

NATIONAL AND REGIONAL SCALE DEMS CREATED FROM AIRBORNE INSAR

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ABSTRACT:

The objective of this paper is to provide an update on a program to create a single uniform DEM (Digital Elevation Model) for Western Europe and for the USA over the next two years. This program is referred to as NEXTMap[®] and utilizes airborne InSAR (Interferometric Synthetic Aperture Radar) technology. In this paper the technology and the platforms with which this program is to be accomplished will be summarized. Some details on the operational implementation and current status will be provided. Moreover it will be placed in context with other programs such as the SRTM, the planned Tandem-X mission and with other technologies such as airborne lidar.

1. INTRODUCTION

The use of DEMs is widely spread and growing, not only in the traditional mapping world but increasingly in support of new applications that are driven by consumer interests. In this new environment, not only do required levels of detail and implicit accuracy vary according to application, but price and current availability are major considerations for the user, many of whom come from outside the geomatics industry. An additional consideration is that some applications, in order to be effective, transcend local political boundaries and require uniform data-sets across regional, national and even continental scales. Meanwhile the advances of enabling technologies such as GPS, communications bandwidth, storage capacity and processing power have been instrumental in the growth of both numbers and capability of systems for DEM creation including both passive and active systems. Among the active systems, both lidar and InSAR (Interferometric SAR) have become major sources of three-dimensional information.

At the high performance end of the performance scale, modern lidars with point densities of several points per msq can achieve DEM accuracies better than 30 cm RMSE routinely, with 2-3 times better accuracy given sufficient effort. Typically prices range upwards from US\$100/kmsq for lidar-generated DEMs and the project areas are often local (some exceptions exist in both the USA and Europe). At the other end of the performance/cost/availability scale, the SRTM DEM with coverage over approximately +/- 60 degrees latitude on a 3" grid (about 90 meters at the equator) and vertical accuracy generally in the 4 -12 m RMSE range is almost universally available at very little cost.

The subject of this paper is Intermap's NEXTMap program in which airborne InSAR is used to create DEM (and image) products with vertical accuracy of 1 meter, sample spacing's of 5 meters, and national-scale coverage in Western Europe and the USA (excluding Alaska) by 2009. In the following sections we will provide a brief background with respect to the InSAR technology, and summarize the specifications and validation of the various DEM and image products. This will be followed by

a discussion of the NEXTMap concept with an update of the current implementation status and a description of the current capacity of the acquisition and processing elements required to achieve the NEXTMap goals and schedule. Examples of the DSM products will be provided in the context of some of the new application opportunities that are developing. Finally the competitive environment relative to alternative technologies will be addressed, followed by a summary and conclusions.

2. BACKGROUND

2.1 InSAR Summary

The interferometric process has been widely discussed in the literature, (e.g. Zebkor and Villsenor (1992), Bamler and Hartl (1998), Rodriguez and Martin (1992)). The geometry relevant to height extraction, 'h', is illustrated in Figure 1. 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 received wave-fronts. The baseline angle 'θ_b' is obtainable from the aircraft inertial system, the aircraft height is known from differential GPS and the distance from antenna to pixel is the radar slant range. Then it is simple trigonometry to compute the target height 'h' in terms of these quantities as shown in equations 1-3.

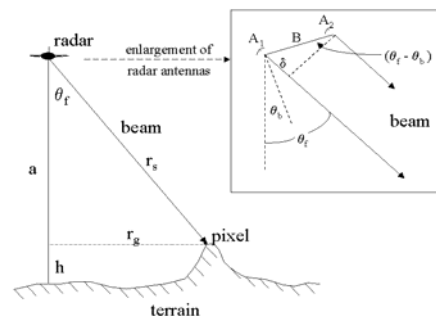


Figure 1. Schematic of Airborne IFSAR Geometry.

$$\sin(\theta_r - \theta_b) = \delta/B \quad (1)$$

$$\delta/\lambda = \varphi/(2*\pi) + n \quad (2)$$

$$h = H - r_s \cos(\theta_r) \quad (3)$$

The path-difference ‘ δ ’ is measured indirectly from the phase difference ‘ φ ’ between the received wave fronts (eqn. 2). Because the phase difference ‘ φ ’ can only be measured between 0 and 2π (modulo 2π), there is an absolute phase ambiguity (‘ n ’ wavelengths) which is normally resolved with the aid of relatively coarse ground control. A “phase unwrapping” technique completes the solution. Thus the extraction of elevation is performed on the “unwrapped” phase. Often the IFSAR is operated in a so-called ping-pong mode which effectively doubles the value of the geometric baseline B . These equations become the basis for sensitivity and error analysis (e.g. Rodriguez and Martin (1996)). For ‘single-pass’ InSAR airborne systems as described in this work, the signals are received almost simultaneously so that errors induced by temporal-decorrelation are not a factor as is the case for satellite systems such as ERS and Radarsat which operate in a ‘repeat-pass’ mode. Provided the baseline length, position (from DGPS) and attitude (from coupled GPS/inertial) are adequately controlled and/or measured, the dominant noise-like error source arising out of these sensitivity equations is ‘phase noise σ_φ ’ so that the signal-to-noise ratio, which is a function of flying height among other system-related factors, becomes a means of (partly) controlling height error specifications. That is, other parameters being fixed, the height noise will increase as a function of flying height. For example, DEMs created from the STAR-3i system (Table 1), when operated at about 9km altitude, has a height-noise level of about 0.5 m (1 sigma, 5 m sample spacing) at the far edge of the swath. Systematic errors, with reference to STAR-3i DEMs, are usually slowly-varying and arise from a variety of sources but are limited through calibration, operational and processing procedures

The schematic idealization of Figure 1 is replaced of course by many factors in the practical implementation of InSAR. For example a complex image containing phase and magnitude information is created from the signal received at each antenna. Subsequent operations on the complex images allow three ortho-rectified products to be derived: DEM, Magnitude and Correlation. The DEM, as noted earlier, is usually referred to as a DSM in recognition that the received signal relates to the scattering surface which may be the terrain or could be an object upon the terrain, natural or otherwise. The magnitude is often referred to simply as an ORI (Ortho-Rectified Image). In relatively open urban or forest situations, it is possible to create a DTM (Digital Terrain Model) from the DSM (Wang, et. al. (2001)) and this has been offered in past as a Core Product along with the DSM and ORI (see Table 2 below). More recent alternatives to this process are beyond the scope of this paper.

2.2 Current Intermap Airborne InSAR Systems

Intermap has developed and currently operates five airborne InSAR systems (Table 1). The first of these systems STAR-3i[®], has been operated by Intermap since 1996. STAR-3i, is an X-band, HH polarization InSAR flown on a Learjet 36 (Tennant and Coyne, 1999). In the last few years, Intermap has replaced all of the software and most of the hardware in order to improve product quality and efficiency of operation. In particular this has led to higher resolution images, and better vertical accuracy of the DEMs (Table 2). Equally important,

software automation has led to improvements in processing throughput. The net result of the modifications is higher quality data sets moving toward decreasing costs and wider availability. The second system, named TopoSAR[®] (formerly called AeS-1 [Schwäbisch and Moreira, 1999]), and is flown on an Aerocommander turbo-prop platform. In addition to X-Band, HH single-pass IFSAR, it supports repeat-pass, fully polarized P-Band InSAR and is currently being used mainly as a research platform.

In order to increase production capacity, a new InSAR system architecture has been created, incorporating elements of STAR-3i and TopoSAR design. The third InSAR system, created in 2004, is named STAR-4, is based completely on the new architecture and is flown in a King Air prop-jet. Two additional systems based on this architecture have subsequently been developed by Intermap in 2006. At the time of this preparation, STAR-5, which is also flown on a King Air platform has been operational for 7 months, while STAR-6, integrated into another Lear Jet, has been operational for about 3 months. Current specifications of the four STAR systems used in the NEXTMap program are summarized in Table 1 and the platforms shown in Figure 2. In principle the acquisition rate for a single system could reach about 7,000 km²/hr for the Lear Jets. In practise, however, the effective acquisition rate is considerably reduced by turning times at end-of-line, side lap (terrain-dependent) and the requirement for partial re-flights due to factors which would otherwise drive the data outside specification.

System / Parameter	STAR-3i	STAR-4	STAR-5	STAR-6
Operational year (Initial)	2002 (1996)	2004	2007	2007
Platform	Lear 36	King Air 200T	King Air 200T	Lear 36
Typical Speed (km/hr)	720	430	430	720
Wavelength / Polarization	3 cm / HH	3 cm / HH	3 cm / HH	3 cm / HH
Peak Transmit Power (kW)	8	8	8	8
Bandwidth (MHz)	135	135 / 270	135 / 270	135 / 270
Baseline Length (m)	0.92	1.02	1.02	1.04
Polarization	HH	HH	HH	HH
Look Direction	Left or Right	Left or Right	Left or Right	Left or Right
Platform Altitude (km)	6 – 12	4 – 8.5	6 – 12	4 – 8.5
Swath Width (km)	8 – 15	6 – 11	8 – 15	6 – 11

Table 1: Selected System Parameters of Intermap’s Airborne InSAR Systems (STAR Series only)



Figure 2. Clockwise from upper left: STAR-3i, STAR-4, STAR-6 and STAR-5.

2.3 Product Specifications

The core products available from Intermap’s online store include an Ortho-rectified Radar Image (ORI) a Digital Surface Model (DSM) and the bare earth Digital Terrain Model (DTM). X-band images are at 1.25-m resolution with similar horizontal accuracy. DSM and DTM are posted at 5m spacing. The elevation products are available in three standard vertical accuracy specifications as illustrated in Table 2 below. It is worth noting that all four of the STAR family of sensors are able to achieve these product specifications despite the nuance of individual system design or platform specifics. Apart from these CORE specifications, other accuracies and image/DEM resolution can be supported to meet specific requirements. Optical/radar merged products are now also becoming available. Varying flying altitudes and operating modes, enables different accuracy specifications to be achieved which may be reflected in cost.

Product Type	DSM		DTM	
	RMSE	Spacing	RMSE	Spacing
I	0.5	5	0.5	5
II	1	5	1	5
III	3	10	-	-

Table 2: Intermap Core Product specifications for InSAR DSMs and DTMs. All units are meters. RMSE refers to vertical accuracy and is with respect to terrain that is moderately sloped, bare (DSM) and unobstructed. DTM specifications apply to areas for which the forest or other above ground cover is ‘patchy’ to a maximum scale of about 100 meters. Details of these specifications may be found at www.intermaptechnologies.com.

2.4 Operational Flow

The operational flow consists of four major stages: (1) planning and acquisition, (2) interferometric processing, (3) editing and finishing, and (4) IQC (Independent Quality Control) after which the data are delivered to the data base repository (the ‘i-Store’). The operational concept has evolved to accommodate the requirements imposed by the current NEXTMap® goals as well as custom projects. The NEXTMap® Europe and USA objectives alone require the data acquisition for an area incorporating more than 10 million km² by the end of 2008. All aspects of production are managed with rigorous QC checks throughout and within the framework of the companies’ ISO9000 certification.

2.4.1 Planning and Acquisition: Typically blocks of 200 km x 200 km are planned. Within these blocks, parallel flight lines are planned according to terrain to ensure that there will be no gaps between swaths. Three tie lines per block are flown, orthogonal to the main data passes in order to assist in the removal of systematic errors during the processing stage. Radar reflectors are pre-sited at the ends of the tie lines and surveyed in precisely. These ultimately fix the DEM and ORI to the reference ellipsoid. In order to achieve the Type II DSM vertical accuracy specification, GPS baselines are kept within about 75km. Formerly this meant deploying ground crews to operate GPS ground stations in the acquisition area: however the densification of CORS networks in the USA and similar GPS networks in Europe, is easing this requirement. Moreover, a recent improvement in process and software has enabled longer line lengths, to 1200 km, to be flown by the Lear Jets, thereby reducing the fraction of lost time due to aircraft turns at the end of lines. Navigation and certain other data are processed and analysed after each mission in order to determine whether the quality limits have been satisfied for the particular data type specified. Data which do not satisfy the quality criteria must be re-acquired, normally before the aircraft has departed from the area.

2.4.2 Interferometric Processing: Because of the multiple platforms, high data volumes, differing product specifications, varying schedule priorities, and the demand for high throughput, the processing task is very complex. This part of the process, now performed in a single processing centre, has been automated to a considerable extent with internally developed software and procedures. The system is PC-based (64-bit blade processors). In particular, the processing architecture has been developed to be scalable in order to accommodate the increasing data volume as acquisition efficiency and platform numbers have increased. The process ingests the raw signal data (‘phase history’), ancillary data and navigation data, performs the interferometric processing to ultimately create strips of image and elevation data. Systematic errors are reduced through an internally-developed adjustment process using the controlled orthogonal tie lines that run across the data block. Output products in the form of 7.5’x7.5’ tiles are created for subsequent refinement.

2.4.3 Editing and Finishing: An independent system referred to as IES (Intermap Editing System) has been developed, incorporating a set of editing tools within a stereo-viewing environment. The input data tiles (images and DSMs) are ortho-rectified so false stereo is created to enable the image to be viewed and manipulated in stereo. The human editor uses the tool set to address hydrological features (e.g. flatten water bodies, ensure rivers run down hill), edit transportation features (roads, railways, airports, etc) and to edit radar artefacts. A set of editing rules determines a consistent application of the IES tools across different geography and across different editors. Editing is the most human intensive component of the operational activity and incorporates many quality control steps within the process. At the end of the process, 15 km x 15km tiles of DSM, DTM and ORI are available for IQC.

2.4.4 IQC (Independent Quality Control): A group separate from the production team reviews the IES output tiles for editing completeness and accuracy. The accuracy checks are usually with respect to publicly-available GCP data such as the NGS (National Geodetic Survey) network in the USA. Tiles that are not judged complete at the 95% level, or whose accuracy checks are outside specification are returned to the production side for re-processing as required. A summary accuracy report for the state of California is noted in the caption to Figure 3. The (normally) successful tiles are forwarded to the i-Store at this stage for entry into the data-base. Subsequent to this stage the data are available to the public under license. A global interface tool allows regions of interest to be displayed for availability and detail including thumbnail presentations.

3. NATIONAL MAPPING PROGRAMS: NEXTMAP

NEXTMap is the term used by Intermap to describe its InSAR-based national and regional mapping programs. Specifically the concept is to make DSM, DTM and ORI products generally available in a seamless fashion over national and trans-national regions where multiple applications and markets may benefit. By retaining ownership and licensing the data to multiple users, the cost is shared, making it feasible for public and private organizations to have access to these data sets or to parts of them. The Type II specification for the DSM creates a level of detail (1m RMSE vertical accuracy, 5 meter samples) intermediate between lidar or photogrammetrically-produced products on the one hand, and SRTM or SPOT5 products on the other (Table 3). The associated ORI carries a resolution of 1.25 m and horizontal accuracy less than 2m RMSE.

NEXTMap Britain was implemented in 2002/2003 (England and Wales) and subsequently extended to include Scotland (for a description, see Mercer, 2004). On the basis of the success of that project, as well as lessons learned, the decision was made to proceed with a NEXTMapUSA project with the goal of 2008 completion. As of April, 2007 about 1/3rd of the 8 million km² had been acquired and over 1/4 of these data had been interferometrically processed. This rate is rapidly accelerating because of the introduction into operations of STAR-6 since then. An example is shown in Figure 3 of the DSM of the State of California.



Figure 3: NEXTMAP USA Example - California DSM
Validated vertical accuracy (1430 check points) 0.76 m RMSE

3.1 NEXTMap Europe: Status

Twelve countries in western Europe are currently scheduled in the NEXTMap Europe program (Figure 4) and this list will

likely be expanded. The data acquisition phase for Germany was completed in a 3-month period of 2006 and the completed products should become available in September 2007. Forecasts for product availability of the remaining countries is shown in Figure 4. Two factors will likely impact these forecasts: (1) the time it takes to obtain overflight permits vary from country to country, and (2) priorities are subject to market forces.

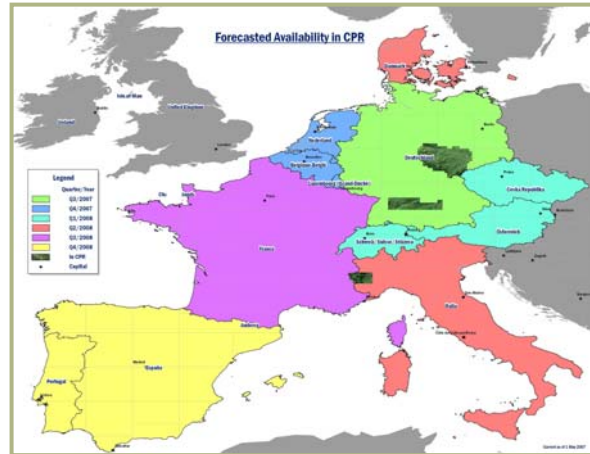


Figure 4: Forecast dates (current, May 2007) for product availability of NEXTMapEurope areas. The various colours starting with light green (September 2007) and ending with yellow (December 2008) show the forecast dates that the data products will be available. Dark green 'thumbnails' are currently in the data base. This forecast may change subject to operational and other priorities.

4. EXAMPLES

In this section we show examples from two potential market areas which should benefit from the availability of NEXTMap coverage. In Figure 5 a flood risk application is exemplified, while in Figure 6 a visualization example is presented. In both cases the DSM is draped by a high resolution colour air photo. Because of the presence of the 1.25 m ORI it is possible to easily ortho-rectify the air photos using rational functions procedures (or similar), making the co-registration of air-photo to DSM relatively simple. The flood risk application involves 3rd-party models for which the DSM product is an important input component. The visualization example relates to many applications and markets ranging from recreation to automotive safety. In this instance it is a scene extracted from a fly-through (Eye-Tour).

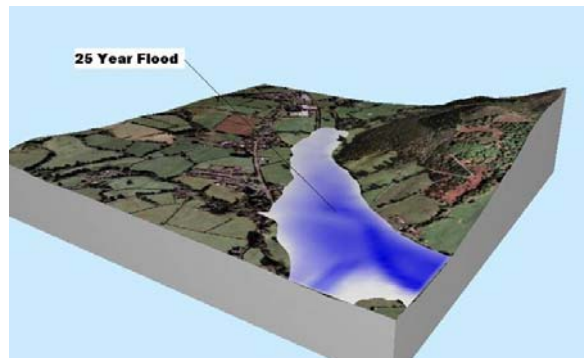


Figure 5: Example from NEXTMap Britain flood risk application



Figure 6: Example from NEXTMap USA - California scene extracted from a fly-through near San Francisco

5. THE COMPETITIVE ENVIRONMENT

From a commercial perspective, any technology must evaluate its position in the competitive environment with respect to alternative choices: in short, what does it offer in terms of familiar factors such as price, product specifications, and availability? In particular it is of interest to review the advantages and limitations of DEMs created by space borne sources as well as airborne lidar relative to the NEXTMap products described in this paper and relative to markets such as those alluded to in this paper. A brief summary is provided in Table 3. The brown colour suggests areas of comparative disadvantage, at least in the market areas suggested here. Intermap currently does not publish a price list. However, based upon previous published information, it could be within the \$3-\$30/km² regime depending on the factors of quantity, license type and other factors. If this assumption is correct, it appears that it will be complementary rather than competitive with lidar, based upon availability and price. Similarly it appears to be complementary to SRTM based upon the difference in detail provided. The Tandem-X space borne InSAR system will create products of comparable detail to NEXTMap if it performs according to specification. However its launch is not scheduled until 2009 and the product is not expected to be available until the 2012-2013 time frame. Therefore it appears that in the context of market, product specification, availability and price the NEXTMap products occupy an attractive niche in the competitive environment.

DEM Sources	Sample Spacing (m)	Vertical Accuracy (m) @90%	Availability	Coverage	Price
SRTM	90 30 (USA)	16 abs 10 rel (5.8 ⁽¹⁾)	Now	Global (almost)	'Free'
SPOT 5	30	10 @ abs	Now	Global (almost)	\$ 4/kmsq ⁽²⁾
Tandem-X	10	10 abs 2 rel	2012 -2013	Global	Commercial TBD
NEXTMap	5	1.65 abs 1 rel	2008 -2009	USA, W.Europe	Competitive ⁽³⁾ (see text)
Lidar	1 to 3	0.3 ⁽⁴⁾ abs	Now	Local	\$150 - 600/kmsq ⁽⁴⁾

Indicates suitability problems for the markets or applications under consideration

(1) Dean Gesch: comparison with NGS benchmarks in USA
 (2) List price SPOT USA
 (3) Dependant on size, license type, etc
 (4) Nominal - project, location and vendor dependant

Table 3: Comparison of different DEM sources with respect to detail, availability, coverage and price. Note that the vertical accuracy is quoted with respect to the 90% confidence level rather than RMSE in this table.

6. SUMMARY AND CONCLUSIONS

The NEXTMap program, based upon airborne InSAR, is in the process of creating a 3-dimensional, homogeneous, seamless database including DSM, DTM and ORI products, for twelve countries of western Europe (in addition to Britain which is already available) and for the USA (excluding Alaska). The DSM is specified at 1 m RMSE vertical accuracy for 5 m sample spacing, while the ORI is specified at 1.25m resolution with better than 2 m RMSE horizontal accuracy. For many applications the combination of detail provided, national and super-national availability and shared pricing through license arrangements, should produce an attractive user opportunity. The creation of the datasets for both areas is well underway and scheduled for completion, in the case of Western Europe, for late 2008 and about 1 year later for the USA. With respect to many market applications such as visualization, flood risk, and auto safety these products should occupy a solid niche, relative to alternative technologies.

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