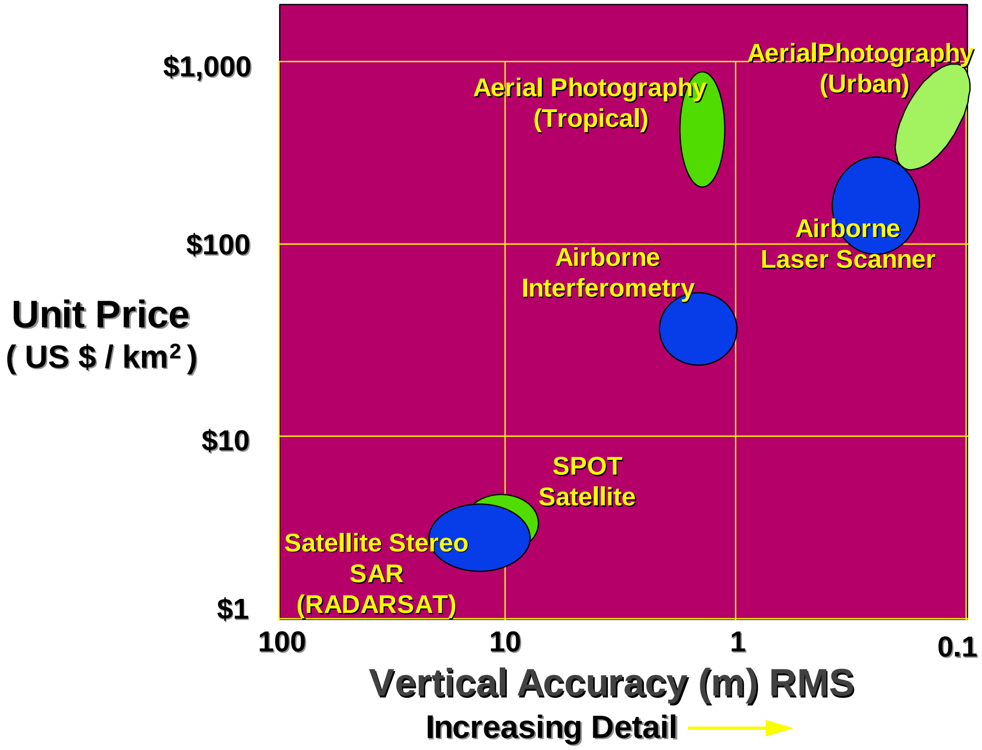


Figure 5: DEM unit price as a function of vertical accuracy.

It is likely, however, that this illustrative graph will change substantially in the near future due to the impact of various factors, both technological and market-related. For example, soft-copy photogrammetry throughput, along with changes in the approach for acquiring ground control will likely reduce cost of DEM production from air-photos substantially as supporting technologies continue to improve. At the same time, the concept of data warehousing provides a means of expanding the user market which will permit costs to be reduced owing to multiple licensing expectations.

Intermap has commenced its 'Global Terrain' marketing strategy in order to create a data-base of DEMs from the STAR3i and TOPOSAR processes decribed in this paper. The Global Terrain data-base will be created over a 2-4 year period starting with areas that have a high user interest. It is expected that the resulting unit prices will be significantly reduced from those depicted in figure 5 owing to the multiple licensing aspect mentioned above as well as the improvement in operational efficiency that can be achieved. The first DEMs provided in this manner will be made available in the spring of 1998.

5. Conclusions

Two new, commercially operational technologies for creation of DEMs and ORIs from radar have been described. They allow rapid acquisition over most of the world of the information needed for spatial data bases at the mapping scales of 1:10,000 to 1:100,000. Tests have demonstrated DEM accuracies (at the 1σ confidence level) of less than 2m for the STAR-3*i* interferometric airborne SAR (5 meter postings) and 10-15 meters (in moderate terrain) for RADARSAT stereo pairs processed by TOPOSAR. These complementary technologies allow cost / accuracy tradeoffs for large area topographic mapping projects. Level of detail and cost differ by roughly a factor of ten between the two solutions. Both are being currently offered commercially as services by Intermap.

‘Global Terrain’, an international DEM data-base, is currently being created using these radar technologies and, with initial availability in early 1998, is expected to create much wider access at significantly reduced cost than is currently possible.

Acknowledgments

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