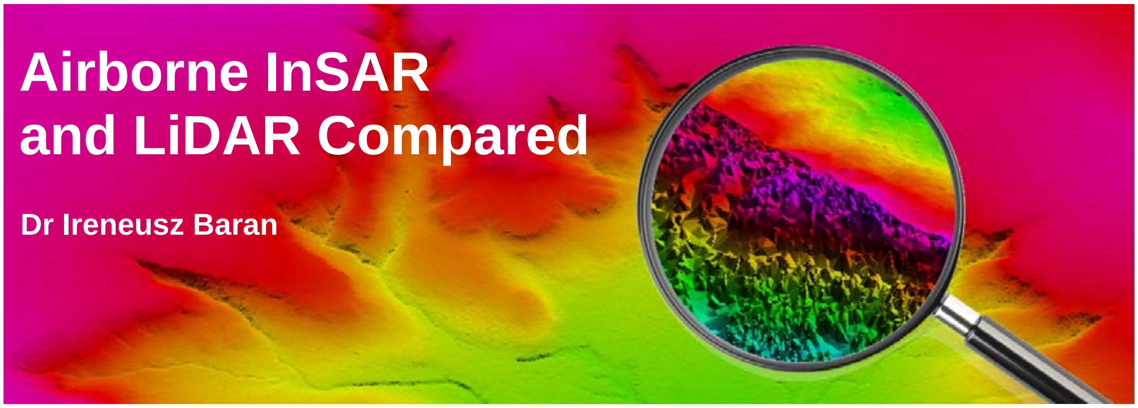

Airborne InSAR and LiDAR Compared

Dr Ireneusz Baran

Abstract

In the last decade, applications of Digital Terrain Models (DTM) and Digital Surface Models (DSM) have rapidly increased. DTMs are routinely used in engineering applications and environmental studies, risk analysis and disaster monitoring. Growing demand and technological advances have accelerated the development of new techniques capable of delivering rapid, high resolution and accurate terrain definitions.

This paper compares Airborne InSAR with a more widely known technology: LiDAR. Advantages and disadvantages of each technology are addressed. This furnishes potential users with salient information to make informed decisions on which technology and products are more appropriate for specific applications.

Key words: LiDAR, InSAR, Radar, Digital Terrain Model, Digital Surface Model.

1. InSAR Explained

Both LiDAR (Light Detection and Ranging, also known as Airborne Laser Scanning) and InSAR (Interferometric Synthetic Aperture Radar, also known as IFSAR) are active sensors which transmit pulses of electromagnetic energy and record the backscattered signal to derive spatial location of the survey target.

LiDAR is now well known and accepted in the commercial environment, with many papers describing its technology, benefits and applications (eg. Jonas, 2007). Although InSAR has also been around for decades, it is only now being considered for adoption in conventional mapping applications.

InSAR sensors are usually installed on a fast moving aircraft capable of flying at high altitudes. Usually two side looking radar antennas (separated by known baseline) are mounted. In this "single pass" configuration one antenna transmits radio waves and both antennas receive backscattered signal (Fig 1B). Such a configuration enables the system to scan the same target simultaneously from two different antenna positions. Advanced Synthetic Aperture Radar (SAR) data processing enables the system to generate a pair of high resolution images of the same scene. Each pixel preserves amplitude and phase of the backscattered signal. This information is exploited in the interferometry process where both images are differentiated. The resulting phase differences are then unwrapped and converted to heights and finally a DSM (Digital Surface Model). Although it is possible to process images acquired at different times (“repeat pass” configuration), simultaneous acquisition has significant advantages as it mitigates temporal decorrelation to improve data quality.

There are only a few commercially available airborne InSAR systems. For example, operating parameters of the STAR-3i owned by Intermap Technologies are listed in Table 1.

Table 1 STAR-3i Operational Parameters (Intermap, 2009)

Operating Altitudes	3000-10 000 m
Typical flight speed	750 km/h
Wavelength	X-Band 3 cm
Incidence Angle	30-60º
Ground swath	3000 -10 000 m
Data sampling	Regular grid
Vertical accuracy	1.0 m
Horizontal Accuracy	2.0 m

The commercially available GeoSAR systems operate X- and P-Band simultaneously on both sides of the airplane. Moreover, the recently developed Ku-Band InSAR system has spatial resolution of 0.3m and vertical accuracy better then 0.5m (Okada et al, 2007).

The radar pulse is typically transmitted at a 20 to 50 degree look angle. As the pulse spreads across the flying path, it hits targets along its way and the system records the corresponding returns (Fig 1B). This means that different targets positioned at the same distance from the sensor cannot be resolved. This is known as *foreshortening* and *layover*. These phenomena, together with *shadows* and multipath of radar signal, are the major limitations of InSAR system.

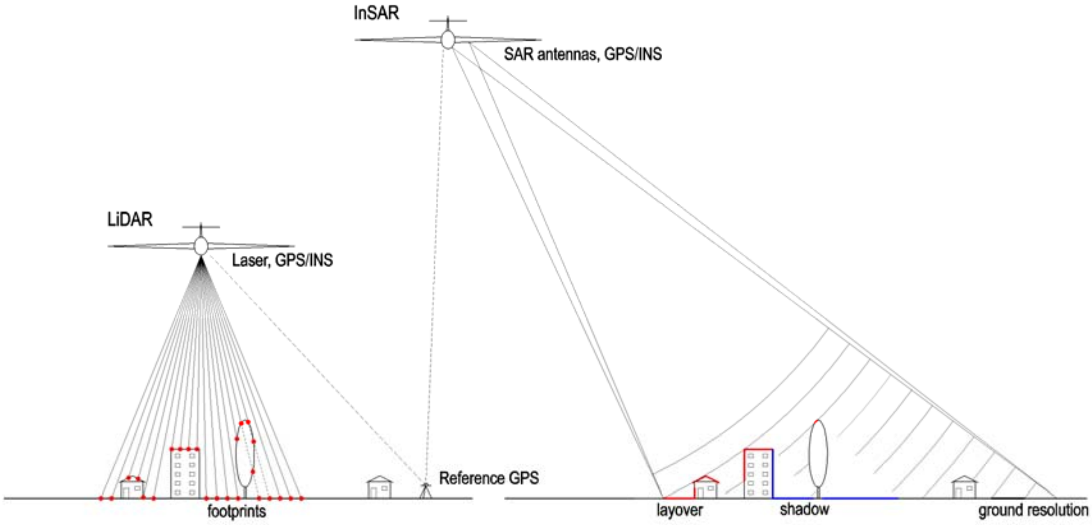

Fig 1 (A) LiDAR and (B) InSAR basic acquisition geometry

InSAR sampling cell contains many individual (volume) scatters located on the ground and above. This causes the ‘noisy’ nature of InSAR elevation data and often introduces unwanted biases. It is especially problematic in urban and forested areas where, for example, a building or tree together with ground is present in a single sampling cell.

The long wavelength of the InSAR system offers its biggest advantage as it can penetrate through clouds, haze and dust. This means that InSAR can operate virtually under all weather conditions. By using different wavelengths, the system penetration capabilities can be altered. For example the X-Band will reflect from the vegetation where P-Band will penetrate to the ground.

InSAR data processing appears more complex than LiDAR, even though this technology is relatively well developed and the processing algorithms very robust. The processing of InSAR data requires highly sophisticated software and – as with LiDAR - trained data processing personnel. Some system and processing induced errors are still problematic and present in the data as noise. Advanced data filtering techniques are applied to improve the data quality (eg. Baran et al, 2003).

Although both systems are capable of recording more data along a single range (LiDAR records more than one return; InSAR uses multiple frequency and/or polarisations) in principle, they capture digital surface definition. Further processing is required to extract digital terrain definition. Many algorithms have been developed to automate this process. However, none of the available algorithms are fully reliable and expensive and time consuming manual data filtering and QA are still required.

Extracting the bare ground from under the vegetation is problematic and both systems tackle this problem differently. X-Band InSAR system will not penetrate the canopies and reach the ground. Moreover, its large resolution cell requires much large patches of unobscured ground in order to capture it reliably. Using longer waves such as P-Band allows the InSAR systems to penetrate the vegetation and often deep into the ground introducing some unwanted biases. P-Band is also more difficult to operate and process as it is less immune to interference and attitude errors. LiDAR's very narrow laser beam is more effective. LiDAR’s nadir looking configuration and ability to pass between the gaps in the canopy allows the system to penetrate through to the ground even thick vegetation canopies.

2. Data Characteristics and Accuracy

The vertical accuracy of LiDAR derived DTMs is typically in the range of 0.10m-0.20m (one sigma) and depends on many systematic errors as well as data calibration and classification. If carefully planned and properly calibrated, a LiDAR system can achieve vertical accuracy better than 0.10m. Interestingly, there are no technical limitations that prevent InSAR systems achieving the same vertical accuracy as LiDAR. It is the high cost of the system and its operation that limits its application to large areas captured from high altitudes and so lower accuracy.

Both systems are sensitive to terrain variations and land cover. LiDAR derived DTMs will be less accurate under heavy vegetation than on clear ground due to reduced laser penetration. The accuracy of InSAR derived DTMs will significantly depend on the band used, terrain variation and land cover. If X-band is used, then there will be no penetration of the vegetation so the "DTM" can only be derived by taking the tree heights and subtracting an estimated tree height. If P-band is used, the penetration of the vegetation is possible, however, the measured range is less accurate. Moreover, P-band tends to penetrate into the ground.

The average error of InSAR derived DTM over vegetated areas may be several times larger than on open ground. This is primarily caused by contributions of many individual scatters being within a much larger resolution cell. However, it is also due to the fact that radio waves interact differently with different materials depending on their conductivity properties. Precipitation, for example, will dramatically change the conductivity properties of soil and vegetation. Such changes during data acquisition will introduce significant errors that are difficult, if not impossible, to mitigate.

Much research has been conducted and papers written on comparison and assessment of LiDAR and InSAR derived DTMs. Dowman et al (2003) compares the 5m NextMap UK to LiDAR, GPS, and photogrammetry and concludes that vertical accuracy of NextMap data strongly depends on different land cover. Its vertical accuracy is best over open fields and deteriorates significantly over the vegetated areas. Comparison of the NextMap and LiDAR DTM over open fields yielded a mean difference in elevation of -0.22m and 1.01m RMSE.

Studies conducted by Norheim et al (2002) also confirm that overall, LiDAR derived DTMs are more accurate, with less biases and less variance. He indicates that both InSAR and LiDAR are capable of producing DTMs, however, LiDAR produces greater accuracy in densely vegetated areas. Figure 2 and 3 show the level of details between LiDAR and InSAR DTMs. The noisy character of InSAR derived DTM is clearly visible.

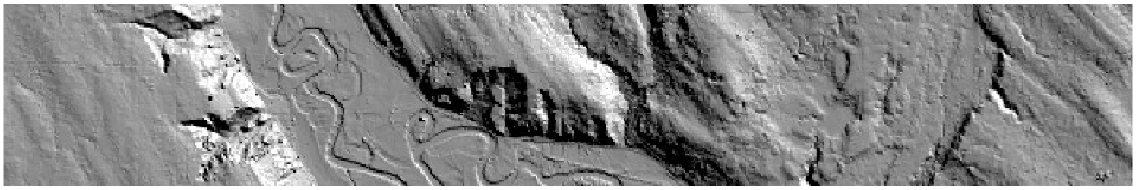

Fig 2 LiDAR derived DTM. Sample size: 2x10km (after Norheim et al, 2002)

Fig 3 InSAR Derived DTM. Sample size: 2x10km (after Norheim et al, 2002)

Table 2 summarises current technical advantages and challenges of LiDAR and InSAR systems.

Table 2 Airborne LiDAR and InSAR Strengths and Challenges

	Technical Strengths	Technical Challenges
LiDAR	• Active sensor • Day/night capability • High vertical/horizontal accuracy • Directly georeferenced (GPS/INS) • High point density • Multiple returns (allow for better ground definition, canopy modelling power line extraction) • Intensity images • Nadir looking geometry and very narrow laser beam (performs well in urban and forestry areas) • Moderate system costs • Engineering standard DTMs	• The final DTM accuracy depends on a calibration procedure • Data filtering is required to produce DTM • Moderate speed and altitude of acquisition • Weather dependent
InSAR	• Active sensor • Day/night capability • All weather conditions including thick smoke • Ortho rectified amplitude images • Directly georeferenced (GPS/INS) • High speed, high altitude of data acquisition • Cost effective data acquisition if large areas of low accuracy are required • Regional Mapping DTMs	• Multipath, foreshortening, layover and shadow cause biases and gaps in the data • Wide resolution cell causes over smoothing and significant biases • Side looking geometry deteriorates performance in urban and forestry areas • Moderate vertical/horizontal accuracy at high altitudes • Changes of atmospheric conditions (turbulence, heavy precipitation) will not prevent data acquisition but will affect the final accuracy • Data filtering is required to produce DTM • Final DTM accuracy depends on a calibration procedure • Short wavelengths do not penetrate vegetation foliage • P-Band (long wavelengths) require longer baselines and stable platform • Resolution cell significantly varies depending on its position across the flight • Very high system costs and very few operators • Generally not well understood by the geospatial industry

3. Applications

There are two important parameters that determine DTM suitability for a specific application: *spatial resolution* and *accuracy*. Usually accuracy refers to the vertical and horizontal aspects. However, as the horizontal accuracy (especially absolute) may not be critical, often DTM accuracy refers to the vertical component only.

Spatial resolution and vertical accuracy (rather than acquisition method) should always decide the methodology to meet the application requirements. This ‘bottom up’ approach will quickly differentiate between different products and ultimately help select a preferred data acquisition technique. In cases when both LiDAR and InSAR accuracies are suitable, differences in data characteristic caused by different acquisition method, as explained in the previous paragraphs, as well as acquisition costs, should be used as a guide.

The two aerial survey techniques generally complement each other along a continuum of requirements.

LiDAR is the preferred technology at the high end of the accuracy scale:
- for engineering applications, earthwork volumes, drainage studies,
- where localised terrain shapes, vegetation penetration and high degree of reliability is required.

InSAR is the preferred technology at the lower end of the accuracy scale:
- for topographic applications, national mapping programs, conceptual planning,
- where high reliability of terrain heights is not cost justified over very large areas.

In between sit those projects which require a closer cost-benefit analysis. A flood study’s whole of catchment DTM can often be satisfied by InSAR at the regional level, but the LiDAR survey will likely be required later anyway if the project has to move to an engineering component or if modelling at a specific location is required. InSAR is valuable when deciding broad planning of remote road corridors … which side of the mountain should one use … but LiDAR will be required if and when the project requires accurate earthwork volumes. InSAR will provide overall DSM information of a cityscape, but the project may benefit from finer definitions of individual buildings, trees or actual powerline conductors. (Refer to Gamba et al 2003 for detailed comparison.)

InSAR operates virtually under all weather conditions. It is also more cost effective over very large areas (hundreds of thousands of sq km) … but “cost effective” only if the project will cope with the resultant data accuracies. InSAR’s final DTM has lower and often neglected varying degrees of accuracy across the captured area. It is the compromising accuracy and marketing strategy (selling pre-captured DTMs to multiple clients) that reduces otherwise high cost of InSAR survey.

Like all survey planning, the geospatial professional should analyse the requirements and available budget to decide the most appropriate survey technique(s).

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Author's Biography

Ireneusz Baran received a M.Sc. Eng. degree in surveying and cartography from the University of Science and Technology (AGH), Krakow, Poland, in 1997, and a Ph.D. degree in Satellite Radar Interferometry from Curtin University of Technology, Perth, Australia, in 2004. From 1995, he worked on several commercial and scientific projects including GPS and InSAR. Since 2006, Dr Baran has been employed with The AAMHatch Group as their LiDAR and InSAR specialist.