COMPARISON OF DEMS FROM STAR-3i INTERFEROMETRIC SAR AND SCANNING LASER

J. Bryan Mercer and Steven Schnick
Intermap Technologies Corp.
Calgary, Alberta, Canada

Tel: (403) 266-0900
Fax: (403) 265-0499
e-mail: bmercer@intermap.ca

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ABSTRACT

Within the past few years there has been a significant increase in the use of Digital Elevation Models (DEMs), for applications as varied as telecommunications and precision agriculture, forestry and flood-risk assessment. Additionally, one may expect that externally-supplied DEMs will be used increasingly for ortho-rectification of high-resolution satellite imagery as it becomes available.

There are now available several technologies from which DEMs may be created, with varying degrees of detail, accuracy, associated cost and availability. In both North America and Europe, government agencies have traditionally provided mapping products, including derived DEMs, to the public. However, the applications noted above are expected to require increasing detail beyond what these government sources currently provide. Three technologies that are currently creating DEMs at increased levels of detail include (1) soft-copy photogrammetry using stereo air-photo, (2) scanning airborne laser or lidar and (3) interferometric airborne radar.

In this paper we examine the capabilities and deficiencies of two of these DEM sources – airborne laser scanning systems and interferometric airborne radar. STAR-3i is an airborne interferometric SAR system carried in a Lear jet and operated by Intermap Technologies Corporation. In the past two and a half years of commercial operation, DEMs have been acquired for several hundred thousand km^2 on several continents. At the same time, several companies have been creating DEMs over smaller areas using airborne laser scanning systems, and comparative data sets are now becoming available.

In this paper, the comparative DEM performance of these two technologies will be demonstrated with respect to three application areas of interest: (i) bald-earth performance for flood-plain risk analysis, (ii) building height extraction in urban areas, and (iii) forested and agricultural areas with respect to vegetation issues. In these examples, the laser-derived DEMs are treated as truth at the 15 cm (1 sigma) level. The radar-derived DEMs, created on a 5 meter grid, are shown to exhibit a 'noise floor' at the 35 cm (1 sigma) level for typical operational altitudes in non-urban bald-earth environments. While the performance is not as strong as that of the laser systems, there are obvious cost and schedule advantages where large area coverage is required. These will be addressed. It is concluded that the technologies tend to provide complementary rather than competitive solutions for many applications.

1. INTRODUCTION

Digital Elevation Models (DEMs) are being used increasingly at a variety of mapping scales, and for a range of applications. The DEM price, irrespective of technology, tends to vary with the level of detail sought – that is, with the desired mapping scale. The introduction of DEMs created from active airborne sensors (specifically interferometric radar on the one hand, and scanning laser or lidar on the other) has, in recent years, expanded the circumstances under which DEMs can be collected.

Radar is able to gather data rapidly over large areas in day/night, cloud-covered conditions. This factor positively impacts both the timeliness and the price of DEMs. Interferometric radar (IFSAR) has received much attention recently because of its potential to improve the level of detail achievable in radar-derived DEMs. Since early 1997, about 750,000 km^2 of DEMs have been acquired over several continents by the new STAR-3i system, an airborne interferometric SAR (Synthetic Aperture Radar), owned and commercially operated by Intermap Technologies. With data collected and presented at sample spacings down to 2.5 meters and with vertical accuracies at the meter to sub-meter level, this presents users with the possibility of obtaining wide area DEM coverage at levels of detail and consistency not previously available in general. On the other hand, the STAR-3i system is an X-band radar and the DEM derived from it references the scattering surface or volume with which the radar beam interacts. This means that scattering objects such as trees or buildings will contribute to the radar-derived DEM. This problem is similar to that of optically-derived DEMs, but of course the radar has its own particularities.

Airborne scanning laser systems are being operated widely with about 35 systems in operation at this time (M. Flood, 1999). Vertical accuracies in the range of 15 to 30 cm (RMSE) are being generally claimed, with data samples ranging from one to five meter spacing.

Because of their high pulse rate (1 to 80 kHz depending on the particular system and operational mode) and relatively small footprint (system- and operation-dependant but typically about 20 cm diameter) these systems are generally successful at penetrating foliage. In particular, they are able to penetrate to ground level with sufficient regularity (at least in leaf-off conditions) to provide 'bald-earth' DEMs beneath forest canopy (Reiter, et al., 1999) with respectable, albeit somewhat de-graded accuracies compared to their bare ground performance. These systems also demonstrate advantages in dense urban core areas for acquiring building and ground elevations because of their relatively vertical geometry (in contrast to the side-looking radar geometry) so that loss of data due to building shadows (occlusions) is less onerous. The two prime disadvantages of laser from a user's point-of-view are (1) cost (see Figure 2 below) and (2) delivery. These issues make the use of laser problematic over large areas.

In this paper we present three examples demonstrating the relative performance of STAR-3i DEMs with respect to three laser systems in three different locations. In this instance, the laser data are being used as comparative 'truth'. However, the argument is presented that by using the systems in a complementary or synergistic fashion, the advantages of both may be exploited and their respective disadvantages muted.

In Section 2, we provide a very brief introduction to the interferometric radar process in deference to the mostly laser-oriented audience at this workshop. The assumption is made that symmetry need not be preserved, as the workshop audience is very knowledgeable regarding the principles of scanning lasers. Section 3 provides a brief operational history of the STAR-3i system and is followed by an overview of the comparative performance parameters and cost relationships in Sections 4 and 5. The three application examples are presented in Section 6 and discussion and conclusions appear in Section 7.

Throughout this paper we use the term DEM to reference the scattering surface whether it be bare-earth, canopy or structures. To differentiate, we refer to the 'bald-earth DEM' as being that surface or DEM from which heights associated with trees, forests, crops and other objects such as buildings have been removed.

2. INTERFEROMETRY BACKGROUND

The interferometric process has been widely discussed in the literature, particularly for the case of repeat pass interferometry (e.g., Zebker and Villasenor, 1992 and Goldstein, et al., 1988). Some of the general issues associated with airborne interferometry have been discussed, for example, in Gray and Farris-Manning (1993). The geometry relevant to height extraction, 'h', is illustrated in Figure 1.

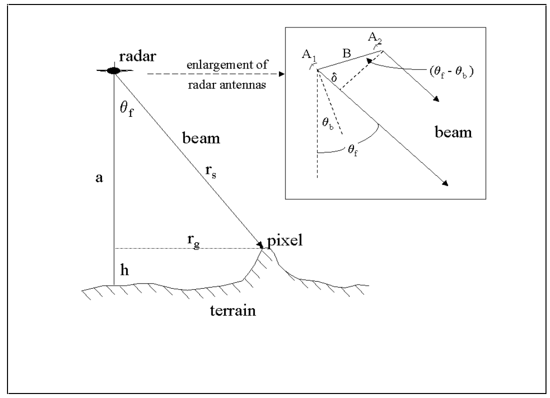

Figure 1: Schematic of Airborne Interferometric SAR Geometry

If the two antennas, separated by baseline 'B', receive the back-scattered signal from the same ground pixel, there will be a path-difference 'δ' between the two wavefronts. The baseline angle 'θ_b' is obtainable from the aircraft inertial system, the aircraft height is known from DGPS and the distance from antenna to pixel is the radar slant range. It is simple trigonometry to compute the target height 'h' in terms of these quantities. The path-difference is measured indirectly from the phase difference between the received wavefronts. 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 a coarse ground elevation estimate and a "phase unwrapping" technique (e.g. Goldstein, et al., 1988). Thus, the extraction of elevation is performed on the "unwrapped" phase.

3. SYSTEM HISTORY, SPECIFICATIONS AND PERFORMANCE

Intermap Technologies has been operating the STAR-3i system commercially since January, 1997. The system was developed by ERIM under contract to DARPA (Defense Advanced Research Projects) and was referred to as IFSARE at that time. The IFSARE system was described by Sos, et al. (1994), and is briefly summarized from an operational point of view in the following paragraphs.

STAR-3i, 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 closely coupled with differentially post-processed GPS. One of its operational mission modes would be performed at 40,000 ft (12.2 km) ASL and in this mode it would collect 2.5 m^2 pixels across a 10 km ground swath. At lower altitudes, the signal-to-noise ratio is larger and thus the height noise decreases (Zebker and Villasenor, 1992) thereby improving relative accuracy; however, swath width is reduced. The DEM created from the interferometric data is post-processed, and an ortho-rectified image (ORI) is simultaneously produced. A correlation image, which reflects the degree of complex correlation between the two antennas, is also created and is used for quality masking purposes as well as in research applications. Most of the operational acquisition is currently done at altitudes of 20,000 ft to 25,000 ft.

Processing is currently performed on a local network of Ultra SPARC II workstations which in the absence of unusual circumstances is able to keep up with the acquisition. Work currently under-way will result in a new processor which will enable field processing and quasi-real time throughput performance.

Numerous tests have been performed of DEM accuracy under various terrain and operating conditions both internally and by independent external organizations. The external tests are summarized on the website http://www.intermap.ca.

4. COMPARATIVE SYSTEM SPECIFICATIONS OF SELECTED PARAMETERS

In Table 1, we show the comparative specifications (selected) of the three laser systems from which the data sets described in Section 6 were acquired. The purpose of this table is to illustrate the major differences among the laser systems with respect to the STAR-3i radar in a standard operational mode. It should be noted that the parameters associated with the laser systems are those believed to be appropriate to the particular data acquisitions described in this paper. A wider choice of operating parameters is of course utilized under different circumstances by the operators, although these may be typical. The data for the lasers was obtained either from their literature or personal communication. The laser accuracies are those claimed by the operators. The radar accuracies relate to the results of the external tests referenced in Section 3. It should be noted that the radar accuracies can be further improved by the simple operational expedient of flying lower; however this would be at the expense of swath width and would impact cost.

The major differences noted between laser and radar relate ultimately to the vertical accuracies and to the acquisition rates. The latter translates into price performance as noted in Section 5.

5. COMPARATIVE DEM PRICES

From the foregoing discussions and comparative performance table, it is clear that laser-derived DEMs offer vertical accuracy performance advantages with respect to the STAR-3i radar system as it is currently operated. On the other hand, the acquisition rate advantage enjoyed by STAR-3i translates into a price advantage which is exemplified in Figure 2.

Typical Operating Parameters
STAR-3i vs. Laser Systems

Parameter	Units	STAR-3i Radar	Earthdata Laser	EagleScan Laser	Topscan Laser
Operational Altitude (this project)	feet	20,000	5,000	6,000	1,000 (est)
Operational Speed	km/hr	750	~200	~200 (est)	~200 (est)
PRF	pulses/sec	1,200	15,000	4,000	2,000
Incidence Angles (this project)	degrees	30 to 55	-20 to +20	-9 to +9	-20 to +20
Swath Width (ground plane)	meters	~8,000	1,100	600	720 (max)
DEM Sample Spacing	meters	2.5, 5 m	4 m	3 - 5 m	4 - 6 m
DEM Vertical Accuracy					
Absolute (RMSE)	m or cm	~1.5 m(5)	~10 cm	~15 cm	~15 cm
Relative (1 σ)	m or cm	< 1.0 m	?	~10 cm	?
DEM Horizontal Accuracy	meters	< 2.5 m	0.5 m	~1 m	~1 m
Collection Rates					
Maximum (km^2/hr)	km^2/hr	6,000	220	130	145
Typical (km^2/hr)	km^2/hr	1,000	?	?	?
Ortho-Rectified Image		Yes	No	Yes	No
Pixel Size	meters	2.5	-	0.30	-
Sensor Source		ERIM	Azimuth	Custom	Optech

Notes:
1 Laser operating parameters may differ for other projects.
2 Laser accuracies as published or quoted by operators and presumably under benign terrain and operating conditions.
3 STAR-3i accuracies as obtained in various published test results and references bald earth, moderate terrain conditions.
4 STAR-3i results assume GPS base station within 200km. Laser results require base station within 20 km.
5 STAR-3i absolute accuracies assume absence of GCPs. With GCPs, absolute accuracy similar to relative accuracy (sub-meter).
6 Typical STAR-3i acquisition rates account for line lengths, turns, overlap, etc.

Table 1: Comparison of typical operating parameters and associated performance specifications for STAR-3i and three commercial laser systems

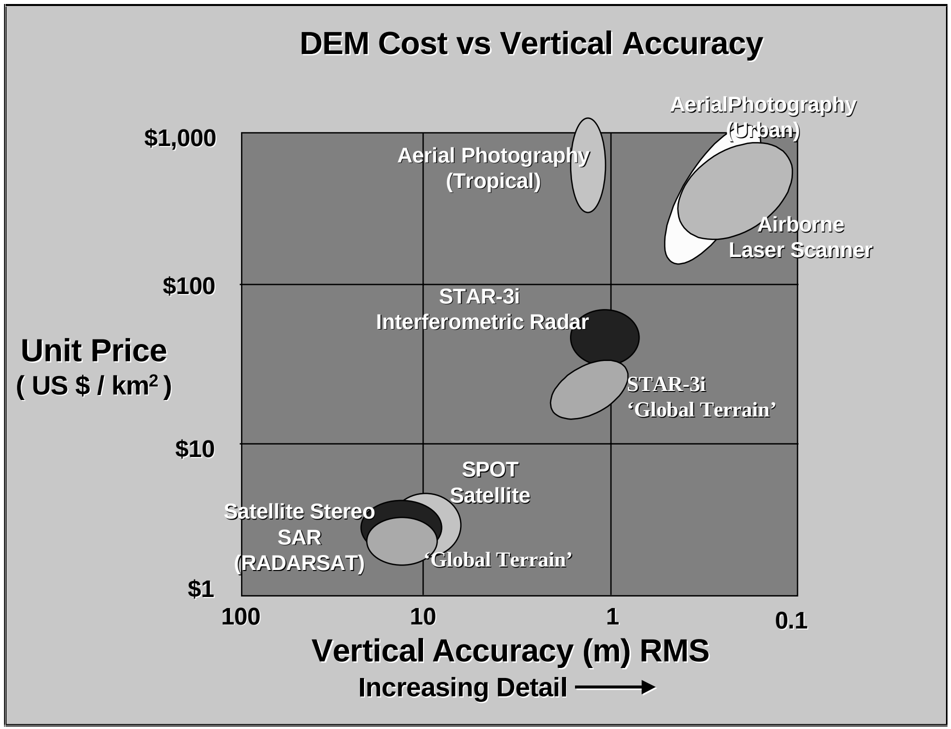

Figure 2: Relative Unit Costs for various DEM extraction methods

This table illustrates the relationship between cost to the user and the spatial 'detail' provided by the particular technology. In this instance, vertical accuracy is used as the metric for detail although more correctly, one should use a three-dimensional metric that incorporates sample spacing or posting as well as vertical accuracy. Also shown for comparative purposes are DEM prices derived from a number of other sensors, including: (i) Radarsat and SPOT stereo at a lower level of accuracy but lower price and (ii) aerial photography which is competitive with laser-derived DEMs. Unit prices reflect many factors including size, complexity, location and other project specifics, so this table is rather general. However, the trend shows that interferometric SAR provides a price advantage of 3 to 10 times that of laser-derived DEMs on a price per unit area basis. This table does not address minimum project areas or mobilization charges which tend to be related to geographic location specifics. Moreover, it reflects current pricing structure which is likely to change over time.

The 'Global Terrain' prices are noted to be lower than project-specific prices, reflecting a 'data warehouse' approach that was initiated two years ago by Intermap. The concept, similar to that widely practiced for satellite imagery, is to license DEM data to the user, hopefully to re-sell multiple times. While this reduces the price for the user, its utility is subject to there being data available in the database for the particular user area of interest.

6. EXAMPLES

6.1 Red-River, North Dakota

The project area was near the Pembina river, a tributary of the Red River which has a history of flooding in the US and Canadian portions of the flood plain. An area of about 4,000 km^2 was acquired by the STAR-3i system on or about November 3, 1998. Within this larger area, a subset of laser data were acquired by EarthData on October 27, 1998 and made available to Intermap for analysis. Both data sets were referenced to WGS-84 horizontally and the NAVD88 geoid vertically. The STAR-3i data were posted at 5 meters while the laser data were received as 3 meter ArcGrid files. The vegetation had been removed from the laser DEM by EarthData, so the data received was in the form of a bald earth DEM. All data (in this and the following examples) were analyzed using a commercial software package (Vertical Mapper from Northwood Geosciences, Ottawa) which is very convenient for doing comparative analysis. The particular area subset for this example is centered on (N 48° 58' 25", W 97° 27' 53"). An overview of the laser DEM (Figure 3) shows the overlapping area, the flight lines and the window within which the following figures are located.

The sub-areas of Figure 4, Figure 5 and Figure 6 are co-registered and have identical color table representations. They depict, respectively, the laser DEM, the radar DEM and the difference surface (radar minus laser) on a 3 meter grid.

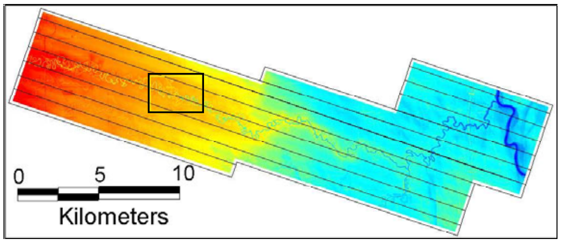

Figure 3: Laser coverage area. Box outlines specific study area

The laser DEM has had the vegetation removed while the radar has not. Therefore, the difference surface includes the vegetation which consists mainly of trees. The light brown colored areas are depicting maximum terrain excursions of about 2 meters. All vegetation, irrespective of height, is shown in green.

Three rectangles show areas where local statistics were derived (refer to Table 2). Boxes A and C are in bald-earth areas. The mean and standard deviation of the individual DEMs describe the characteristics of the surface with noise and offsets superposed while that of the difference surface represents just the combined noise and offset differences inherent to the sources. If the majority of the noise is assumed to originate with the radar, then the standard deviation of the difference surface represents a 'noise floor' of about 30 cm for STAR-3i under these operating conditions.

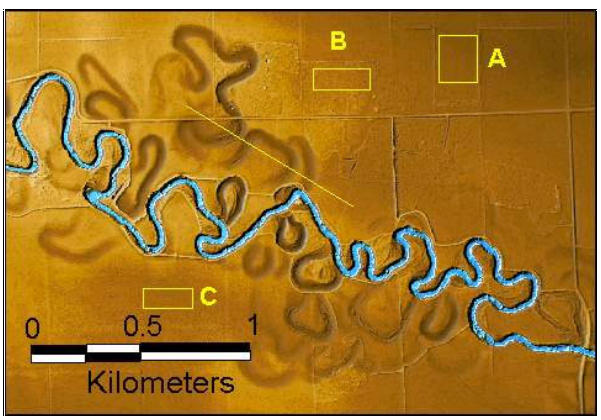

Figure 4: Laser DEM (vegetation removed) – see text. Note boxes A, B, C for statistics samples

Independently of this analysis, more than a thousand check points were measured using DGPS along roads in the larger area (more than 500 in the overlapping 200 km^2 laser area) and provided to Intermap by TEC (the US Army Topographical Engineering Center). The mean difference (STAR-3i minus checkpoints) was about 10 cm over the laser overlap area with a standard deviation of 69 cm. This larger variation represents the addition of wider-area systematic errors superimposed upon the STAR-3i noise floor.

It should be noted that the EarthData laser, at this time, was subject to a processing problem that caused a systematic ripple and offset error to appear in the DEM.

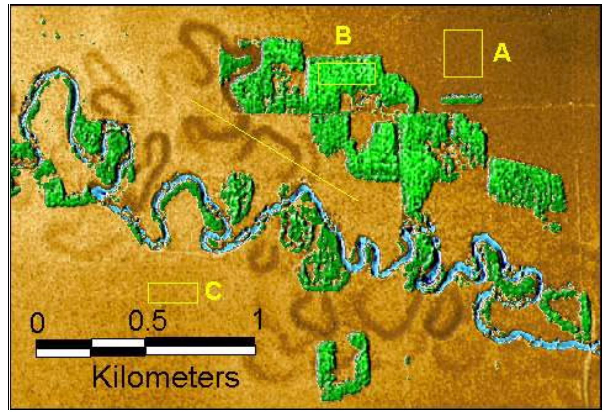

Figure 5: Radar DEM – all elevations greater than three meters above mean are colored green and represent vegetation

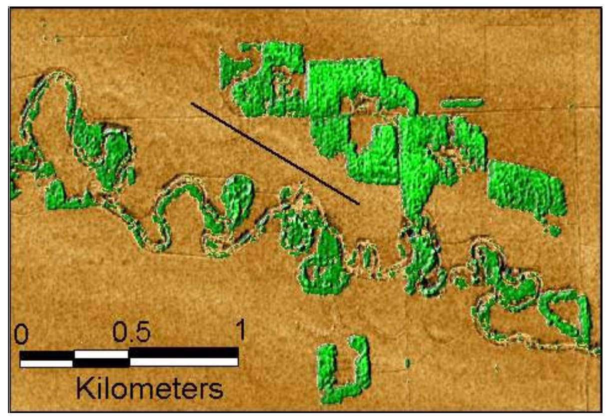

Figure 6: Difference Surface (Radar minus Laser)

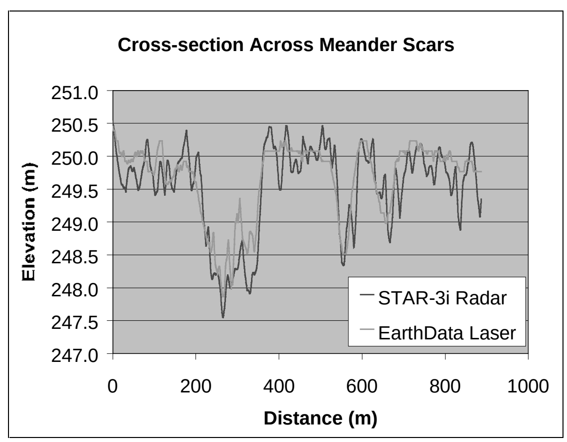

Figure 7: Elevation profile of radar and laser across meander scar features – see text.

This is responsible for the mean differences observed in the two boxes and for the appearance of the color ripple aligned with the laser flight lines in Figure 6. The problem is apparently understood and currently being corrected (EarthData, Private Communication).

The statistics for Box B are descriptive of the local canopy. The mean difference represents the mean scattering level perceived by the radar – in this case 12.8 meters – and the standard deviation reflects the variability of this level which is 1.7 meters in this instance. These statistics, of course, are dependant on canopy and radar viewing geometry and suggest interesting topics for study, not to be pursued here.

STAR-3i and EarthData Laser				
Data Set		Mean (m)	Std Dev (m)
A Bare	STAR-3i Radar	248.1	0.29
	EarthData Laser	247.4	0.29
	Difference	0.7	0.33
B Forest	STAR-3i Radar	261.8	1.79
	EarthData Laser	249.0	0.15
	Difference	12.8	1.71
C Bare	STAR-3i Radar	249.6	0.27
	EarthData Laser	248.7	0.09
	Difference	0.9	0.27

Table 2: DEM and difference surface statistics for three regions of the Red River data set

It is interesting to compare a cross-section across the two DEMs as presented in Figure 7. Because of the previously noted offset of the laser data, the latter has been incremented by +1.0 meter to facilitate comparison. The radar data are somewhat noisier than the laser data, as expected, but the profiles track quite well with some small but real differences presumably caused by small bushes in the dry river channel (meander scar) which are observed in the radar but not in the laser bald earth DEM.

6.2 Baden-Wurttemberg, Germany

The second example is for an area of mixed forest and agriculture in Germany. Unlike the previous flood plain example, the terrain consists of rolling hills and valleys. The radar data were collected of the whole state of Baden-Wurttemberg by the STAR-3i system in July, 1998. During this period, the vegetation was in full leaf and crops were well developed so the radar DEM would, of course, reflect the crops and forests as well as buildings and other objects. The state mapping agency (the LVA, or Landesvermessungsamt), had acquired laser data for a sub-region of dimensions (10 km x 15 km) about 80 km NNW of Stuttgart. The data were acquired by Topscan in January, 1996 during leaf-off conditions. The residual vegetation and other objects had been removed by Topscan to create a bald-earth DEM.

The LVA kindly provided the laser data to Intermap for test purposes. In return, the radar data were provided to Karlsruhe University (Dr. Manfred Sties) for reciprocal analysis on behalf of the LVA. Because the laser data were referenced to a local datum and geoid, while the STAR-3i data were referenced to the WGS-84 ellipsoid (horizontally and vertically), it was necessary for each party to transform the other's data into the preferred reference system. This was done using common transformation parameters provided by the University of Karlsruhe. The independent analyses will be jointly published in a forthcoming article. In this paper, we present only a small subset of the results obtained by Intermap in order to illustrate the theme of the paper.

The area presented here includes a strip about 0.8 km x 2.5 km in Northing and Easting respectively. The colorized DEMs from the laser and radar are shown in Figure 8 and Figure 9 respectively, while the difference surface is presented in Figure 11. The ortho-rectified image (ORI) from the radar is displayed in Figure 10.

The terrain heights range from about 257 meters in the valley (blue) to about 303 meters on the highest ridge (red). As noted earlier, the laser DEM represents a bald-earth surface while the radar DEM includes the trees, crops and other objects above the ground. An interesting feature on the lower left side is a deep gravel quarry. Areas depicted in white are due to under-sampling – that is, the absence of data within the 15 meter threshold placed on the surface interpolator. The difference surface shows the forest (and some buildings) in green, while the bald earth and low crops (< 2 meters) are in shades of cream and brown.

The field conditions are quite evident in the ORI of Figure 10. Forest and crop patterns as well as a village (lower right) are evident. Some of these characteristics are also evident in the difference surface of Figure 11. In particular, the forest, buildings, and some crop types are manifested by their height. It should be noted that the ORI is a measurement of radar back-scatter and hence of roughness. Therefore, some low crops (e.g., cabbage) will appear rough and relatively bright in the ORI but will not appear in the difference surface. On the other hand, crops such as corn appear in both.

Difference Surface Statistics STAR-3i minus Laser			
Data Set		Mean (m)	Std Dev (m)
A	Bald Earth	-0.47	0.28
B	Crops	0.66	0.34
C	Forest	21.04	2.16

Table 3: DEM and difference surface statistics for three regions of the Baden-Wurttemberg data set

Three polygons reference different surface conditions to be sampled statistically. Polygon 'A' is interpreted as bare-earth, 'B' is a crop (type unknown), and 'C' is forest. Mean and standard deviation for the difference surface is provided for each of them in Table 3.

The areas sampled are relatively small (~100m x 100m) and the resulting standard deviation for the bald earth area is about 28 cm, similar to that described as the 'noise floor' for the Red River example (and constant with more extensive sampling in this project area). The variability is slightly larger in area 'B', as would be expected in a crop covered region. The crop sample is about 1.1 meters higher than the bald-earth, and probably represents a scattering level lower than the visible surface. Sampling of bald-earth areas over the whole test area incorporates systematic errors of about 50 cm into

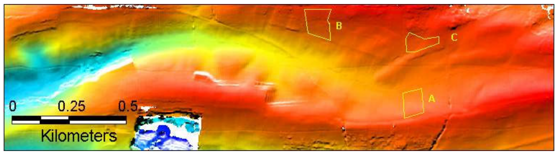

Figure 8: Laser DEM

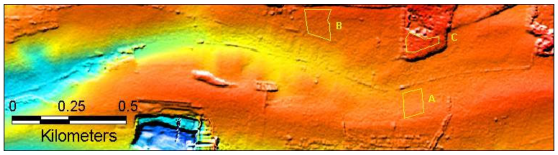

Figure 9: Radar DEM

Figure 10: Radar Magnitude Image (ORI)

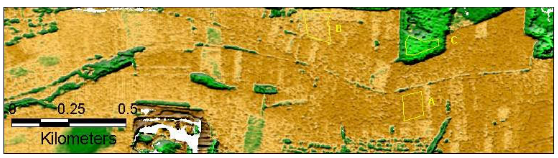

Figure 11: Difference Surface (Radar minus Laser)

the radar DEMs upon which the 30 cm noise floor is superposed. These systematic variations can be removed with control.

The other note of interest is the forested area which shows an effective mean height of 21 meters and a variability of about 2 meters. This is a reflection of the relative uniformity of the forest sample.

6.3 Denver, Colorado, USA

The third example is with respect to the extraction of building heights in a non-core area of a large urban center. Modeling of urban areas usually concentrates on the urban core areas although these may represent only a small percentage of the total urban area of interest. Because of the narrow canyons in the core areas, characterized by very densely-packed, high-rise structures, the modeling of buildings can most successfully be accomplished by use of sensors with near-vertical viewing geometry such as laser or photo. However, urban areas often are very extensive (hundreds to thousands of km^2), typically with small core areas surrounded by mixtures of residential, industrial and recreation areas, suburban developments, etc.

For many applications, it may be more cost- and schedule-effective to use radar-derived DEMs. However, one of the questions is the capability of radar to determine the heights of tall structures, such as apartment buildings, that exist in isolation or clusters outside the core areas. There are a number of radar-related issues associated with the radar response to high buildings, including shadowing, layover and other factors (Mercer and Gill, 1998, Gamba and Houshmand, 1999). As a result, there is usually a significant loss of data in front of and behind (as defined by the radar viewing direction) tall buildings. This makes the detection of building heights problematic and motivates the work summarized here.

The area chosen for analysis is Leetsdale in Denver, Colorado. A laser DEM was acquired from Eaglescan of a 1 square mile (2.5 km^2) area which was created in 1996. The data set received had been edited to remove vegetation, vehicles and other non-stationary objects. However, buildings remained in the laser data set, permitting comparison with radar response. Digital Ortho-Images produced by ImageScans, Denver, were also available and very useful despite the earlier acquisition date (1993). Preliminary results from a single data set were published in Mercer and Gill (1998). More recently, a series of acquisitions from similar and orthogonal viewing directions enabled a more extensive investigation. Work is ongoing and will be published elsewhere, but we summarize here a set of interim results.

The study included a set of 17 high-rise buildings in Leetsdale as denoted in Figure 12. The buildings range in height from about 10 to 45 meters. The radar data summarized here include DEMs from four data sets denoted as m60 (1997), m130 (1998), m130 orthogonal, and m166 (1999). In the foregoing, 'm' refers to the mission number, and the bracketed date is the year of acquisition. Three of these sets had similar viewing directions (westward) while the fourth was orthogonal, viewing southward. Additionally, some of the data were re-processed with lower correlation threshold.

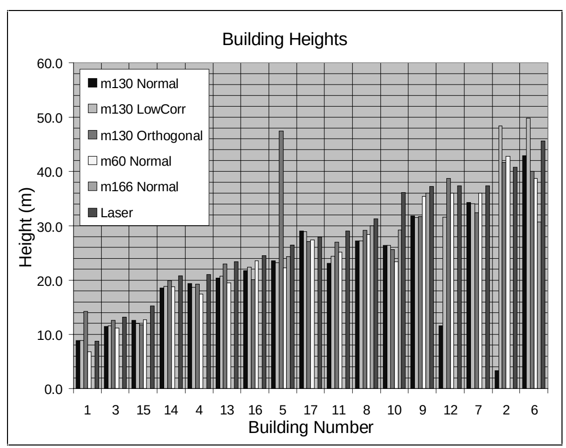

Figure 12: Bar Chart of Building Heights in Leetsdale Test Area

The maximum height was determined for each of the 17 buildings in the laser DEM and in each of the radar DEM data sets described above. The method was first to determine a region at the base of each building which appeared to be representative of the ground elevation. The ground elevation was then subtracted from the maximum elevation to determine the maximum height in each case.

In Figure 12, a bar chart shows the radar in terms of ascending building heights. All of the results are shown for each building, referenced to the laser height which is presumed to be 'truth'. Of the 17 buildings, 14 show quite good consistency with respect to the laser truth. Two of the buildings (#2 and #12) have anomalously low heights which are correctly recovered upon re-processing with reduced correlation threshold ('LowCorr'). At present, only one data set ('Orthogonal') for one building (#5) shows anomalous height without reason and is being investigated. Excepting these 'outliers', the associated regression graph (not shown here) indicates a typical 3 meter RMS variability among the radar-only heights; the radar-derived heights tend to be about 2 meters lower than the laser-derived heights again with a scatter of about 3 meters RMS. There is a trend (not yet confirmed) for the uncertainty to grow with height but to maintain a variability of about 10% of height.

7. CONCLUSIONS

In this paper we have presented the argument that laser- and radar-derived DEMs are complementary for a variety of applications. The major virtues of the laser systems are that they have finer vertical accuracy (15 to 30 cm RMS depending on conditions), they can penetrate tree canopies (particularly in leaf-off condition), and because of near vertical geometry, they can acquire information in dense urban cores. Comparatively, the major advantages of interferometric SAR (as demonstrated by STAR-3i) are price (3 to 10 times lower than laser) and delivery, enabling DEMs of large areas to be acquired with similar grid spacing but reduced vertical accuracy.

In support of the foregoing arguments, the performance of STAR-3i was demonstrated in two non-urban examples and one urban example:
(1) In the two non-urban areas, it was demonstrated that STAR-3i, in its standard operating mode, exhibits an elevation noise floor of about 30 cm (1σ) at similar sample spacing to the laser. Systematic errors in the STAR-3i DEMs, which manifest themselves over larger areas and are usually project-specific, can be removed to some level by the use of ground control. In the examples shown here, the systematic error component was at the 50 to 70 cm level, although in some projects it is higher.
(2) In the urban example, it was demonstrated that in non-core areas, building heights can be extracted using STAR-3i with an uncertainty of about 10% of the building height over a height range of 10 to 45 meters.

The implication is that laser should be used in areas where its unique characteristics are required and that radar can be effectively used over larger areas with reduced accuracy as a trade-off for significantly reduced cost and earlier delivery.

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REFERENCES

Flood, Martin (1999). Commercial Development of Airborne Laser Altimetry – A review of the Commercial Instrument Market and Its Projected Growth. Proceedings of the ISPRS Working Groups III/5 and III/2 Workshop, La Jolla, in press.

Gamba, P. and B. Houshmand, (1999). Integration of High Resolution Imagery With LIDAR and IFSAR Data for Urban Analysis Application. Proceedings of the ISPRS Working Groups III/5 and III/2 Workshop, La Jolla, in press.

Goldstein, R.M., H.A. Zebker, and C. Werner, (1988). Satellite Radar Interferometry: two dimensional phase unwrapping. Radio Sci. Vol. 23: Number 4, pp 713-720.

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.

Mercer, J. Bryan. and Michael Gill, (1998). Radar-Derived DEMs for Urban Areas: Proceedings of the ISPRS Commission II Symposium, Cambridge, Vol 32, Part 2, pp210 – 216.

Reiter, T., O. Eckmullner, and W. Rieger (1999). Laser-Scanning for Derivation of Forest Stand Parameters. Proceedings of the ISPRS Working Groups III/5 and III/2 Workshop, La Jolla, in press.

Sos, G. Tim, Herbert W. Klimach and Gray F. Adams, (1994). High Performance Interferometric SAR Description and Capabilities. Tenth ERIM Thematic Conference on Geologic Remote Sensing, San Antonio, Texas, Vol. II, pp. 637-649.

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.