Countrywide Coverage of RADAR DTMs – The Intermap Approach

BRYAN MERCER, Calgary

ABSTRACT

Three-dimensional data-sets as manifested in Digital Surface Models (DSMs) and Digital Terrain Models (DTMs) have become an integral part of most geospatial applications, both traditional and emerging. However, one difficulty for the user is that there has existed a gap between the broad coverage, low cost DSM afforded by SRTM and the highly detailed but costly and sporadic coverage of lidar. Moreover, in the European context, the historical data sets are referenced to a variety of datums, ellipsoids and geoids. On the other hand, many applications do not stop at political boundaries. NEXTMap® Europe is Intermap's solution to fill the gap with a 1 meter vertical (RMSE) , 5 meter gridded elevation data set that is trans-national across a broad portion of Western Europe. In May 2009, Intermap announced the completion of its current NEXTMap® Europe program. The resulting data set spans 15 countries and 2.2Million km². In this paper we provide the technical and operational background to this accomplishment, demonstrate the wide-area consistency of the vertical accuracy supported by the data and provide a few examples from a range of applications.

1. INTRODUCTION

The use of Digital Elevation Models (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 Interferometric SAR (InSAR) have become major sources of three-dimensional information.

In particular, airborne InSAR, as demonstrated in the following sections, is contributing to the wide-spread availability of DEMs over continent-sized areas and across national boundaries with properties of accuracy, resolution and price that are intermediate between those of lidar and SRTM. The objective of this paper is to provide an update on the NEXTMap® programs for creating DEMs of Western Europe (in particular) and the USA using well-developed operational airborne X-Band InSAR technology.

In the following sections we will first provide a brief background with respect to InSAR technology in general and then with respect to the Intermap STAR-series of platforms and the 3D core products that result. The operational context of the acquisition, processing, editing and QA phases is described and recent internal accuracy validation results presented. This will be followed by a discussion of the NEXTMap® concept with an update of the current status for Europe and the USA. A small set of representative applications examples completes the review.

2. INSAR BACKGROUND

The interferometric SAR (InSAR or IFSAR, used interchangeably here) process has been widely discussed in the literature, (e.g. Zebkor and Villsenor, 1992; Bamler and Hartl, 1998; Rodriguez and Martin, 1992). In the following brief description we summarize the basic elements of InSAR in the context of an airborne, ‘single-pass’ system.

The geometry relevant to height extraction, h, is illustrated in Figure 1. If the two antennas, A1 and A2, 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, determined by the ‘look angle’, θ_f, the tilt angle of the rigid baseline, θ_b, with respect to horizontal, and the baseline length, B as shown in Eqn.1. The path-difference δ is measured indirectly from the phase difference φ between the received wave fronts (Eqn. 2), where λ is the received wavelength. Then it is simple trigonometry to compute the target height h in terms of these quantities as shown in Equations 1-3. The baseline tilt angle θ_b is obtainable from the aircraft inertial system, the aircraft height, H, is known from differential GPS and the distance from antenna to pixel is the radar slant range, r_s.

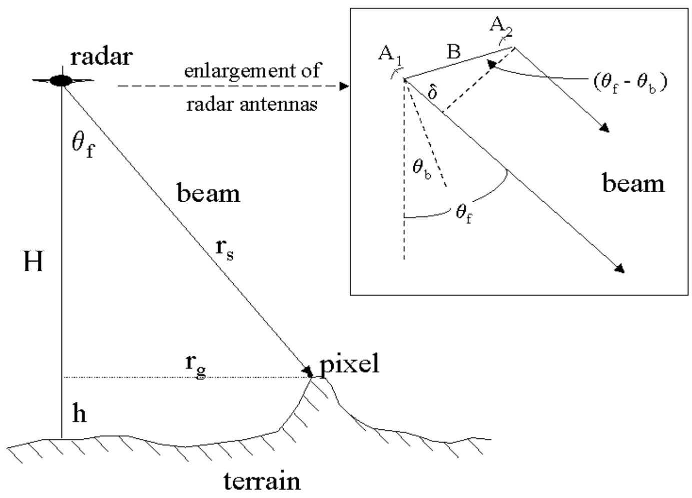


Fig. 1: Schematic of Airborne InSAR Geometry.

$$\sin(\theta_f - \theta_b) = \delta/B \quad (1)$$
$$\delta/\lambda = \varphi/(2\pi) + n \quad (2)$$
$$h = H - r_s \cos(\theta_f) \quad (3)$$
$$k_z = 4\pi\,[B/\lambda H]*[\tan(\theta_f)/\cos(\theta_f)] \quad (4)$$

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, which removes the phase ambiguity, completes the solution. Thus the extraction of elevation is performed on the ‘unwrapped’ or absolute phase. Often the InSAR 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, 1992). The sensitivity of the system to phase errors can be estimated in terms of $k_z = \Delta\varphi/\Delta h$, (Eqn. 4), where we have assumed a horizontal baseline and ping-pong mode. For example, with typical STAR-3 parameters (see below), at H=9000m and 45°

look angle (approximately mid-swath), a phase increment (or phase error) of approximately 3/4° would correspond to a height increment (or error) of about 20 cm. Because of the geometrical term in Eqn. 4, the height error increases across the swath.

Provided the baseline length, the sensor position (obtained from DGPS), and attitude (obtained 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. The phase noise can be approximated as a function of the signal-to-noise ratio (SNR) (e.g. Rodriguez and Martin, 1992) so that the SNR, 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-3*i* system, when operated at about 9km altitude, has a height-noise level of about 0.2 m (1 sigma, 5 m sample spacing) near the middle of the swath increasing to about 0.5m near the far edge of the swath. Systematic errors, with reference to STAR-3*i* DEMs, are usually slowly-varying and arise from a variety of sources but are limited through calibration, operational and processing procedures

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 interferometric mode (the SRTM on the other hand was a single-pass interferometric system).

3. STAR-SERIES AIRBORNE INSAR SYSTEMS

Intermap commenced operations with its STAR-3*i* airborne InSAR platform in 1997. In order to meet the schedule requirements of its NEXTMap® programs (Section 6) in Europe and the USA, as well as other projects, Intermap has recently developed three additional operational airborne InSAR systems (Figure 2) to supplement the acquisition capability of the STAR-3*i* system. STAR-3*i*, is an X-band, HH polarization InSAR flown on a Learjet 36 (Tennant and Coyne, 1999). In the last few years, all of the software and most of the hardware has been replaced in order to improve product quality and efficiency of operation. The three new systems are based on a common architecture and are flown in 2 King Air and 1 Lear Jet platforms respectively. The systems are described in somewhat greater detail in Chapter 6 of (Maune, 2007). The addition of these systems has greatly improved scheduling flexibility and acquisition capacity.

Azimuth resolution of all systems is about 0.5 m (before pre-summing) and slant range resolution is either 0.55 m or 1.11m (depending on which bandwidth option is selected). The standard ‘Type II’ mode for the acquisition examples discussed below results in a ground pixel image sample of 1.25 m x 1.25 m. Further phase smoothing results in elevation samples of 5 m x 5 m.

The major operational difference between the two types of platform is that the LearJets fly faster and somewhat higher than KingAir with the result they have higher acquisition capacities. Typical swath widths (altitude dependent) are about 8.5 km and 10 km for the two platform types. Viewing angles (or look angles) across the swath range from approximately 30° to 60° with respect to nadir. Line lengths, depending on various factors, can be up to 1200 km. The radar antennas, attached to a rigid frame, can be rotated upon command to point either left or right of the aircraft. Operational procedures are such that all images in a project are illuminated from the same direction.

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

4. CORE PRODUCT SPECIFICATIONS

The core InSAR 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). The DTM is derived from the DSM. X-band images associated with the Type II or III products are at 1.25-m pixel spacing (approximate resolution) with horizontal accuracy specified as 2 meters (RMSE). Following a recent upgrade, a new mode Type I+ allows for image resolution of 0.6 meters. The DSM and DTM are posted at 5m spacing. The elevation products are available in three standard vertical accuracy specifications as illustrated in Table 1 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 resolutions can be supported to meet specific requirements. Optical/radar merged products are now also available and are exemplified in Section 8.

	DSM		DTM		ORI	
	RMSE	Spacing	RMSE	Spacing	RMSE	Pixel
Type I+	0.5	5	0.7	5	<2	0.625
Type I	0.5	5	0.7	5	2	1.25
Type II	1	5	1	5	2	1.25
Type III	3	5	-	-	-	1.25

Table 1: Intermap Core Product specifications for InSAR DSMs, DTMs and ORIs. All units are meters. RMSE refers to vertical accuracy (DSM and DTM) 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.intermap.com. For the ORI, 'pixel' refers to pixel spacing, while RMSE refers to horizontal (circular) error.

5. OPERATIONAL ELEMENTS

The operational flow consists of four major stages: (1) planning and acquisition, (2) interferometric processing, (3) editing and finishing, and (4) Independent Quality Control, after which the data are delivered to the data base repository. The operational concept evolved to accommodate the requirements imposed by the NEXTMap® goals (see section 6) as well as custom projects. The NEXTMap® Europe and USA objectives alone required the data acquisition of an area incorporating approximately 2.2 and 8.0 million km^2 which were completed in the spring of 2009, only a few months behind the original schedule. All aspects of production are managed with rigorous QC checks throughout and within the framework of ISO9000 certification.

During the acquisition phase, a typical area is acquired as a rectangular block with multiple overlapping strips (swaths) ultimately merged together. Orthogonal tie lines are flown with 50 km spacing (for Type I and II programs). Each of the tie lines has corner reflectors (trihedrals) positioned in the scene. The coordinates (X, Y, Z) of these reflectors have been precisely surveyed relative to local networks and are used as ground control for the block. Systematic errors are thereby largely removed through an adjustment process incorporating all the primary lines and tie lines, controlled ultimately by the corner reflectors. The amount of overlap of the primary lines in the block is determined during flight planning which also takes account of mountainous terrain. In severe shadow/layover circumstances, additional flights are planned for orthogonal illumination.

The interferometric processing stage is largely automated, optimized and scalable using internally-developed software and procedures. It ingests aircraft navigation data, signal data and ancillary data and outputs data as merged DSM and DTM tiles (normally 7.5' x 7.5') and corresponding ORI mosaics. Data are referenced to the appropriate ellipsoid and geoidal models (see Core Product Handbook at the Intermap website). The data-handling and capacity challenges are quite formidable given the need to incorporate the needs of NEXTMap along with those of custom projects. The current steady-state processing capacity is about 400,000 km^2/month.

An independent editing and production process receives the DSM, DTM and ORI tiles delivered by the interferometric processing stage. An internally-developed system referred to as IES (Intermap Editing System) provides the support for this activity. The purpose is to remove artifacts from the data such as spikes and wells that occur near voids in the data, to flatten water bodies, to ensure river drainage is monotonic and appropriately stepped, to smooth roads and to ensure that a number of other cartographic requirements are satisfied. A set of edit rules may be found in the Core Product Handbook (www.intermap.com) which discusses the requirements in detail. The IES workstation is a set of custom editing tools implemented in a stereo environment within which pseudo-stereo is created from the ORI and DSM. Certain tasks are automated or semi-automated while others require significant operator inspection and intervention. Currently more than 150 workstations are used for editing tasks. Ramp-up to current capacity has occurred over several years but is now consistent with interferometric processing output rates.

All editing output is examined by an 'Independent Validation and Verification' (IV&V) group within the company before release to the data store. One of the tasks of IV&V is to validate accuracy of the final products with respect to independent check points (CPs). Typically the check points are obtained from government agencies of the various countries. Usually they are accompanied by descriptions which enable a pre-selection of those points that are suitable for use in the validation activity. For example the check point must be unobstructed to be suitable for this purpose. In addition to the survey description, high resolution photography is usually inspected to confirm the suitability of the screened check points. The check point pre-screening is performed before their use for validation. Vertical differences (DSM – CP) and (DTM – CP) are created and statistics computed, on a country or state basis usually. The results of one set of validations are presented in section 7 below.

6. NATIONAL MAPPING PROGRAMS: NEXTMAP

NEXTMap® is the term used by Intermap to describe its airborne 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 in whole or part. The Type II specification for the DSM (Table 1.) creates a level of detail intermediate between lidar or photogrammetrically-produced products on the one hand, and SRTM or SPOT5 products on the other.

NEXTMap Britain was implemented in 2002/2003 (England and Wales) and subsequently extended to include Scotland (Mercer, 2004). On the basis of the success of that project, as well as lessons learned, the decision was made to proceed with a NEXTMap USA project. Soon after, NEXTMap Europe was also initiated. This trans-national program, was initiated in 2006 and currently includes fifteen countries in a single block comprising 2.2 million km^2 combined area. The data acquisition phase of NEXTMap Europe was successfully completed in 2008 and the processing, editing, IV&V and data-base transfer phases were themselves completed in the spring of 2009. In Figure 3 we show an overview of its location and associated DSM.

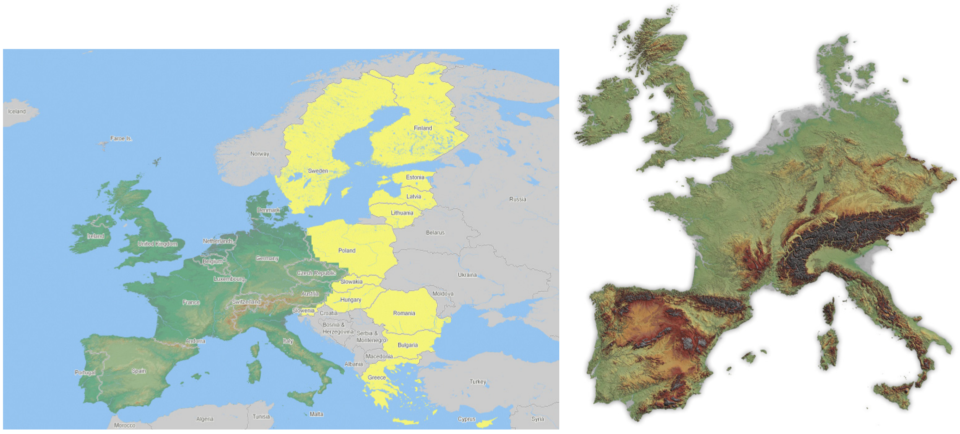


Fig. 3: Left: Outline of the current data-base coverage of NEXTMap Europe including the 15 countries listed in the text. Right: DSM of the area comprising approximately 2.2 million km².

The fifteen countries currently in the NEXTMap Europe data-set include: Austria, Belgium, Czech Republic, Denmark, France, Germany, Ireland, Italy, Luxembourg, Malta, Netherlands, Portugal, Spain, Switzerland, and the United Kingdom. Other countries will be added in the future.

Meanwhile the development of NEXTMap USA (as well as other projects) has been continuing in parallel. As of May, 2009 all 8 million km^2 in the USA (lower 48 states) had been acquired and over 40% of these data were delivered to the data base repository. The current completion date is scheduled for early 2010.

7. TRANS-NATIONAL ACCURACY CHECK

Internal vertical accuracy validation, summarizing the results for five countries in Western Europe, is shown in Table 2. Considering the DSM, we note that mean difference <(DSM – CP)> is within +/-0.25 meters, which indicates the effectiveness of the adjustment process described earlier in section 5. The observed standard deviations are consistently between 0.5 and 0.8 meters across the country-wide samples. The phase noise (section 2) accounts for part of this magnitude while slowly varying systematic errors are likely to contribute to most of the remainder. Compared with Table 1, the observed RMSE at this scale of analysis is well inside the Type II specification of 1.0 meters. Similar sets of results have been obtained for several states within the USA where the process is complete.

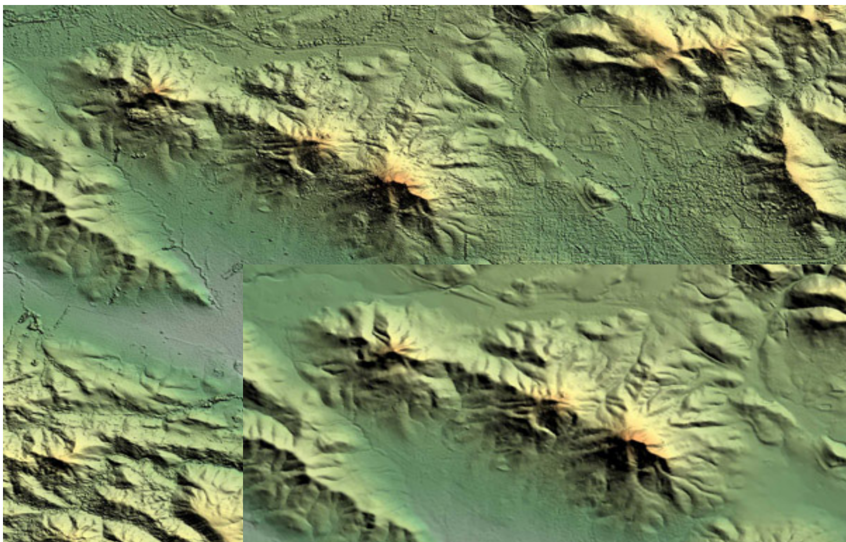
Difference Statistics (meters)	Belgium		France		Germany		Italy		Spain	
	DSM	DTM	DSM	DTM	DSM	DTM	DSM	DTM	DSM	DTM
Mean	0.23	0.12	0.01	-0.22	0.01	-0.16	-0.11	-0.38	0.22	-0.27
Standard Dev'n	0.57	0.58	0.53	0.59	0.68	0.68	0.60	0.78	0.67	0.73
RMSE	0.61	0.58	0.53	0.63	0.68	0.69	0.61	0.87	0.70	0.78
95 Percentile	1.18	1.10	1.06	1.33	1.42	1.47	1.13	1.85	1.38	1.59
No. Check Pts.	53	53	987	987	690	690	703	703	2619	2619

Table 2: Vertical accuracy validation results for five countries in the NEXTMap Europe data set. The difference statistics refer to $(DSM - CP)_i$ and $(DTM - CP)_i$ respectively where CP_i is the ith check point height where i= 1,…n and n varies from country to country as shown in the final row. The check points were pre-screened for suitability as described in the text.

8. EXAMPLES FROM NEXTMAP EUROPE

8.1. DSM and DTM Core Product Examples

Examples of DSM and DTM of a mixed-mountainous area in Italy are shown in Figure 4.



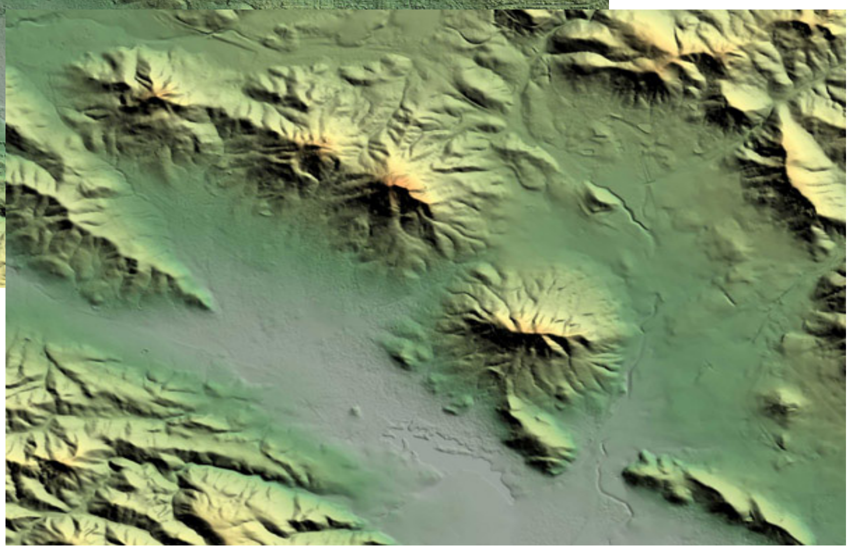
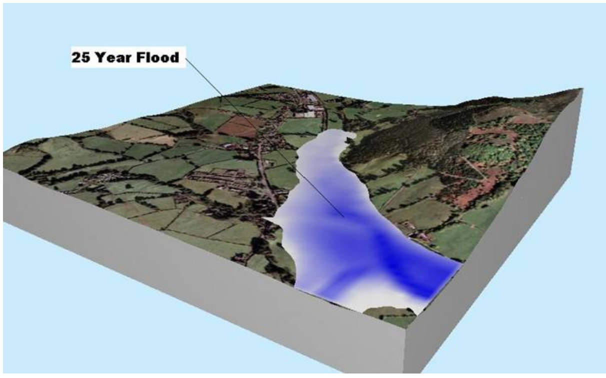


Fig. 4: DSM (upper left); DTM (lower-right). The urban area visible in the north-eastern part of the DSM has been replaced by the bare-earth representation in the DTM.

8.2. Applications

Apart from standard mapping applications there are a series of emerging applications that will benefit from the seamless trans-national NEXTMap Europe data-set. In this paper we sample three diverse applications among many. Many more are provided at www.intermap.com.

Flood Risk Mapping: World-wide flood-losses in 2007 totaled more than 51 Billion Euros and the insurance industry as well as individual property owners must contend with what appear to be increasing risks due to climate change. The problem is to how to manage the risk at a satisfactory level of detail. The underlying requirement of a flood risk model is a DTM of sufficient detail for the purpose. A new flood risk product is being developed by Intermap which combines the base DTM data, ancillary data, and flood models (including coastal surge and river flood models) that are integrated into a platform which enables flood risk to be implemented at the level of individual building addresses. This will become available to stakeholders over a broad scale: from re-insurance companies to initial property owners.



Optical Image Ortho-Rectification: Many of the users of the data from high-resolution optical satellites require the product to be ortho-rectified. The use of an external DEM can be a cost-effective solution to the orthorectification problem through use of Rational Polynomials or other models. However the requirements for improved DEM accuracy become increasingly stringent as satellite acquisition occurs at large off-nadir angles. Through use of the NEXTMap ORI and DTM it is possible to ortho-rectify the satellite imagery at these larger angles to horizontal accuracy levels of 2 meters (RMSE) or better which is satisfactory for many applications. Similarly, aerial photography that that has been acquired with minimal overlap for non-stereo applications, can be orthorectified using an external DTM and ORI. This is an enabling factor for some of the visualization applications noted below.

Visualization Applications: There are a number of applications that are based upon realistic 3D 'fly-through' scenarios. These include in-cockpit simulators, hand-held devices (PND's, GPS units and now the iPhone), motor vehicle systems and web-based services. Intermap, for instance, has developed an application called AccuTerra which provides 2D or 3D information of specific interest to an outdoor recreational market through hand-held devices. The basis for this is the DSM upon which color air-photo imagery is draped. An example is shown in Figure 5.

Fig. 5: Mock-up of a 3D visualization in a hand-held device showing overlays of published trails and other information choices available to the user. AccuTerra is an example of such an implementation which is now commercially available on certain hand-held, GPS-enabled platforms.

9. CONCLUSIONS

The purpose of this paper was to provide an update on the status of the NEXTMap programs, and particularly that of NEXTMap Europe. This program has seen the creation, over a 3-year time period, of a complete 3D trans-national data set, across 15 countries of Western Europe incorporating 2.2 Million km². The objective of the program has been to make available under license to all, a seamless, consistent data-set of high quality DSM, DTM and ORI that can be used in a variety of traditional and new geospatial applications. In this paper we have provided a summary of the InSAR technological basis behind the data-set and have described the major operational activities performed in its implementation. Tests of vertical accuracy of DSM and DTM using about 5,000 check points from five countries, has demonstrated RMSE values in the 0.6 – 0.8 meter range in conditions of obstruction-free, moderately sloped terrain. This is well within the 1 meter RMSE vertical specification for the Type II product that has been created, and in particular demonstrates the continent-scale consistency of the data. Lastly, we have provided a sampling of some of the emerging applications that will benefit from this data-set: these examples range from flood risk analysis to visualization with hand-held devices but represent only a fraction of the possibilities.

10. ACKNOWLEDGEMENTS

My many colleagues in different parts of Intermap were responsible for the NEXTMap achievements summarized in this paper. In particular I would like to thank Stephen Cliffen for providing the validation data and several anonymous colleagues for creating the various image examples.

11. REFERENCES

Bamler, R. and Hartl, P., 1998. Synthetic aperture radar interferometry, Inv. Probl., Vol. 14, pp. R1-R54.

Maune, D. F. ed., (Chapter 6 by Hensley, et. al.) 2007. Digital Elevation Model Technologies and Applications: The DEM Users Manual, 2nd Edition, ASPRS.

Mercer, B., 2004, DEMs Created from Airborne IFSAR – An Update, Proceedings of the ISPRS XXth Congress, July 12-23, Istanbul, Turkey.

Rodriguez, E., and Martin, J. M., 1992. Theory and design of interferometric synthetic aperture radars. IEE Proceedings-F, Vol. 139, No. 2, pp. 147-159.

Tennant, J. K. and Coyne, T., 1999. STAR-3i interferometric synthetic aperture radar (INSAR): some lessons learned on the road to commercialization. In: Proceedings of the 4th International Airborne Remote Sensing Conference and Exhibition/21st Canadian Symposium on Remote Sensing, June 21-24, Ottawa, Ontario, Canada.

Zebker, H. A. and Villasenor, J., 1992. Decorrelation in Interferometric Radar Echoes, IEEE Transactions on Geoscience and Remote Sensing, Vol. 30: Number 5, pp 950-959.