INTEGRATION OF LIDAR AND IFSAR FOR MAPPING

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ABSTRACT

LiDAR and IfSAR data is now widely used for a number of applications, particularly those needing a digital elevation model. The data is often complementary to other data such as aerial imagery and high resolution satellite data. This paper will review the current data sources and the products and then look at the ways in which the data can be integrated for particular applications. The main platforms for LiDAR are either helicopter or fixed wing aircraft, often operating at low altitudes, a digital camera is frequently included on the platform, there is an interest in using other sensors such as 3 line cameras of hyperspectral scanners. IfSAR is used from satellite platforms, or from aircraft, the latter are more compatible with LiDAR for integration. The paper will examine the advantages and disadvantages of LiDAR and IfSAR for DEM generation and discuss the issues which still need to be dealt with. Examples of applications will be given and particularly those involving the integration of different types of data. Examples will be given from various sources and future trends examined.

INTRODUCTION

Geospatial databases are becoming increasingly important in many areas. There is an increasing demand for National Mapping Agencies to provide geospatial data – to be used by utility companies, environmental agencies, transport agencies and industry such as telecoms. At the same time mapping organisations are looking to use new technology to satisfy these requirements. Two of these important new sources are LiDAR and IfSAR, acquired from airborne and spaceborne platforms. Data from these sensors has been applied to a number of novel applications such as mapping flood plains, powerlines and transport infrastructure. This paper sets out to define the role of photogrammetry and remote sensing in this, and. in particular, the role of IfSAR and LIDAR.

The paper will first set out the characteristics of the sensors and the data, and the products being generated. It will then deal with airborne data collection also look at the data producers and discuss some of the open questions relating to the use of LiDAR and IfSAR. Some characteristics and aspects of spaceborne IfSAR will be considered. Finally the paper will look at how the technology and applications are progressing.

2. THE CHARACTERISTICS OF LiDAR AND IfSAR

2.1 LiDAR

The principles of LiDAR are well known. These have been described by Baltsavias (1999b). To summarise: range is measured from a platform with a position and attitude determined from GPS/INS using a scanning device which determines the distance from the sensor to the ground of a series of points roughly perpendicular to the direction of flight. Figure 1 shows schematically a laser scanner and its main components. As a result, the raw airborne LiDAR data is collected in the GPS reference system WGS 84.

The wavelength in which most lasers operate is in the range of 1040-1060 nm. (Baltsavias, 1999a) Airborne laser scanners can record up to 5 different returns (multiple returns). If a laser pulse or a part of the pulse is reflected from a roof top or the top of a tree, the sensor will record the first return. However, a part of the pulse might partly penetrate the tree canopy and/or travel through and reach the ground as it can be seen in figure 1. In that case, the sensor will also record intermediate returns when the pulse hits various parts of the canopy and the last return, the return from the ground.

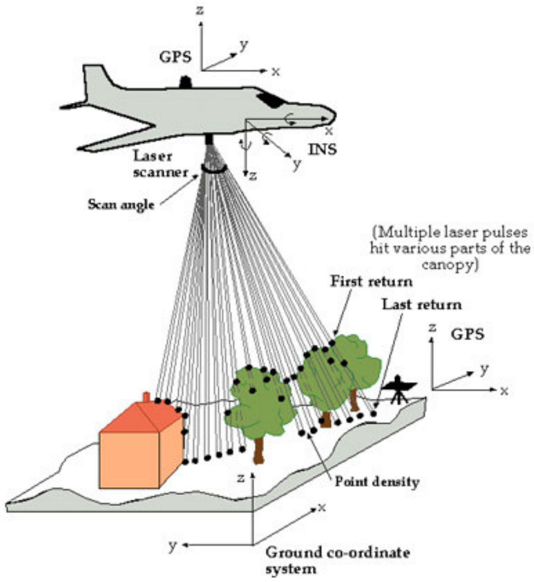


Figure 1. Illustration of Airborne LiDAR

Not all laser scanners collect multiple returns, in many cases only single returns (first or last pulse) are recorded. In addition, most systems record the reflected intensity image.

Lasers also operate as continuous wave sensors which can depict the interaction between the laser energy and the elements of the vegetation canopy.

There are currently many LiDAR systems available and these operate from fixed wing and helicopter airborne platforms at altitudes from 50 – 3500m. The latest systems operate at 100Hz and can produce point densities from helicopters of 30 points per m^2. There are now many companies operating LiDAR systems, most of which work commercially to provide data to order, using systems such as Optech, TopEye, FLI-MAP, TopoSys, TerraPoint and Leica.

Spaceborne LiDARs are also in operation, the most important of these is the Geoscience Laser Altimeter System (GLAS) on ICESat. GLAS produces a series of approximately 70 m diameter spots that are separated by nearly 170 m along track.

2.2 IfSAR

Synthetic Aperture radar determines the amount of scattered energy returned to the antenna, its range and position along track (azimuth). SAR can operate in a number of frequencies shown in table 1.

Band	**Wave length**	**Frequency**
X	3cm	9.6GHz
C	5.3cm	5.6GHz
L	24cm	1.3GHz
P	68cm	0.3GHz

Table 1. Typical wave length and frequency for SAR bands.

Two SAR images can be combined to use the technique of interferometric SAR (IfSAR) to generate digital elevation models. The principle of IfSAR is shown in figure 2.

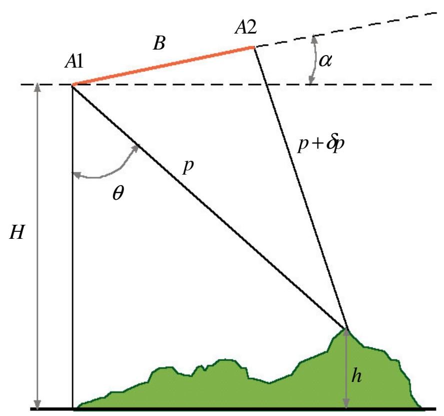


Figure 2. Geometry of single-pass Interferometric SAR

The two antennae are shown at A1 and A2. H represents the altitude above the reference ellipsoid, h indicates the topography of the Earth's surface. The baseline, i.e. the separation between antenna 1 and 2 , is given by B. The slant range (look direction of the antenna) to the target is given by p, the look angle at target location is represented by θ and the angle of the baseline with respect to the horizontal is given by α. Assuming θ is known, the elevation of the targeted point on the Earth's surface can be calculated from:

$$h = H - p\cos\theta$$

$$(p+\delta p)^2 = p^2 + B^2 - 2pB\cos(90-\theta+\alpha)$$

Where δp is the slant range difference

$$\delta p = \lambda\phi / 2\pi$$

Where λ is the wavelength of the radar pulses and φ the phase difference between the two returns. The phase difference can be measured only as a variable with 2π period. Therefore, phase unwrapping needs to be applied in order to resolve the absolute modulo-2π ambiguity, i.e. to determine the integer portion of φ.

The two scenes may be obtained from a repeat pass, usually from satellites, where the images are acquired from two passes of the sensor in very similar orbits. Single pass data is acquired from an aircraft or spacecraft on which there are two antenna separated by a known base length. The suitability of a pair of images for generating IfSAR DEMs is measured by the coherence between them. Poor coherence is caused if the returned radar signals are different on the two images, phase unwrapping cannot then be carried out. Coherence is usually good on single pass images but can be poor on repeat pass, especially if there is a significant time difference between images. Errors due to the atmosphere are also reduced.

The elevation measured for any pixel (resolution cell) results from a combined signal of scatterers located in the resolution cell (sample area). Elevations measure the 'volume scatter', i.e. there will be some penetration into the canopy and the range recorded will not depict the true height of the tree (first surface). Therefore, areas covered by vegetation will include more height measurement noise than areas covered by specular scatters (i.e. buildings). The wavelength of the radar will determine the penetration on the signal into the vegetation, X band will not penetrate as far as L band.

In addition, the surface area represented by one pixel may consist of a combination of different scatterers. Height measurements could be biased due to a interaction of these surface features. The backscattered signal (radar response) is integrated over a square footprint (resolution cell) somewhat larger (about 50%) than the 5m DSM sample distance. (Mercer, 2002) Therefore, the elevation measured for any DSM sample (resolution cell) will result from a combined signal of scattering objects located in this sample area. If hedges and shrubs are closely located to a road, both, the raised objects and the road itself (bald earth) will contribute to the elevation value measured for this DSM sample.

IfSAR has been widely used from spaceborne platforms, the ERS Tandem mission and the Shuttle Radar Topography Mission (SRTM) are the two prime examples. The main airborne IfSAR is the Intermap STAR-3i. This is a single-pass across-track IfSAR system operating commercially since January 1997. The system is an X-band SAR interferometer carried on board a LearJet 36. The two antennae are separated by a 1m baseline. Accurate positioning and orientation is achieved through the use of an on-board laser-based inertial navigation system and an on-board differential GPS (Global Positioning Systems) system. (Mercer & Schnick, 1999). Other airborne SARs are operated by research organisations such as NASA and DLR.

2.3 Products and data providers

Data from LiDAR or IfSAR is usually provided as digital surface models (DSM), digital terrain models (DTM) and orthoimages. The generation of the DSM will be done by the organisation which has collected the data and will involve calculation of the ground co-ordinates from the GPS, INS and range measurement, and must include corrections derived from the system calibration and from the atmosphere, and of course be delivered on a specified datum in a known map projection. An image can be formed from the SAR data and may also be collected with LiDAR. The DTM and orthoimages can be derived from the DSM and image; this will be discussed in section 5.

3. ISSUES

During the past 5 years a number of workshops have been held to discuss the developments in LiDAR and IfSAR and from these a number of conclusions can be drawn. Table 2 compares a number of characteristics of the two data types.

	LiDAR	**IfSAR**
Operational	Acquired from fixed wing and helicopter platforms, at altitudes from 50m to 3500m. Space borne systems also in use. Operates in day and night and in moist atmospheres.	Acquired from aircraft at high altitudes using single pass systems and from satellite platforms using single and repeat pass systems. Operates in all conditions, although atmosphere can affect accuracy.
Image	Intensity image available with some sensors. Frequently flown with digital camera.	Amplitude image created as part of system from SAR.
Calibration	Not fully developed.	Well developed and essential.
Processing	XYZ co-ordinates generated directly to form DSM.	Complex processing now using mature algorithms for DSM and orthoimage generation. Layover and shadow will cause problems from once only acquisition, but can be overcome by multiple acquisition. Coherence not a problem for single pass systems.
Post processing	Produces DSM which needs processing to DTM. Good algorithms exist, but still not fully reliable. Processing packages available.	Produces DSM which need processing to DTM. Significant editing still required. Response from different types of surface cover not fully understood.
Characteristics of DSM	Density varies with sensor and altitude. Footprint size also varies. Ground and tree surface can be seen with multiple returns. Gaps in data due to occlusions.	Footprint larger than LiDAR, tends to smooth out features. Some penetration from trees, varies with frequency.
Accessibility to data	Point cloud easily understood. Many companies offer data acquisition and processing. Software available for filtering, feature extraction etc.	Complex processing generally done by system operator. SAR data not familiar to many people and nature of the DEM not always understood. Few operators.
Accuracy	Best accuracy around 10cm in Z	Best accuracy around 0.5m in Z
Applications	Applications over limited areas with high accuracy.	Suited to larger areas with lower accuracy.
Cost	\$500 per m^2	\$5 per m^2
Standards	LAS standard developed in USA. Specification and standards also being developed.	Reliant on system operator.

Table 2. Comparison of airborne LiDAR and IfSAR.

4. PROCESSING AND CALIBRATION

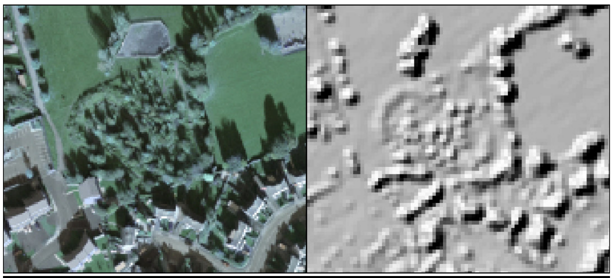
Calibration of LiDAR data by the user is not well developed. Normally a calibration surface will be measured prior to a flight to determine bore sight alignment and any systematic error. A datum shift can be applied to the measurements if necessary. Some operators do not consider this to be necessary. In fact there are many sources of error which are not accounted for. Katzenbeisser (2003) has studied these and shows that “most of the corrections, which might be applied have to be used at a very early stage of the data processing. Even if so called “raw data” (i.e. all echo coordinates) are available, the correction is limited to GPS (or positioning) errors.” He goes to to write that “The usual calibration flights (at the beginning and at the end of a survey) over flat terrain do not allow the detection of distance errors, of varying deflection errors, of time delays between measurements, etc. It seems that it is much more essential to understand the composition of a sensor system and what the manufacturer has done to avoid most of the effects.” Katzenbeisser also suggests that general software for processing real raw data (i.e. position, orientation and distance) may never exist, as it would have to take into account a large number of parameters assigned with the individual manufacturing of a sensor system and which can not be generalized. Filin (2003) has also investigated correction of systematic errors in LiDAR and indicates the need for an error model for LiDAR.

The processing of the IfSAR data is now well established but there are still problems, especially when high accuracy is required. The main inherent problems are the presence of layover and shadow, loss of coherence and the size of the footprint.

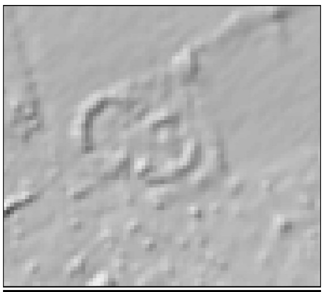
5. BARE EARTH DATA (DTM) AND EDITING

The DSM is an accurate product derived directly from the observations, however for many purposes a terrain model (DTM), or bare earth model, is required. Much effort has been expended to develop algorithms for this purpose, mainly concentrating on LiDAR data. Sithole and Vosselman, (2003) have reported on an ISPRS test of such filters. Less work has been done on filtering IfSAR, where the scale is generally smaller and the problems greater because of the footprint size and the amount of penetration, or lack of it, of the microwaves through vegetation.

Filtering algorithms generally incorporate a thresholding function to decide whether a point lies on the terrain or on the observed surface. The threshold may depend on elevation of a point or group of points, or it may depend on slope between adjacent points and these algorithms suffer from the problem of assigning a value to the threshold. Figure 3 gives an example of filtering from LiDAR carried out with the recursive terrain fragmentation filter (RTF) developed at UCL, (Sohn and Dowman, 2002).



a. Aerial Image. b. LiDAR DSM.



c. LiDAR DTM

Figure 3. Filtering of LiDAR data using the RTF filter.

It can be seen that although the major surface features have been removed, the terrain is still not smooth. This is in part due to small man made features, such as vehicles, and small natural features, such as bushes, which fall below the assigned threshold. Sithole and Vosselman, (2003) found problems with complex objects, attached objects, vegetation on slopes and discontinuities. Different filters cope differently with these problems. Smoothing filters can be used, but they can introduce their own errors.

With LiDAR, some of these problems can be overcome if multi return systems are used. Figure 4 shows LiDAR returns over forest area, taken with an Optech 2033, in which the ground surface can be confidently predicted from the last pulse return. As point density increases, this becomes more reliable.

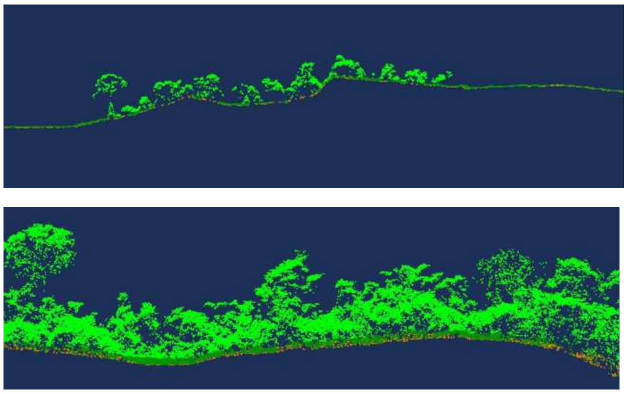


Figure 4. Multiple returns from a forest canopy.
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Less work has been done on testing filtering of IfSAR DSMs. An evaluation of the Nextmap UK data was carried out at UCL. This is discussed in detail in section 6. Figure 5 shows a comparison of the Nextmap DSM, DTM and a GPS profile over an unvegeatated flood plane to the left and a a forest to the right. It can be seen that the forest has not been removed by the filter used. Zhang et al (2004) have recently published an algorithm developed specifically for IfSAR.

We can conclude that bare earth filtering still has problems and that there will inevitably be a need for manual editing after the automatic processing. Filtering of LiDAR is probably more effective that that of IfSAR.

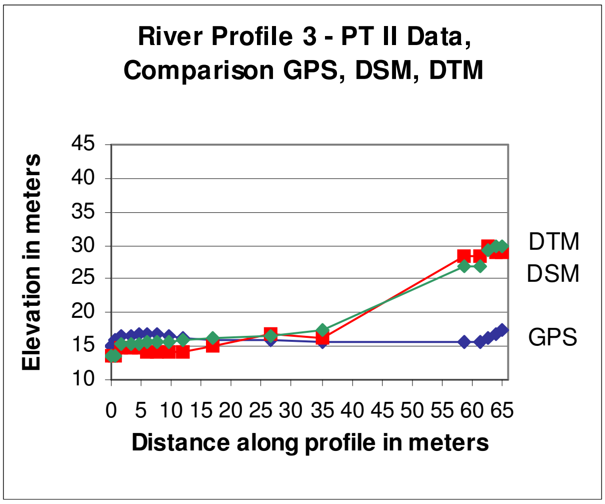

Figure 5. Profiles across a flood plane and forest from the NextmapUK data.

6. ACCURACY

The accuracy of both LiDAR and IfSAR is now quite well established in empirical terms, but there are still error sources which are not well understood or quantified, as discussed in section 4.

Ahokas et al (2003) have carried out an analysis of fixed wing and helicopter LiDAR from different altitudes, over different surface material and also looked at the effect of observation angle. They concluded that 'The analysis of the factors affecting the total accuracy of the laser scanning is not as simple and as straightforward as it was thought. ….. It was observed that there is a flight line-dependent systematic and random error affecting on the total accuracy obtained. It was observed that the higher the flight altitude, the higher is the random error of terrain models. 800m flying altitude gives poorer results than 100m flying altitude. Laser measured heights are in general above the real ground surface. For asphalt surfaces a standard deviation of 10cm is obtainable from H=550m and from lower altitudes the results are even better. A systematic error of typically 10 cm was observed due to observation angle changes.'

Abdullatif et al (2003) have also investigated the accuracy of LiDAR and report systematic errors, but an overall accuracy of about 12cm. Overall accuracy of LiDAR can be as good as 10cm, but in practice varies according to the quality of the calibration and the terrain surface.'

Airborne IfSAR can achieve accuracies of 0.5m, but also varies according to calibration, altitude and terrain surface. Mercer (2003a) discusses the trade offs between accuracy and swath width and states that the theoretical accuracy from 30,000ft is 0.45m and 0.30 m at 10,000ft.

UCL has carried out an analysis of the Nextmap Great Britain dat which used two test areas (Dowman et al, 2003) and made use of LiDAR, GPS and aerial photography as reference data. The initial comparison of Kinematic GPS with the Nextmap DSM showed unexpectedly large errors, which turned out to be due to the effects of hedges and trees on the Nextmap due to the footprint size. These were removed by filtering in order to eliminate outliers due to vegetation that bias the accuracy measures. The 3σ threshold was used as starting point for filtering the difference data (KGPS minus Nextmap DSM). It is clear that points on the DSM are measured to be higher than their true value because of the size of the footprint of the Nextmap data. If the bare earth algorithm is effective, these errors should be corrected in the DTM, results are shown in table 3. It can be seen that a shift of between 0.3m and 0.8m has occurred and that this has therefore significantly improved the root mean square error.

Photogrammetric check points collected from the stereo-model of aerial photography in open bare earth areas, clear of surrounding surface features within a 5m radius were compared with the DSM and the results can be found in Table 3. The Nextmap DTM and the photogrammetric checkpoints are in good agreement. A mean difference in elevation of -0.61m from the check points and a rmse of 0.83m was observed.

Furthermore, the vertical accuracy of the Nextmap data was evaluated by comparing the Nextmap DTM bald earth surface with Lidar derived reference DTMs. Results of these comparisons are also listed in Table 3. The Nextmap DTM was subtracted from the reference DTMs (reference DTM minus Nextmap DTM.

Two sub areas of open terrain type were selected and difference statistics produced. The Lidar DSM and the aerial photography DSM were chosen as a reference. Both, the Nextmap DSM and the DTM product were compared to the reference data sets. The results of these different comparisons are given in tables 4 and 5.

The best accuracy of the Nextmap data is obtained over an open field, which is interpreted as bare earth, where a mean difference between the Nextmap and aerial photography is 0.23m (Nextmap higher) and the rmse is 0.43m. The mean difference between the Aerial DSM and the Nextmap is effectively zero. This suggests that the bare earth algorithm has removed a mean difference of 0.23m in bare earth area. This corresponds to the finding discussed earlier, which also indicates that the bare earth algorithm affects the mean. This result needs further investigation.

The Nextmap and Lidar surfaces are in good agreement in both the sub areas. Over a cropped area the Nextmap DSM has a mean difference of –0.61m and rmse of 0.77m, from the Lidar DSM. The Nextmap DTM has a mean difference of -0.38m and rmse of 0.48m from the Lidar reference DTM.

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Comparison	**Terrain Type**	**Land cover**	**n**	v_{min}	v_{max}	v_{Mean}	**σ[m]**	**$Rmse_z$ [m]**
KGPS 3 vs. Nextmap DSM points > ±1.5m removed	Mixed (hilly, flat)	KGPS located along roads (bare earth)	1994	-1.50	0.05	-0.95	0.34	1.00
KGPS 3 DTM vs. Nextmap DTM	Mixed (hilly, flat)	KGPS located along road network (bare earth)	2647	-1.52	0.48	-0.66	0.32	0.73
KGPS6 DSM vs. Nextmap DSM points > ±1.9m removed	Mixed (hilly, flat)	KGPS located along road network (bare earth)	1475	-1.85	1.00	-0.96	0.49	1.08
KGPS 6 DTM vs. Nextmap DTM	Mixed (hilly, flat)	KGPS located along road network (bare earth)	1568	-1.73	3.58	-0.14	0.45	0.47
Air photo check points vs. Nextmap DSM	Mixed	Bald earth	66	-1.66	0.43	-0.61	0.57	0.83
Lidar DTM vs. Nextmap DTM (5)	Mixed (hilly, flat)	Bald earth	85362	-9.20	12.04	-0.22	0.10	1.01

Table 3. Summary of results from NUI Nextmap DTM evaluation of Shrewsbury area
Notes: All DEMs have 5m grid. KGPSi refers to ith profile recorded along roads.

Sub Area	Comparison	Terrain Type	Land cover	n	v_{min}	v_{max}	v_{Mean}	σ[m]	$Rmse_z$ [m]
1	Lidar DTM (5m) vs. Nextmap DTM	hilly (46-61m)	crops	11484	-1.55	0.52	-0.38	0.30	0.48
2	Lidar DTM (5m) vs. Nextmap DTM	Flat (49-53m)	crops	2166	-1.14	0.04	-0.41	0.21	0.46

Table 4. Lidar compared to Nextmap DTM (selected areas)

Sub Area	Comparison	Terrain Type	Land cover	n	v_{min}	v_{max}	v_{Mean}	σ[m]	$Rmse_z$ [m]
1	Aerial DSM vs. Nextmap DSM	hilly (46-61m)	crops	11484	-10.01	1.094	-0.31	0.44	0.54
1	Aerial DSM vs. Nextmap DTM5	hilly (46-61m)	crops	11484	-0.97	0.54	-0.07	0.20	0.21
2	Aerial DSM vs. Nextmap DSM	Flat (49-53m)	crops	2166	-1.38	0.99	-0.23	0.37	0.43
2	Aerial DSM vs. Nextmap DTM	Flat (49-53m)	crops	2166	-0.54	0.37	-0.00	0.17	0.17

Table 5. Aerial photography compared to Nextmap DTM (selected areas)

The areas chosen for validation in Shrewsbury and Worcester cover a flood plain of the River Severn with some relief of about 60m above the river. It also contains a variety of land cover types, including bare ground, crops, woodland and built up suburban areas.

The main conclusions are as follows:

- The vertical accuracy of the Nextmap data varies according to the type of the terrain where the comparison is made, and in particular the land cover. For example, it is known that forest and dense urban areas significantly decrease vertical accuracies of Digital Elevation Models. In general it can be stated that the mean surface of the Nextmap data is higher than the reference data. This is expected because of the size of the Nextmap footprint, and the general effect of vegetation in IfSAR measurements. The elevation measured for any IfSAR DSM sample (square footprint somewhat larger than the 5m DSM sample distance) result from a combined signal of scattering objects. Thus, raised objects such as trees and hedges located in the sample area, contribute to the elevation value measured.

- When comparing the Nextmap DSM with photogrammetric checkpoints, which were measured in open terrain, a mean difference in elevation of -0.61m and an rmse of ±0.83m were observed.

- The best accuracy of the Nextmap DTM is obtained over an open field, which is interpreted as bare earth, where a mean difference between the Nextmap and aerial photography was –0.001m and the rmse was ±0.17m (Nextmap higher).

- The Nextmap and Lidar surfaces are in good agreement, overall. Over a cropped area the Nextmap DSM had a mean difference of –0.61m and a rmse of ±0.77m, from the Lidar DSM. Over the whole area the Nextmap DTM was -0.22m difference with a rmse of ±1.01m, from the Lidar DTM.

- The GPS profiles along the roads show good agreement with the Nextmap DTM data when the effects of trees and hedges have been removed.

The evaluation of the Nextmap Great Britain data reveals a number of characteristics of the IfSAR and LiDAR data, and of the filtering techniques, which are general to this type of data. It also reveals unexplained differences which need further study.

7. VALIDATION

The validation of any DEM is clearly very important. This however can be quite difficult and expensive when the precision of the product is so high, and interpolation is necessary in the process. Some operators have high confidence in their product and do not consider validation necessary. The quality of the positioning can be checked from the GPS record. The normal procedures for validation include the use of reference data such as check points located as targets or points on open surfaces, reference DEMs or profiles. Checks can also be made for consistency and for outliers, and correlations can be investigated between the data and vegetation or slope. Where the point density is high enough, targets provide an very good validation surface for LiDAR. The Highways Agency (HA) in the UK specifies that boards, 1.2m x 1.2m, centred over a co-ordinated point and accurately levelled must be used. The HA requires a point density of 7 – 10 points per m^2, and thus about 10 points are expected to fall on the board, allowing significant statistics to be generated. An illustration is shown in figure 6.

For IfSAR this is not usually appropriate but traditional corner reflectors can be used. Because of the footprint size of IfSAR comparisons over large areas or profiles are better suited. Kinematic GPS profiles along roads have proved to be very useful for checking both LiDAR and IfSAR. Examples are given in Morley et al (2000) for the Landmap project and Dowman and Fischer (2003) for Nextmap UK.

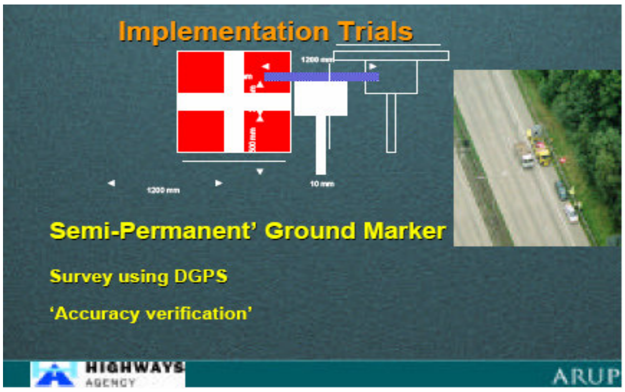

Figure 6. Specification of the UK Highways Agency control panels with location along the highway indicated.

8. COST AND ECONOMY

There is a clear separation between the costs and the applications of airborne LiDAR and IfSAR. LiDAR is generally high cost and high accuracy, and suited to covering small areas. IfSAR is less accuracy but can cover large areas very economically. Mercer (personal communication) quotes costs of about \$5 per km^2 for the IfSAR data of Nextmap Britain and about \$500 per km^2 for Airborne LiDAR. Wulder (2003) quotes Canadian \$1900 per km^2 for LiDAR with 30cm posting. Some of the shortcomings of IfSAR can be overcome at additional cost. For example problems with occlusions can be solved if an area is flown from two look directions.

There are some important points to consider when looking at the accuracy of products:

- The product must be fit for purpose with suitable accuracy and point density
- The data must fit to other data - very important with web delivery to non specialist users
- Accuracy must be specified

9. STANDARDS

As LiDAR becomes more widely used, it becomes more essential that data can be easily read by standard mapping systems, and passed between users. This implies a need for standards and interoperability.

In the USA a standard has been established for the formatting of LiDAR data (http://www.lasformat.org/). The LAS format has been accepted by the American Society for Photogrammetry and Remote Sensing (ASPRS) and is being widely used This has also been incorporated into the Highways Agency Specification for LiDAR in the UK. In the USA, FEMA (2000) has a standard specification for LiDAR and ASPRS are developing a handbook of operational LiDAR Mapping. ISO 19130 TC 211 "Geographic information / geomatics" project team of "Sensor and data models for imagery and gridded data" has published a Committee Draft of an ISO standard for photogrammetry and remote sensing but this does not include sensor models for LiDAR and SAR.

It is important that these initiatives are carried forward; this is an opportunity to define standards for a new sensor and new products at an early stage in their development.

10. SPACEBORNE IfSAR

Spaceborne IfSAR is more established as a source of DEMs that is airborne. The ESA ERS Tandem mission has acquired very wide coverage of interferometric SAR pairs and this is much used for the generation of regional DEMs. For example the Radarmap of Germany produced by DLR (Kosmann et al, 1994) and the Landmap project in UK (Morley et al, 2000). The Shuttle Radar Topography Mission (SRTM) has also produced DEMs and orthoimages between 60˚ North and 56˚ South. In addition RadarSat, JERS, and ENVISAT all produce interferometric data and in the future RadarSat 2 and ALOS PALSAR will join the ranks of IfSAR data generators. IfSAR has also had an important application in differential mode for monitoring tectonic movement and subsidence.

With the exception of SRTM, satellite IfSAR uses repeat pass data, and this can suffer from the problem of poor coherence and atmospheric effects, which degrade the data and can cause gaps in the DEM. SRTM also suffers from problems, particularly layover in mountainous areas, and the SRTM dataset does contain some gaps.

The accuracy of IfSAR DEMs from spaceborne platforms varies significantly, depending on the coherence, itself dependent on the interval between acquisition of the two images and stability of the weather and atmosphere, and the terrain.

11. DATA FUSION

Data fusion exploits the synergy of two or more data sets to create a new data set which is greater that the sum of the parts. The ISPRS Journal of Photogrammetry and Remote Sensing (Vol 58(1-2), 2003), published a theme issue on multi-source data fusion for urban areas which clearly demonstrates the range and importance of data fusion. Data fusion can be used for many applications. Some of the established ones are:

- Assisting phase unwrapping
- Eliminating errors and blunders
- Atmospheric correction
- Providing orientation in areas where there is no control
- Terrestrial images to LiDAR
- Feature extraction, such as buildings and roads
- Other aspects of feature extraction and environmental analysis (see ISPRS Journal 58(1-2)).

Some examples of how DEM data from LiDAR or IfSAR can be combined with other imagery or map data for feature extraction are given in section 13.5. Honikel (2002) shows how ERS If SAR and SPOT DEMs can be fused and develops a theory for this; Csanyi and Toth (2003) also discuss the theoretical aspects of merging IfSAR and LiDAR data.

SRTM provides another interesting case study. Because SRTM provides a near global data set which is geocoded with accuracy which is better than any other comparable global DEM, it can be used to give initial orientation for higher accuracy data and be used to assist with phase unwrapping and atmospheric correction.

12. USER CONSIDERATIONS

LiDAR and IfSAR are relatively new products and it is therefore necessary to overcome the reluctance of users to make use of them. Educated users, especially research organisations, will always be keen to look at new products, but users more familiar with photographic products will take more time. Some of the major users of both airborne LiDAR and IfSAR have been new users, for example power generation companies for powerline survey, and insurance companies for assessing flood risk. But there can be problems with such users not understanding the characteristics of the data, nor the accuracy which can be expected.

LiDAR can produce a high density of points, and although this is an advantage in some situations, it can also cause problems, for example in the volume of data to handle. High density might be necessary to identify detail on the ground, small gullies or crash barriers on highways for example, but not on the main carriage way. Thus there is a problem on how to this the data to retain only what is needed. Intensity images may appear to be useful in order to make it unnecessary to fly a camera as well, but their quality is not as good, and there is no standard for measuring intensity. On the other hand flying a camera with the LiDAR can be a disadvantage as it means that the lighting conditions must be good enough for the camera, whilst the LiDAR could operate in poorer lighting conditions.

IfSAR is a complex system and users do not need know the intricacies of the processing, but they do need to understand that SAR samples a footprint which is quite large and that different types of land cover give different responses. They also need to understand the meaning of orthocorrection, (terrain orthoimages and true orthoimages), the need for compatibility of projection and datum, and the significance of error statistics. In other words the users need to be educated to some degree and the data provider needs to ensure that they are.

In the United Kingdom, the Highways Agency has produced a specification for LiDAR surveys which has been produced in close consultation between the data providers and the client. This ensures that the client gets what is needed, for example in terms of data formats, and visualisation of products to help new users, and the provider understands what is required.

13. APPLICATIONS

13.1 Introduction

There are now a great many applications for DEMs from LiDAR and IfSAR data and it is beyond the scope of this paper to deal with all of them. We will therefore briefly review some of the innovative applications and concentrate on those which involve the use of data from more than one source.

13.2 Regional and global mapping

IfSAR has proven itself for low cost DEM generation over large areas. The prime example is SRTM, but large areas have also been mapped with ERS data, for example the Radarmap of Germany (Kosmann et al, 1994). Airborne systems have been used for generation of DEMs and orthoimages over large areas such as the Nextmap Britain project (Mercer, 2003a, Dowman and Fischer, 2003). The Nextmap data was originally commissioned for an insurance company for flood risk analysis, but is now being used more widely than that, and is complementary to LiDAR, which is useful in denser urban areas. Intermap have carried out IfSAR surveys in many parts of the world including Malaysia and Indonesia, and are starting on a coverage of the whole of the USA.

13.3 Environmental applications

A major application for environmental use is forestry. The ScandLaser Scientific Workshop of Airborne Laser Scanning of Forest, held from September 3-4, 2003 in Umea, Sweden, gives a very detailed view of the current status of LiDAR for forestry, e.g Wulder (2003), Naesset (2003), Hyyppa et al (2003).

Hamdan (personal communication) has noted that Dubayah and Drake (2000) listed the key forest characteristics that can be measured directly or indirectly by LiDAR. Among the parameters that can be retrieved directly are canopy and tree height, timber volume, forest mixtures according to tree species, natural age classes, forest canopy closure, decision of forest / non-forest and sub canopy topography. Beside this, above ground biomass and volume, basal area, mean stem diameter, vertical foliar profiles, canopy volume and large tree density can either be modelled or inferred from LiDAR measurements. Other important parameters for forest such as canopy cover, leaf area index (LAI) and life form diversity need different approach where data fusion from lidar and other sensor is essential. In this case, the vertical component provided by LiDAR should be fused with information from passive optical, hyperspectral, thermal and radar remote sensing (Hill et al.,2003). Apart from that, LiDAR data like other optical remote sensing techniques are restricted by clouds and dense atmospheric haze. This can attenuate the signal before it reaches the ground. Another limitation of LiDAR is the lack of algorithms and data processing expertise required for operational use of the data. All these enhance the integration of this data with other satellite system.

An interesting new development is the combination of airborne LiDAR with terrestrial LiDAR for forestry and the creation of virtual forest environments. (Evans, 2003). Off shore tidal area are anther important application area. A LiDAR survey has been done for Willapa Bay in Washington, USA, demonstrating the utility of the technique in intertidal areas.

13.4 Engineering applications

LiDAR has been used for engineering work such as railways, powerlines and highways because of its high vertical accuracy and the density of points. The application for power lines, (Silver, 2001) and the ability to accurately determine the position of the cables is an excellent indication of the usefulness of LiDAR.

When a camera is flown with the LiDAR, even if a non metric camera, then large scale mapping can be carried out. Figure 7 shows a plot of a highway intersection with detail and contours. Compiled from the LiDAR DEM and a digital image acquired at the same time as the LiDAR data.

The use of LiDAR for the generation of 3D city models is well established and some techniques are discussed in section 13.5. High density point clouds can be used to extract buildings and roof detail by fitting planes to the points. TerraScan provides tools for creating fully dimensional vectorised models of buildings from LiDAR data based on identification of planar roof surfaces. Chayakula (2004) has investigated the use of airborne IfSAR in urban areas and shown that useful information can be extracted. Houshmand and Gamba (2001) have also worked on this topic (see below).

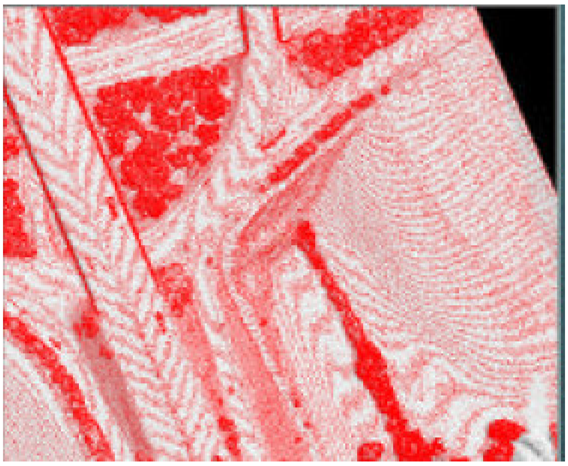

Figure 7. Detail plot from LiDAR and digital photo.

13.5 Combining data for feature extraction

LiDAR is very important for feature extraction and has been widely used with other data sources for this purpose. Haala & Brenner (1999a) have demonstrated the combination of LIDAR data with multispectral aerial images for the automatic classification of buildings and trees. Haala and Brenner (1999b) have also shown automatic 3D building reconstruction in a system which combines 2D GIS data and LiDAR. Based on given outlines of the respective buildings which were integrated with dense surface data from airborne LIDAR measurements, virtual city models were created for an extensive number of test sites using this software. Sohn and Dowman (2004) have combined low density LiDAR with high resolution satellite sensors to extract buildings. Dell'Acqua et al, (2003) have combined LiDAR with IfSAR in urban areas. The paper shows that it is possible to exploit LIDAR DEM to improve to some extent the two- and three-dimensional representation of buildings extracted from IfSAR data. The method helps in recovering building displacement and distortion due to the side-looking nature of radar. This is shown in figure 8.

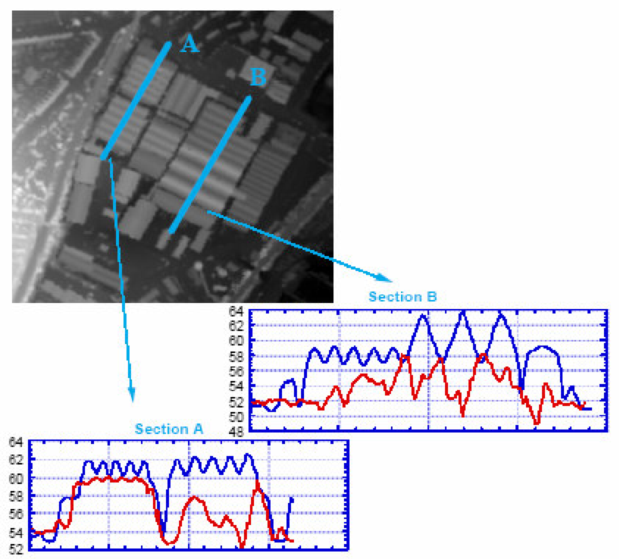

Figure 8. 3D characteristic of buildings from IfDSAR and LiDAR. After Dell'Acqua et al, (2003).

14. DISCUSSION

It can be seen that LiDAR and IfSAR are important new sources of data for generating geospatial products. They have opened up new markets by filling gapes which could not be filled by aerial photography or optical satellite imagery. It can also be seen that LiDAR and IfSAR are themselves complementary, and also complementary to other sources of data. It has been shown that IfSAR is more economical for wide area coverage, provides an intensity image, which can be orthorectified, a coherence image and multifrequency and multipolarised data which can give more information about the land cover than hitherto possible. LiDAR on the other hand gives a high density cloud of 3D points which can accurately define both elevation and plan position. There are however a number of restriction on wider use of LiDAR and IfSAR and open questions on their future development.

Although LiDAR has the potential for application in building extraction and 3D city modelling, automatic feature extraction is still not mature and therefore the output is unreliable, and manual editing is very expensive. LiDAR is also very expensive for small areas. Wider use of LiDAR may therefore have to wait until better feature extraction algorithms are available. New airborne technologies such as 3 line optical sensors could also compete with LiDAR when they become more mature and can acquire data with higher resolution than at present. Three line data avoids occlusions and adds redundancy to the data set. Multi sensor data could also do this. The use of a digital camera with LiDAR is already commonplace, but a good model for reconstruction and error analysis is needed. In order to inspire confidence in the data better theoretical models are required, both for single sensors, and for data fusion, in order that the errors can be better understood. Potential errors such as multipath and transparency effects also need to be studied much more. More comparative tests, especially with different algorithms, need to be carried out, although this is now happening through ISPRS (Vosselman and Sithole, 2003) and EuroSDR (http://www.oeepe.org/2002/index.htm), for example.

IfSAR could also benefit from comparative testing and the establishment of international test sites would be beneficial. CEOS and EuroSDR could contribute to this.

A better understanding of the quality measures and error statistics, and development of understandable uncertainty measures would also be beneficial. Organisation such as USGS and Ordnance Survey are establishing good practice in this area by showing heritage and uncertainty in their data; this should be encouraged, and their methods publicised.

15. NEW DEVELOPMENTS

A number of clear trends have been identified. These include more accurate, higher density data, new applications and the development of new algorithms. High density LiDAR point clouds mean that buildings can be better extracted, and details of highway surfaces and infrastructures can be surveyed more easily.

The main developments in progress are in the area of IfSAR, particularly the development of multi frequency, multi polarised SAR. The ESA spaceborne ENVISAT mission is already operating the ASAR sensor and other mission such as the Japanese ALOS PALSAR will be launched shortly. Satellite SAR resolution is being improved, as is the positional and orientation accuracy. Constellations of small satellites are planned which will extend the availability and flexibility of IfSAR data.

GeoSAR is a dual-frequency, dual-polarimetric, interferometric airborne radar mapping system that generates DEMs and orthorectified radar reflectance maps near the tops of trees as well as beneath foliage, (http://southport.jpl.nasa.gov/html/projects/geosar/geosar.html). The GeoSAR system collects radar data in two frequencies. The X-band maps the first surface, near the top of trees and the P-band maps beneath the foliage and assists in the production of a bare-earth terrain model and the detection of structures beneath trees. Mercer (2003b) reports on the use of Polarimetric P band data for generation of DEMs of forest areas, and compares this with X band InSAR.

We are beginning to see the economy of airborne IfSAR being used for wide area DEMs to complement the global data from SRTM. These can be created from a single source, hence providing a homogeneous data set, generated over a short period of time. The use of permanent scatterers to monitor subsidence with IfSAR is also being developed (Ferretti et al, 1999)

A better control infrastructure is becoming established to allow woder and easier use of GPS, INS systems. National mapping agencies are establishing permanent continuous recording GPS stations, but operators prefer to set up their own base stations. The introduction of Galileo will further extend the use of positioning systems.

The importance of validation and improved quality assurance is being recognised and the introduction of internationally accepted standards is being discussed.

As the data becomes more widely used, new image processing systems are becoming available. TerraSolid is widely used now for processing LiDAR data, and more tools are becoming available. Packages such as eCognition are particularly suited to use with SAR data and DEMs. Intelligent systems such a ALFIE, (Automated Linear Feature Information Extraction), a new system for generating simulations for military use being developed in the UK (Wallace et al, 2004). The system is based on existing algorithms integrated into a toolkit within a processing environment which can automatically select which tools to use with particular data for specified applications, and which can also make use of context in extracting features. ALFIE is also linked to an object oriented data base and works with a developed feature extraction environment.

16. CONCLUSIONS

It has been shown in this paper that LiDAR and IfSAR are now widely used and that this type of data is opening up new markets and new opportunities in areas such as powerline surveys, flood risk mapping and large area mapping. The two types of data are complementary with each other and each can be used with other data sources to generate new value added products.

That having been said, we have also shown that there are still problems with using the data and more development needed before the technology is fully mature. The calibration of LiDAR data is not well developed, and neither are specifications or quality assurance techniques. The generation of bare earth models (DTMs) are still liable to error and manual editing is still needed. The main areas for further research are to develop threoretical models for sensors and data fusions, to improve bare earth filtering and to improve feature extraction. User need to be educated more and to aid the greater use of the data, standards need to be defined for products and for data exchange.

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