THREE-DIMENSIONAL MAPPING WITH AIRBORNE IFSAR BASED STAR TECHNOLOGY ─ INTERMAP'S EXPERIENCES

X. Li, K. Tennant, G. Lawrence

Intermap Technologies Corp., 2 Gurdwara Road, Suite 200, Nepean, Ontario, Canada K2E 1A2
(xli, ktennant, glawrence)@intermaptechnologies.com

Commission III, WG III/3

KEYWORDS: High resolution, Interferometer, SAR, Mapping, DEM/DTM, Orthoimage

ABSTRACT:

Airborne Interferometric Synthetic Aperture Radar (IFSAR or INSAR) is maturing as a cost-effective three-dimensional mapping technology. It is attracting increased attention in the geospatial community because of its unique operational advantages. Various mapping products are being generated by Intermap's STAR technology which is based on high-resolution airborne IFSAR. More significantly, these STAR derived products are being used for applications traditionally supported by other mapping technologies and this list of applications is growing. This trend is due to the ever-increasing customer confidence towards the STAR derived data. Involved with IFSAR technology since 1993, Intermap is diligently working to exploit the potential of this technology and to develop new, market specific applications. To reach a more widespread acceptance and a deeper and wider application base, Intermap's STAR technology and its mapping products are continuously presented to the general geospatial public from the early adopters through the general provider. Experiences obtained from those applications are highly beneficial to potential users. The objective of this paper is to give the reader a general picture of airborne IFSAR mapping in order for them to better understand the strengths and limitations of the technology and the products.

1. INTRODUCTION

There is a growing demand for high-quality and low-cost three-dimensional (3-D) mapping data for many geospatial applications. Recent advances in sensor development and geo-referencing technologies, coupled with the continuous improvement of digital computing power now enable unparalleled functionality and flexibility in geospatial mapping.

Currently, several technologies are being used to generate map products at various scales, details and accuracy, with strengths and limitations associated with each technology. Leaders in the geospatial community are gradually realizing that airborne Interferometric Synthetic Aperture Radar (IFSAR or INSAR) is maturing as a complementary or competitive cost-effective 3-D mapping technology, evidenced by the several ongoing nation-wide airborne IFSAR mapping efforts.

IFSAR attracted much attention in the geospatial community since data became widely available from the microwave sensor on the ERS-1 satellite. Also, the Shuttle Radar Topographic Mission (SRTM) that flew successfully in February 2000 provided a further impetus for mapping applications using IFSAR technologies. Advantages associated with airborne IFSAR mapping include flexibility of system deployment, near weather-independent operation, cloud penetrating capability, versatile map products, and quick turn-around time.

Three-dimensional mapping products generated by Intermap's STAR technology based on high-resolution airborne IFSAR are being used for applications traditionally supported by other mapping technologies. The product family consists mainly of digital surface models, digital terrain models, and orthorectified radar imagery. In addition, other value added products such as topographic line maps, colorized radar images, and fly-through are produced. The list of applications for these products is growing continuously due to the appropriateness of the data and the ever-increasing client confidence towards them.

The objective of this paper is to give the reader a general picture of STAR technology and its mapping products in order for them to better understand the strengths and limitations of the technology employed to collect and process the data. In the paper, after a brief introduction to IFSAR technology and operating principles, typical mapping mission implementation is outlined. Generation of STAR technology based mapping products is described. Conclusions and the future of airborne IFSAR mapping are given at the end of the paper.

2. AIRBORNE IFSAR TECHNOLOGY – IMPLEMENTATIONS, ADVANTAGES AND LIMITATIONS

Enabled by cost-effective sensor positioning and orientation solution using Global Positioning System (GPS) and Inertial Navigation System (INS) technologies, airborne IFSAR technology is being used as an accurate and reliable 3-D mapping tool. In the early 1970s, airborne IFSAR was applied for topographic mapping studies. Nevertheless, the first commercial airborne IFSAR system entered the mapping world in 1996 – Intermap's STAR-3*i*®. Since then, considerable efforts have been applied and many lessons have been learned on the road to commercializing the STAR IFSAR systems (Tennant and Coyne, 1999; Tennant et al, 2003). As a result, the STAR technology has become more robust and practical, generating mapping products for end users faster and better.

2.1 Single-pass and Dual-pass Mode

Radar interferometry for topographic mapping needs to coherently combine microwave signals collected from two cross track displaced antennae. These antennae can be mounted on a single platform – single-pass mode, or with a single antenna passing over the area twice – dual-pass mode. While space systems typically use a dual-pass configuration (the notable exception is SRTM), most modern airborne implementations are single-pass across-track. Single-pass mode is desirable as it eliminates the primary problem with dual-pass mode – the scene and atmosphere change during the period of acquiring both datasets causes temporal decorrelation.

2.2 Airborne and Spaceborne Implementation

Compared with their spaceborne counterparts, airborne IFSAR implementations have many operational advantages such as flexible system deployment, higher spatial resolution, and a lesser degree of influence from the atmosphere. These advantages provide for the creation of a product of greater accuracy. The most aggressive spaceborne IFSAR application was the SRTM project of which Intermap played a key role in production. The SRTM data is the most ambitious product to date providing elevation data between 56^{o} south and 60^{o} north latitude with a 16-m vertical accuracy.

2.3 Capabilities and Advantages

2.3.1 Weather Independence: IFSAR is an active microwave sensor and can operate in conditions and environments where other mapping technologies cannot. These environments include: operation at night, through cloud cover, through light rain or snow and dust. This makes IFSAR very useful and cost-effective to map through the smoke of a forest fire, rain clouds during a flood, or at night.

2.3.2 First Surface and Terrain Models: By nature of the radar sensor, the original elevation models generated are of the first surface and not the underlying bare-earth. While the first surface DEMs have many applications, bare-earth DEMs are traditionally expected and required for many topographic mapping purposes. A bare-earth DEM can be satisfactorily derived from the first surface DEMs for many terrain types using appropriate processing technologies, such as Intermap's TerrainFit® (Wang et al, 2001). The combined use of both the first surface and bare-earth DEMs has expanded applications of the DEMs.

2.3.3 Orthorectified Radar Imagery: The STAR systems also generate high-resolution orthorectified radar imagery together with DEMs. This imagery is beneficial for users to create value-added mapping products in a cost-effective way and is also useful for many remote sensing applications.

2.3.4 Quick Turn-around Time: STAR technology can efficiently map large areas in a short time frame due to its weather independence, fast data acquisition and high level of production automation. This is attractive for many emergency-mapping, regional and nation-wide mapping applications.

2.3.5 Cost competency: The cost to generate high resolution and highly accurate mapping data for large areas becomes insurmountable for other mapping technologies when mapping products with similar quality are expected. STAR technology is very cost competent.

2.4 Limitations and Mitigations

As with any remote sensing technology, airborne IFSAR mapping also has limitations that need to be understood and addressed. IFSAR service and data providers are adopting various ways to mitigate the effects caused by those limitations.

2.4.1 'Area-like' Sensing: IFSAR is an averaging sensor that essentially averages through the integration process for each ground resolution cell. An IFSAR elevation observation is made up from the integration of responses over extent of the cell. As a result, the spatial density of the height samples is dependent on the radar resolution applied within the interferometric process. The STAR technology will represent a 5 x 5-m^2 averaging area for the height estimate. Higher resolutions are available if the aircraft is flown lower. However, this is not a standard product.

2.4.2 Side-looking Imaging Geometry: IFSAR is a side-looking sensor and does not view the nadir. For certain terrain conditions, foreshortening, layover, and shadow phenomena may appear on the radar imagery and influence the product quality. These phenomena affect correlation between the two interferometric channels, causing a loss in accuracy and possibly a loss in data for the affected region. Interpolation can be used to fill small areas of missing data. However, multiple flight lines with different radar look direction may also be required to minimize those artifacts when the situation is severe, typically over areas with significant terrain.

2.4.3 Weather Restriction: While IFSAR can be operated in nearly all kinds of weather conditions, there still are some situations that should be avoided to ensure data accuracy. One issue is air turbulence at acquisition altitudes. IFSAR missions require the platform to be as reasonably stable as for accurate trajectory reconstruction from the navigation data. Turbulence makes this task difficult and thus degrades the quality of the resultant mapping products. If the weather is too turbulent to successfully collect radar data, flights are postponed until conditions improved. Heavy moisture accumulation in clouds (severe thunderstorm clouds) must also be avoided as they can absorb a significant portion of the radar energy.

3. INTERMAP'S STAR SYSTEMS

A strong heritage of photogrammetric and radar mapping experience positions Intermap Technologies very well as a manufacturer of geospatial data product. Its commercial capacity and professional reputation to meet demand for high-quality and low-cost geospatial data are attracting worldwide attention, especially since the launch of its NEXTMap® effort and off-the-shelf data availability business model.

Intermap currently owns and operates three aircraft outfitted with its advanced STAR technology. These are called STAR-3*i*®, installed in a Learjet; TopoSAR®, installed in an Aero Commander; and STAR-4, installed in a King Air 200 (Figure 1). Table 1 lists major technical specifications of the three systems. These systems are configured as an across-track X-band SAR interferometer with single-pass 3-D radar mapping capabilities.

STAR-3*i* TopoSAR STAR-4

Figure 1. Intermap's STAR Systems

	STAR Systems		
Parameters	**STAR-3*i***	**TopoSAR**	**STAR-4**
Aircraft	Learjet 36A	Aero Commander 690-1000	King Air 200
Typical flight velocity	750 km/hour	400 km/hour	400 km/hour
Typical flight altitude above sea level	3 – 10 km	3 – 9 km	3 – 9 km
Ground swath width	3 – 10 km*	3 – 8 km*	8 – 11 km*
Center frequency	9.57 GHz (X-Band)	9.55 GHz (X-Band)	9.58 GHz (X-Band)
Range bandwidth	67.5 & 135 MHz	Up to 400 MHz	67.5, 135 & 270 MHz
Antenna elevation	30 – 60^o	30 – 60^o	30 – 60^o
Polarization	HH	HH	HH
IFSAR Baseline	0.9 m	0.6 or 1.8 m	0.98 m
Best image resolution	1.25 m	0.5 m	Typical 1.25 m Up to 0.5m**

Table 1. Major Technical Specifications of Intermap's STAR Systems

* Terrain dependent
** Planned - not yet tested

4. AIRBORNE IFSAR MAPPING PROCESS

IFSAR mapping is essentially a process of producing 3-D map products by processing raw radar data collected by airborne IFSAR systems. Thematic information for a scene is derived from the synthetic aperture radar (SAR) images. Height information is obtained by using the phase difference between two coherent SAR images simultaneously obtained by two antennae separated by an across-track baseline in a single-pass mode (Figure 2). The following outlines the production chain of a typical airborne IFSAR mission. Figure 3 illustrates a high-level production flowchart.

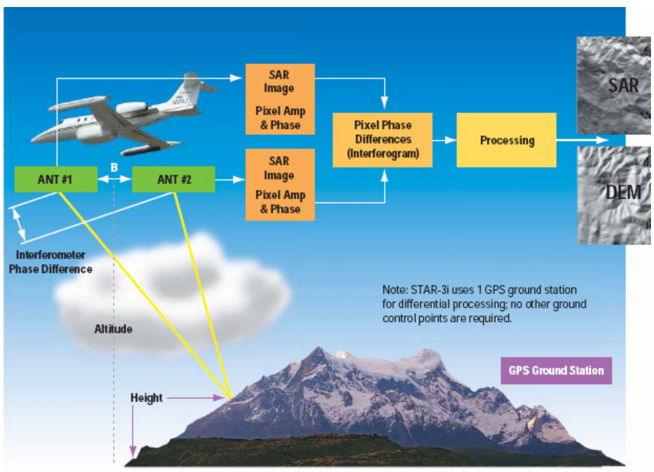

Figure 2. Concept of Airborne IFSAR Mapping

4.1 Mission Planning and Data Acquisition

Raw radar data, sensor navigation data, and ground GPS data are collected simultaneously as pre-determined by the mission planning. Data collection requirements are determined through a mission planning that takes into account the mission requirements and terrain conditions. Mission planning translates mission requirements into operating parameters required to complete the mission successfully and effectively. The following are the main components that constitute a typical mission plan:

- STAR radar operating parameters
- Flight altitude and speed
- Number, orientation, length and distribution of flight lines (regular parallel lines and tie lines)
- Multiple look direction requirement
- Number and location of ground-based GPS station(s)
- Number and location of ground control points (not always necessary) for map product validation and removal of systematic biases.

4.2 SAR Processing

Collected raw radar data are unloaded from the onboard storage media. Signals from the two antennae are processed separately and combined later in the interferometric process. The navigation processor combines the airborne navigation data (GPS/INS) with ground based GPS data to generate the precise information necessary for SAR image formation and interferometric processing. Single-look complex image pairs are generated with one image per antenna through an image formation process.

4.3 Interferometric Processing

For STAR technology image registration is maintained via a very precisely known baseline. An interferogram is created, which is a two-dimensional map of phase difference between the two images. Phase difference contains many integer multiples of 2π and a fraction part from 0 to 2π. The above-formed interferogram only represents the fractional part of the phase difference. To put an IFSAR pixel into 3-D space, the absolute phase must be determined through a phase unwrapping process. Once this is complete the phase difference and the navigation information are used to generate a height for each sample. The result is a strip of orthorectified image and DEM.

4.4 Post-Processing

These multiple radar strip images and DEMs are merged into a single image and DEM with a common datum and map projection in a mosaicking process. Data gaps can be filled using an appropriate interpolation method or left undefined. Interactive data editing, primarily for DEMs, is conducted to detect and correct potential blunders inherent in the dataset, and for quality control purposes. The finished first surface DEM can then be further processed and edited to remove objects such as trees, buildings, towers etc. At the end of the post-processing, core products that meet pre-defined and consistent specifications are stored in the Company's online *iStore*. Core products include orthorectified radar images, first surface and bare-earth DEMs.

4.5 Value Adding and Customization

Value adding and customization are conducted to fit-for-purpose, when customers need products that are different from the core products in terms of product types, contents/extents, projection/datum, resolution etc.

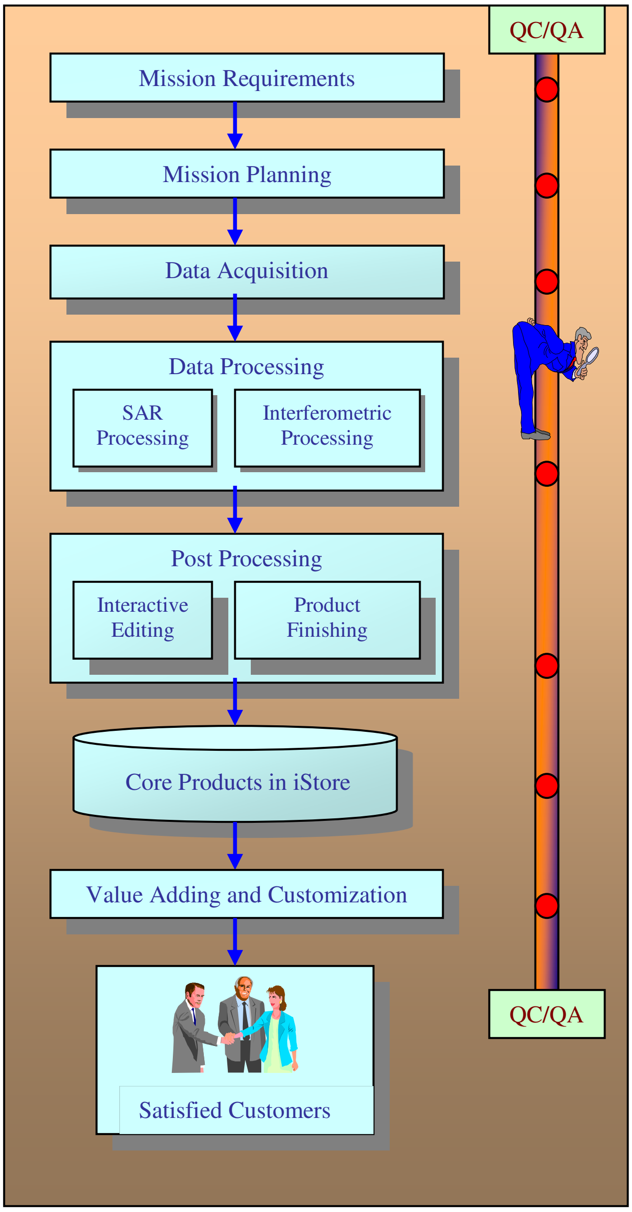

Figure 3. A high-level STAR Production Process

5. AIRBORNE IFSAR MAPPING PRODUCTS

5.1 Digital Elevation Models (DEMs)

The STAR technology directly produces a first surface model or a digital surface model (DSM), not the underlying bare earth digital terrain model (DTM). Unlike a DTM that only represents the topographical surface without vegetation or buildings, a DSM contains elevation measurements for every surface visible to the radar sensor. While DSMs have many applications, DTMs are mostly expected by the geospatial market and required for many topographic mapping purposes. With Intermap's proprietary bare-earth processing technologies, a DTM can be automatically derived from the original DSM for many terrain types. However, to obtain a satisfactory DTM product, manual editing will be required in many cases which can be a lengthy and costly process. Furthermore, the high accuracy of the original DSM cannot always be maintained for the resultant DTM. In areas such as the urban core, DTM accuracy will be lower than the DSM accuracy. Figure 4 and 5 show an example of a DSM and the DTM after the bare-earth processing, respectively.

5.2 Orthorectified Radar Images (ORIs)

An ORI is a grayscale image of the earth's surface that has been orthorectified to remove geometrical distortions using the simultaneously generated DEM. Currently, ORIs from Intermap's STAR systems have a pixel size of 1.25 m (and up) and a planimetric accuracy of 2.0 m RMSE. The ORIs provide a means of viewing the earth's surface in a way that accentuates features far more than is possible with aerial photography. Therefore, they can be used for cultural features (such as road networks and buildings) extraction, and land cover and geological analysis. Figure 6 gives an example of an ORI.

Table 2 lists the major parameters for the three core products.

STAR Product	Post Spacing /Pixel Size	RMSE Accuracy	Datum Coordinate Systems*	Format
DSM	5m (nominal)	Type I: 0.5m Type II: 1.0m Type III: 3.0m	WGS84/ EGM96/ Geographic	32-bit .bil and header info
DTM	5m (nominal)	Type I: 0.7m Type II: 1.0m	WGS84/ EGM96/ Geographic	32-bit .bil and header info
ORI	1.25m or 2.5 m** (nominal)	2.0m	WGS84/ Geographic	8-bit GeoTiff

Table 2. Specifications of Intermap's Core Products

* Other datum, projections and coordinate systems are also supported depending on the area and requirements.
** Archive ORI products before January 2002 have a 2.5-m pixel size.

5.3 Value-Added Products

Many value-added products can be generated from the core products. For example, topographic line maps (TLMs) at scales up to 1:10,000 are generated using STAR DEMs and ORIs. They are used to create a stereo radargrammetric compilation environment where TLM features are extracted (Tighe and Baker, 2000). Automatically derived contour lines (Figure 7), 3-D fly-through (Figure 8), and colorized radar imagery – STARplus (Figure 9) are also in the value-added product list.

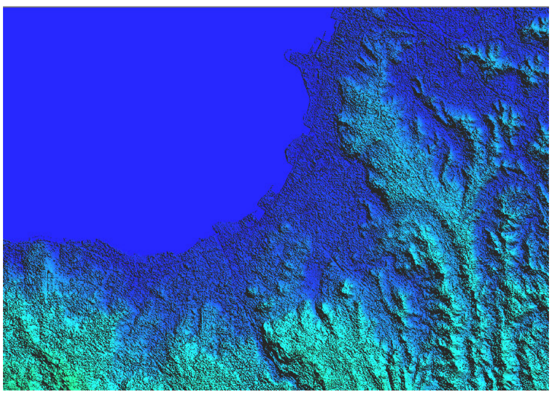

Figure 4. A STAR DSM Product

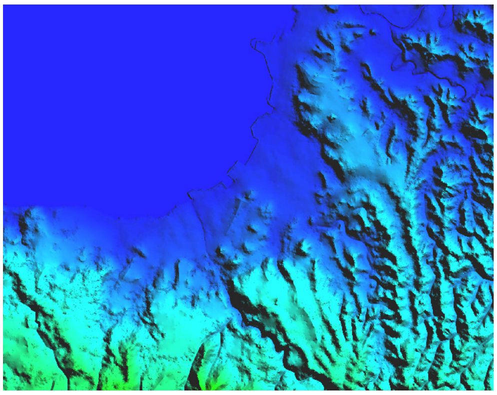

Figure 5. A STAR DTM Product

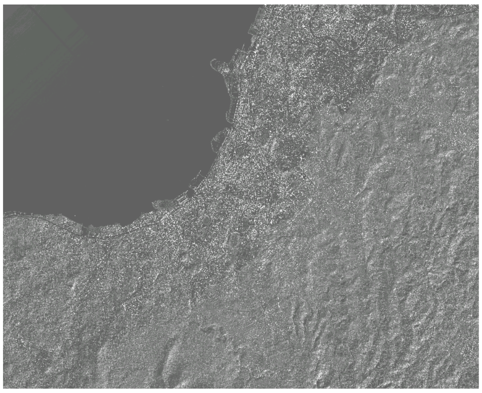

Figure 6. A STAR ORI Product

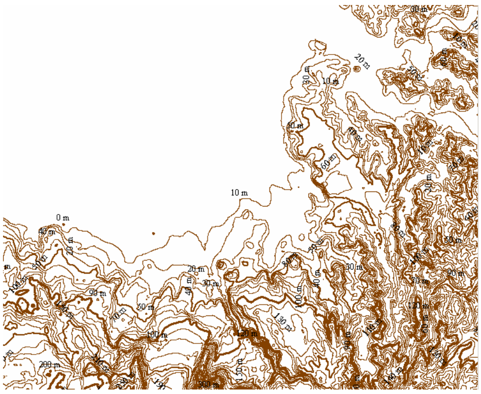

Figure 7. A STAR Contour Product

Figure 8. Flight Simulation Application using STAR DSMs (Courtesy of Horizon Simulation Ltd and Getmapping PLC)

Figure 9. A STARplus Product (Courtesy of Imagelinks Inc.)

6. QUALITY CONTROL AND QUALITY ASSURANCE

The quality of geospatial data products has recently gained escalating interest from both the data manufacturers and the users. From the data manufacturers' point of view, they need to ensure that the data they produce and deliver meet the specifications. On the other hand, the data users need to determine whether the data they receive meet the pre-agreed specific requirements for their applications.

At Intermap, this has not been of recent interest – quality has been built into the manufacturing process to produce quality data consistently and predictably from the beginning. A series of quality control and quality assurance (QC/QA) activities are conducted within the whole manufacturing life cycle. The quality management system is established tactically to integrate various QC/QA tasks to facilitate the production process while keeping the productivity. Li et al (2004) describes in detail Intermap's quality management system for its STAR process.

More importantly Intermap reviews its quality systems regularly with the focus on continual improvement. A public display of this commitment was the recent formation of Customer Care Division, headed by a Vice President. Intermap is an ISO 9001:2000 registered company and is audited on a regular basis by Underwriters Laboratories, Inc.

7. NEXTMAP® – INTERMAP'S AMBITIOUS EFFORT

Intermap identified several evolving commercial markets with a common interest in acquiring wide-area terrain data for the same geographic areas. These include commercial satellite vendors, as well as air and auto navigation businesses. Intermap clearly recognized the needs to develop a new innovative business model to cater to the market demands.

The new business model is entitled NEXTMap – nation-wide mapping using STAR based mapping technologies. The resultant data products are available to users off-the-shelf through the Company's online *iStore*. This new approach replaces the traditional single-sale model of pre-paid, contractor-to-government custom collection efforts with multiple sale/shared geography commercial business-to-business opportunities (Tennant et al, 2003). Experience with Intermap's NEXTMap Britain, NEXTMap Indonesia, as well as other NEXTMap missions are showing that this business model is a win-win situation for both Intermap and end users of products.

More recently, Intermap has launched its largest ever nation-wide mapping effort – NEXTMap USA, "the mapping event of the decade." NEXTMap USA is a program to remap the entire continental United States in just a few years, including the creation of terrain elevation and imagery data accurate to 1-meter or better covering nearly 7.9 million square kilometers of the continental United States.

8. CONCLUSIONS AND PROSPECTS

In this article, airborne IFSAR mapping is presented to the readers from Intermap's operational standpoint, encompassing the technology, operating principles, mission implementation, quality management, and business model. It can be concluded that STAR based technology has proven to be a robust, fast, accurate and cost-effective technology for large area 3-D mapping.

No single mapping technology can meet all application requirements and the paper has presented the unique advantages and limitation of the STAR technology. Service and data providers are taking various actions to mitigate the effects caused by the limitations in the final product. Dependent upon the application requirements, STAR based IFSAR mapping products can be either complementary or competitive to products generated using other mapping technologies. Under the well-planned mission and well-controlled production chain, 3-D STAR products can meet pre-designed goals and are being used efficiently for many applications. Continuously increased application of STAR products is a testament to the success of the technology.

Intermap is making significant contributions in transforming science and research efforts into practical accomplishments on its road to commercialization. At present, Intermap is developing and refining its automated facilities to further improve the quality and the cost-effectiveness of its products to meet the NEXTMap mission requirements and market challenges. An online data store – *iStore* – is under construction to broaden its e-commerce capability. Efforts are being made to extend the current infrastructure to increase throughput, on both data acquisition and data manipulation aspects. The company continues to enhance the quality control and assurance system with an ever-lasting objective to bring 3-D mapping products to the end users in a better and faster manner.

Look into future; market confidence towards this technology and the various resulting data products is building in geospatial community. STAR technology is becoming increasingly important in the advancement of the overall spatial information industry associated with mapping, GIS and remote sensing. It is envisioned that with the continuous development of IFSAR and supporting technologies and the increased understanding of the application requirements, the performance of IFSAR 3-D mapping will be further enhanced to reach a deeper and wider application base.

9. REFERENCES

Li, X., G. Lawrence and T. Hutt, 2004. Quality control and assurance in an IFSAR mapping environment. In: *Proceedings of the ASPRS 2004 Annual Conference*, Denver, Colorado, USA, 23-28 May.

Tennant, J. K, and T. Coyne, 1999. STAR-3*i* 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*, Ottawa, Ontario, Canada, 21-24 June.

Tennant, J. K, T. Coyne and E. DeCol, 2003. STAR-3*i* interferometric synthetic aperture radar (INSAR): more lessons learned on the road to commercialization. In: *Proceedings of ASPRS/MAPPS Conference "Terrain Data: Applications and Visulization – Making the Connection*, North Charleston, South Carolina, USA, 27-30 October.

Tighe, M. L. and A. B. Baker, 2000. Topographic line map production using high resolution airborne interferometric SAR. In: *Proceedings of the 19th ISPRS Congress and Exhibition*, Amsterdam, The Netherlands, 16-22 July.

Wang, Y., B. Mercer, V. C. Tao, J. Sharma and S. Crawford, 2001. Automatic generation of bald earth digital elevation models from digital surface models created using airborne IFSAR. In: *Proceedings of 2001 ASPRS Annual Conference*, St. Louis, Missouri, U. S. A., April 23-27, 2001.