Three-dimensional Mapping with Single-pass Interferometric Synthetic Aperture Radar (IFSAR) Technology ─ Airborne and Spaceborne Implementations

Xiaopeng Li
Mapping Scientist, Intermap Technologies Corp.
2 Gurdwara, Suite 200, Ottawa, ON, Canada, K2E 1A2
xli@intermap.com

Trina Kuuskivi
NEXTMap Production Manager, Intermap Technologies Corp.
2 Gurdwara, Suite 200, Ottawa, ON, Canada, K2E 1A2
tkuuskivi@intermap.com

Henry Gansen
Senior Project Manager, Intermap Technologies Corp.
2 Gurdwara, Suite 200, Ottawa, ON, Canada, K2E 1A2
hgansen@intermap.com

Keywords: Three-dimensional, Radar Mapping, IFSAR, Digital Elevation Model, SRTM.

Abstract

Interferometric Synthetic Aperture Radar (IFSAR or INSAR) is attracting increased attention in the geospatial world. The technology has matured as a cost-effective tool with its unique operational advantages for three-dimensional wide area mapping. IFSAR mapping is being conducted in single-pass mode using two across-track antennae onboard a single platform, or in dual-pass mode with a single antenna passing over the area twice. Single-pass is desirable as it eliminates the temporal decorrelation problem with dual-pass mode. IFSAR mapping can be carried out with either an airborne or a spaceborne implementation.

The objective of this paper is to discuss the IFSAR mapping process and spatial accuracy of the products from airborne and spaceborne IFSAR execution. Processes and products of airborne and spaceborne IFSAR mapping are presented. Digital elevation models from both implementations covering the same areas are analyzed in terms of accuracy and detail.

1. Introduction

IFSAR (or INSAR) has matured as a powerful three-dimensional (3-D) mapping technology and it is attracting increased attention in the geospatial world. The cost-effectiveness and the unique operational advantages of this technology over other technologies make IFSAR well suited for 3-D wide area mapping. Various IFSAR products are being generated and used for applications traditionally supported by other mapping technologies and the list of applications is growing rapidly.

IFSAR mapping can be implemented in *single-pass* mode using two across-track antennae onboard a single platform, or in *dual-pass* mode with a single antenna passing over the area twice. Since single-pass eliminates the temporal decorrelation problem associated with dual-pass, it is desirable for practical mapping tasks. In parallel, IFSAR mapping is being carried out with either an *airborne* or a *spaceborne* implementation. Intermap's STAR technology and the U.S. National Aeronautics and Space Administration (NASA)/the National Geospatial-Intelligence

Agency's (NGA) SRTM (Shuttle Radar Topography Mission) are representative airborne and spaceborne implementations, respectively.

This paper discusses the airborne and spaceborne IFSAR execution in terms of the mapping process and performance of the products. The paper is organized in six sections. Section 1 is this introduction. In Section 2, advantages associated with IFSAR technology are discussed. System implementation of airborne and spaceborne IFSAR is described in Section 3. In Section 4, mapping process and products for both executions are sketched. Section 5 depicts a detailed comparative analysis of the digital elevation models from both implementations covering the same areas. Finally, Section 6 is devoted to conclusions and prospects.

2. Strengths of IFSAR Mapping Technology

IFSAR technology uses microwave signal to map the earth in three dimensions. It possesses the following principal strengths compared with other mapping technologies:

- *Weather Independence.* Using an active microwave sensor, IFSAR can operate in conditions and environments where other mapping technologies cannot, such as at night, through cloud cover, through light rain or snow and dust.
- *Orthorectified Radar Imagery.* IFSAR can also generate orthorectified radar imagery together with DEMs. If available, this imagery is beneficial for users to create other mapping products (e.g. topographic line maps) in a cost-effective way and is also useful for many remote sensing applications.
- *Quick Turn-around Time.* IFSAR 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.
- *Cost Competency.* The cost to generate high resolution and highly accurate mapping products for large areas becomes insurmountable for other mapping technologies when mapping products with similar quality are expected.

However, as with any remote sensing technology, IFSAR mapping also has limitations, such as 'area-like' sensing (a single elevation for one ground resolution cell, e.g. 5 x 5 m^2, through the integration process), side-looking imaging geometry (potential foreshortening, layover, and shadow phenomena), etc. IFSAR service and data providers are adopting various ways to mitigate the effects caused by those limitations (Li et. al., 2004).

3. System Implementation of Airborne and Spaceborne IFSAR Mapping

3.1 Single-pass and Dual-pass Mode

Three-dimensional IFSAR mapping coherently combines microwave signals collected from two across-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 execution. 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.

3.2 Airborne and Spaceborne Implementation

Airborne IFSAR implementation commonly uses high-performance business jet or turbo-prop aircraft (e.g. Learjet36, Dornier DO228, Gulfstream) as platform. 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. On the other hand, spaceborne IFSAR missions typically utilize the space shuttle as the platform. The only single-pass spaceborne IFSAR execution so far is the SRTM that was a joint effort between the U.S., Germany and Italy.

3.3 SRTM Spaceborne and STAR-3*i* Airborne IFSAR Systems

While the SRTM (flown during an 11-day mission in February 2000) is the only single-pass spaceborne IFSAR mission (Figure 1), there are many different airborne implementations. Among the airborne systems, Intermap Technologies' STAR-*3i*® (Figure 2) is the first commercial implementation and has been in operations since 1996. Table 1 summarizes major technical specifications of the SRTM spaceborne and STAR-3*i* airborne IFSAR systems.

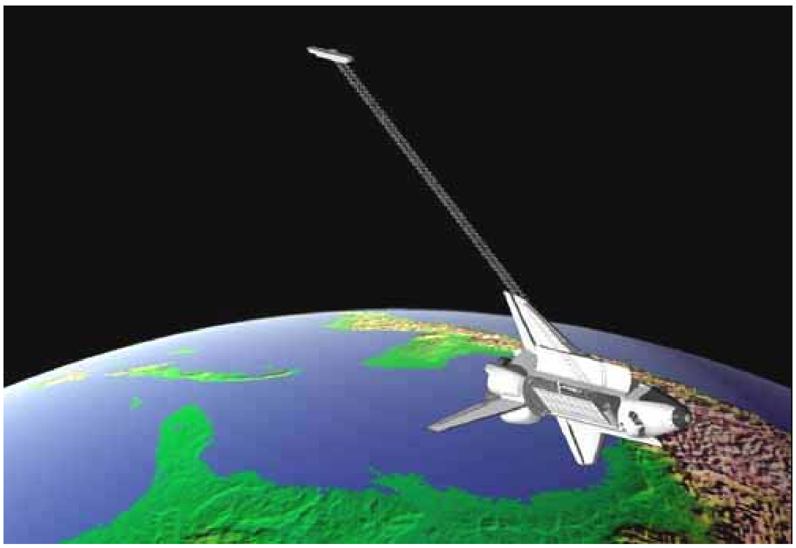


Figure 1. SRTM Single-pass Spaceborne IFSAR System

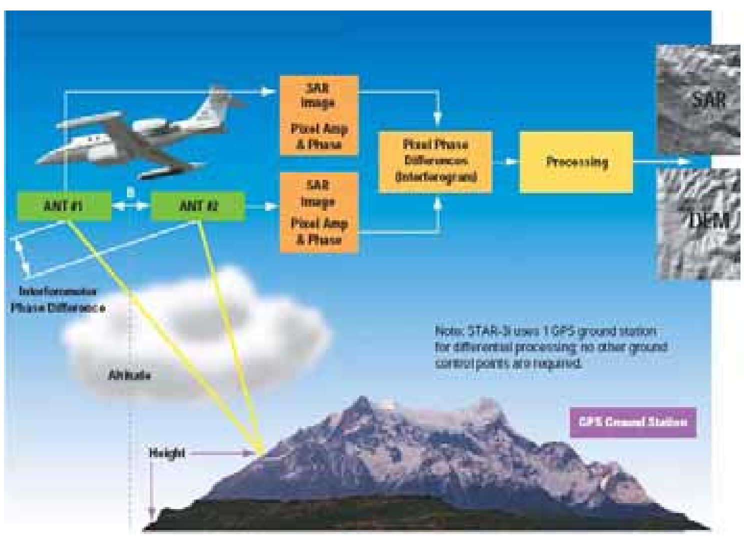


Figure 2. STAR-3*i* Single-pass Airborne IFSAR System

Table 1. Major Technical Specifications of Typical Airborne and Spaceborne IFSAR Systems

Parameters	STAR-3*i*	SRTM*	
		X-Band	C-Band
Platform	Learjet 36A	Space Shuttle Endeavour (STS-99)	
Flight altitude	3 ~ 10 km	233 km	
Ground swath width	3 ~ 10 km	50 km	225 km
Center frequency	9.6 GHz (X-Band)	9.6 GHz	5.3 GHz
Wavelength	3.1 cm	3.1 cm	5.8 cm
Polarization	HH	VV	HH/HV/VH/VV
IFSAR Baseline	0.9 m	60 m	
Image resolution	1.25 m	30 m	

* Compiled from Japan Aerospace Exploration Agency (JAEA) (1999)

4. IFSAR Mapping Process and Products

4.1 IFSAR Mapping Process

IFSAR mapping is essentially a process of producing 3-D map products by processing raw radar data collected by IFSAR systems. While there are differences between the airborne and spaceborne IFSAR mapping process, the common thread of IFSAR processes typically consists of:

- *Mission Planning and Data Acquisition:* Mission planning translates mission requirements into operating parameters required to complete the mission successfully and effectively.
- *SAR Processing*: Signals from two antennae are processed separately and combined later in the interferometric process. Single-look complex image pairs are generated with one image per antenna through an image formation process.
- *Interferometric Processing:* An interferogram is created, which is a two-dimensional map of phase difference between the two single-look complex images. To put an IFSAR pixel into 3-D space, the absolute phase must be determined through a phase unwrapping process.
- *Post-Processing*: Multiple radar strip images and DEMs are merged into appropriate single image and DEM with a common datum and map projection in a mosaicking process and then cut into to working units (e.g. 7.5' x 7.5' for STAR-3*i* and 1^{o} x 1^{o} for SRTM) for subsequent data editing and finishing.
- *Data editing:* Interactive data editing or data finishing, 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 also be further processed and edited to remove objects such as trees, buildings, and towers etc.
- *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.

4.2 IFSAR Mapping Products

The SRTM acquired radar data covers approximately 80 percent of the Earth's landmass. These data were used in the production of SRTM Digital Terrain Elevation Data (DTED®), a first-surface DEM product. During SRTM production, the data were edited — also referred to as "finishing"— delineating and flattening water bodies, better defining coastlines, removing "spikes" and "wells", and filling small voids. The "finished" SRTM DTED® products are distributed and are publicly available as part of the DTED® product set through the USGS EROS data center. Readers can find more information on SRTM products in JPL (2005) and USGS (2005).

While the publicly available product from the SRTM is DSM, common mapping products from airborne IFSAR mission include digital surface model (DSM), digital terrain model (DTM) and orthorectified radar imagery (ORI). For more details regarding airborne products, readers can refer to Intermap (2005) – Intermap's online Product Handbook.

Tables 2 and 3 list the major parameters of these products.

Table 2. Product Specifications of SRTM Spaceborne IFSAR Mapping

Product	**Unit Extents** (Longitude x Latitude)	**Post Spacing**	**Absolute Vertical Accuracy**	**Datum/ Coordinate Systems**	**Format**
DSM	1° x 1°	SRTM DTED® Level 1: - 3" x 3" (0° to 50° latitude) - 6" x 3" (50° to 60° latitude) SRTM DTED® Level 2: - 1" x 1" (0° to 50° latitude) - 2" x 1" (50° to 60° latitude)	16 m LE90 or 9.7 m RMSE	WGS84/ EGM96/ Geographic	16-bit .dt1 /dt2

Table 3. Product Specifications of Intermap's Airborne IFSAR Mapping

Product	**Unit Extents** (Longitude x Latitude)	**Post Spacing or Pixel Size**	**Absolute Accuracy**	**Datum /Coordinate Systems**	**Format**
DSM	7.5' x 7.5' (0° to 56° latitude) 15' x 7.5' (latitude > 56°)	5 m x 5 m (nominal)	0.5 m ~ 3.0 m RMSE (vertical)	WGS84/ EGM96/ Geographic	32-bit .bil and header info
DTM		5 m x 5 m (nominal)	0.7 m ~ 1.0 m RMSE (vertical)	WGS84/ EGM96/ Geographic	32-bit .bil and header info
ORI		1.25 m x 1.25 m (nominal)	2.0 m RMSE (horizontal)	WGS84/ Geographic	8-bit GeoTiff

5. Comparative Analysis of DEMs from Airborne and Spaceborne IFSAR Mapping

To analyze the characteristics of the above-mentioned DEM products, three test sites were selected where both airborne and spaceborne IFSAR DEMs are available. This section is devoted to discussing the analysis and results.

5.1 Test Sites

Three test sites (Figures 3, 7 and 8) in different continents were chosen for the comparative analysis based on the geographic location, DEM resolution and the terrain conditions (terrain relief, ground coverage etc.) as well as the availability of the test datasets. Table 4 summarizes the major characteristics of the test sites and various datasets used in this study.

Table 4. Three Test Sites for Analysis

Test Site	Datasets and Specifications	Description
Morrison site	- SRTM 3" DTED® Level 1 and 1" DTED® Level 2 - Intermap 5m DSM and DTM - Lidar DEM with a 2-m average point density and a 15-cm vertical accuracy - Twenty (20) ground control points with 10-cm positional accuracy	- Area: 12 km X 14 km - Location: south of Denver, Colorado, U.S. - Terrain conditions: different types of terrain, e.g. roads, waterways, residential area, mountains etc. - Terrain relief: 1661 ~ 2404 m
Wales site	- SRTM 6" x 3" DTED® Level 1 - Intermap 10m DSM	- Area: 10 km x 10 km - Location: Northern Wales, U.K. - Terrain conditions: a coastal mountain area with the Dee River flowing into the Irish Sea. Eighty-five percent of site is land. - Terrain relief: 0 ~ 721 m
Sulawesi site	- SRTM 3" DTED® Level 1 - Intermap 5m DSM	- Area: 28 km x 28 km - Location: central Sulawesi, Indonesia - Terrain conditions: a coastal hilly area with mountains being in the east of the area - Terrain relief: 0 ~ 2560 m

5.2 Procedures of the Analysis

The main objective of the comparative analysis is to study the accuracy performance of DEM products from airborne and spaceborne IFSAR executions. The following procedures were followed to analyze the datasets in different test sites:

- For Morrison site where there are many datasets for study purpose, high-accuracy ground control points (GCPs) were used to compare the vertical accuracy of various DEMs, i.e. Lidar DEM, 5m Intermap DSM and DTM, SRTM DTED® Level 1 and Level 2.
- For all test sites, high-resolution airborne Intermap DEMs were resampled to the same resolution of the SRTM DTED® (Level 1 or 2). Difference images were generated using SRTM minus resampled Intermap DEMs. Statistics of the difference images were calculated.
- In addition, every elevation in the high-resolution Intermap DEMs was compared with the interpolated SRTM DTED® elevation, meaning every Intermap DEM post was used as a vertical ground control point. In Sulawesi site, three subsets of different types of terrain, i.e. flat, hilly and mountainous (where there are no voids) were further studied. Different features (e.g. lakes, open areas, highways, overpass, residential areas) in airborne and spaceborne DEMs were analyzed.

5.3 Results

- *Morrison Site:* Table 5 lists the accuracy evaluation results of various DEMs at Morrison site using eight (8) GCPs (Figure 3). Table 6 contains the comparison results between SRTM DTED® Level 1 and 2 based on all 20 GCPs. Statistics associated with the difference image (the right image in Figure 3) (SRTM DTED® Level 2 - resampled Intermap DSM) are given in Table 7. Due to the availability of rich test datasets in this site, depiction of different features were also investigated. Figures 4, 5 and 6 illustrate some examples.

- *Wales Site:* The right image in Figure 7 shows the difference between the SRTM DTED® Level 1 (6" x 3") and resampled Intermap DSM (from 10m original resolution). Table 8 summarizes the accuracy statistics of the differences between the two DEMs.
- *Sulawesi Site:* Figure 8 shows the Sulawesi test site and the difference image of the SRTM DTED® Level 1 (3" x 3") and resampled Intermap DSM (from 5m original resolution). Table 9 gives the statistics of the difference images, including the whole site and three subsets of different terrain conditions (flat, hilly and mountainous).

Table 5. Vertical Accuracy Evaluation of Different DEMs of Morrison Site

	SRTM DTED® Level 1 (3" x 3")	**SRTM DTED® Level 2 (1" x 1")**	**Intermap DSM (5m)**	**Intermap DTM (5m)**	**Lidar DEM (2m)**
Terrain relief	1560 m ~ 4340 m				
Area	12 km X 14 km				
Number of GCPs	8				
Mean difference (DEM – GCP elevation)	3.4 m	2.9 m	1.6 m	0.1 m	0.1 m
Maximum difference	-1.3 m / 9.0 m	-1.5 m / 8.3 m	-0.7 m /7.0 m	-1.3 m / 3.6 m	-0.4 m / 0.5 m
RMS difference	4.9 m	4.3 m	2.9 m	1.5 m	0.3 m

Table 6. Vertical Accuracy Evaluation of SRTM DTED® Level 1 & 2 of Morrison Site

	SRTM DTED® Level 1 (3" x 3")	**SRTM DTED® Level 2 (1" x 1")**
Terrain relief	1661 m ~ 2404 m	
Area	86 km x 110 km	
Number of GCPs	20	
Mean difference	3.9 m	3.3 m
Maximum difference	-1.3 m / 9.0 m	-5.3 m / 8.3 m
RMS difference	4.8 m	4.7 m

Table 7. Morrison Site Difference Image (SRTM DTED® Level 2 – resampled airborne DSM)

Terrain relief	1664 m ~ 2403 m
Area	12 km x 14 km
Image dimension	393 x 466
Mean difference	2.5 m
Maximum difference	-58.0 m / 61.0 m
RMS difference	4.8 m

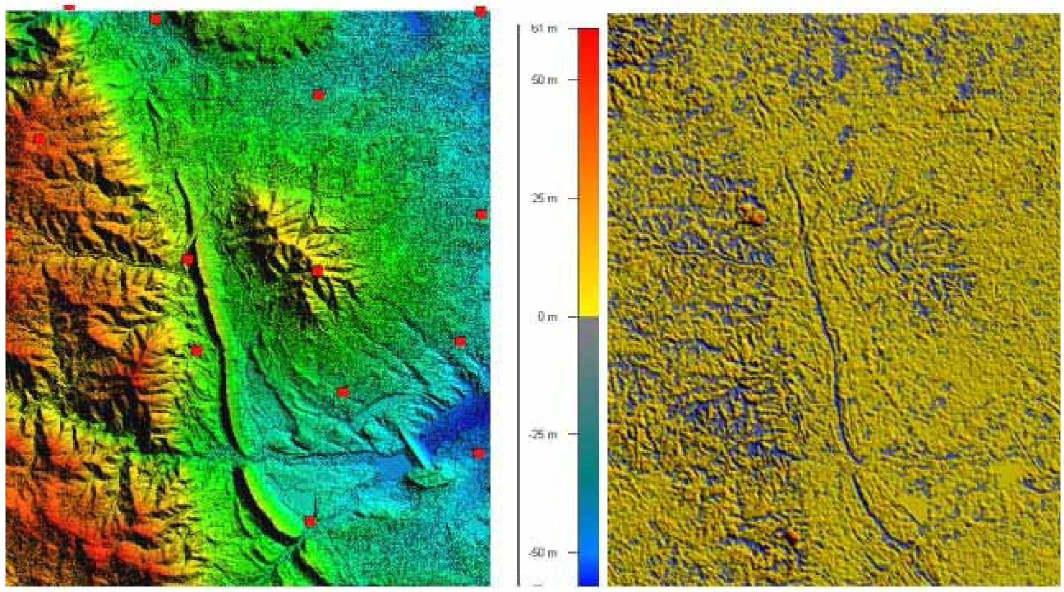
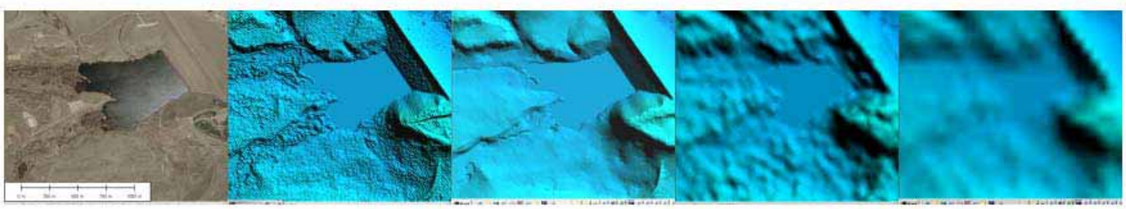


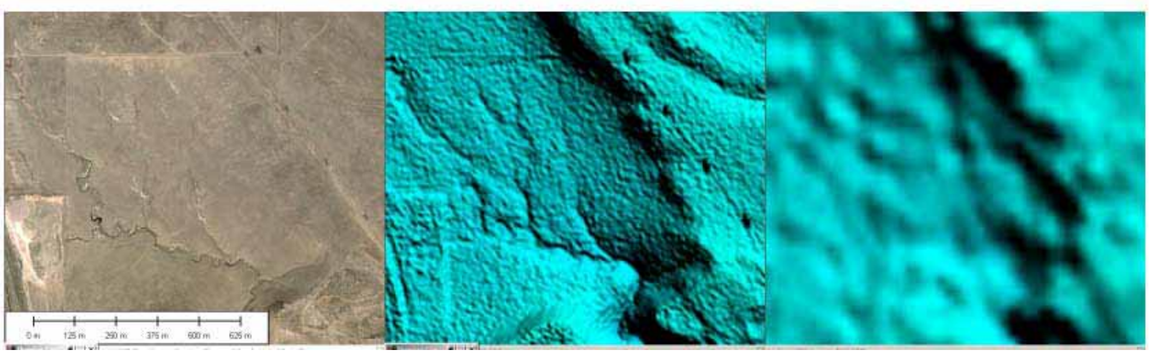
Figure 3. Morrison Site (Left) and Difference Image (Right)

(Red squares in the left image are the GCPs)



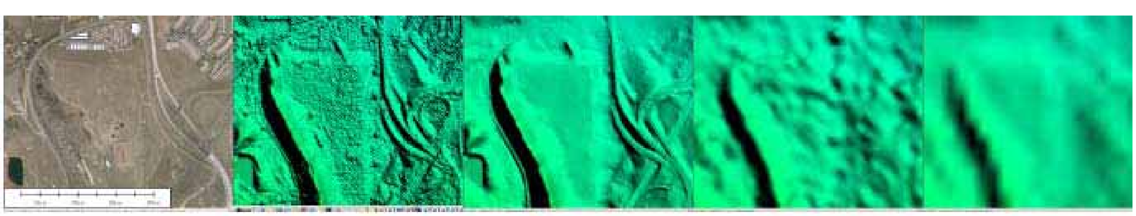
Optical image Intermap 5m DSM Intermap 5m DTM SRTM DTED® Level 2 SRTM DTED® Level 1

Figure 4. A Lake Depicted in Different DEMs



Optical image Intermap 5m DSM SRTM DTED® Level 2

Figure 5. An Open Area with A Stream



Optical image Intermap 5m DSM Intermap 5m DTM SRTM DTED® Level 2 SRTM DTED® Level 1

Figure 6. Highway and Overpass Depicted in Different DEMs

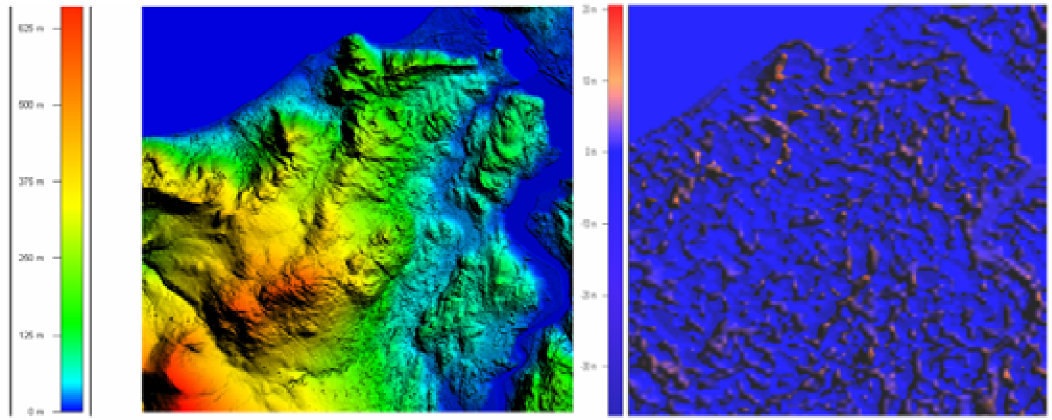


Figure 7. Wales Site (Left) and Difference Image (Right)

Table 8. Wales Site Difference Statistics

	Using Intermap DEM Elevation as GCPs	**Whole Site Difference Image** (SRTM DTED® Level 1–Resampled STAR-3*i* DSM)
Terrain relief	0 m ~ 720 m	
Area	10 km x 10 km	
Number of elevations interpolated and compared / Image dimension	820, 872	85 x 99
Mean difference	-0.2 m	-0.2 m
Maximum difference	-55.6 m / 34.3 m	-42.0 m / 25.0 m
RMS difference	3.4 m	4.0 m

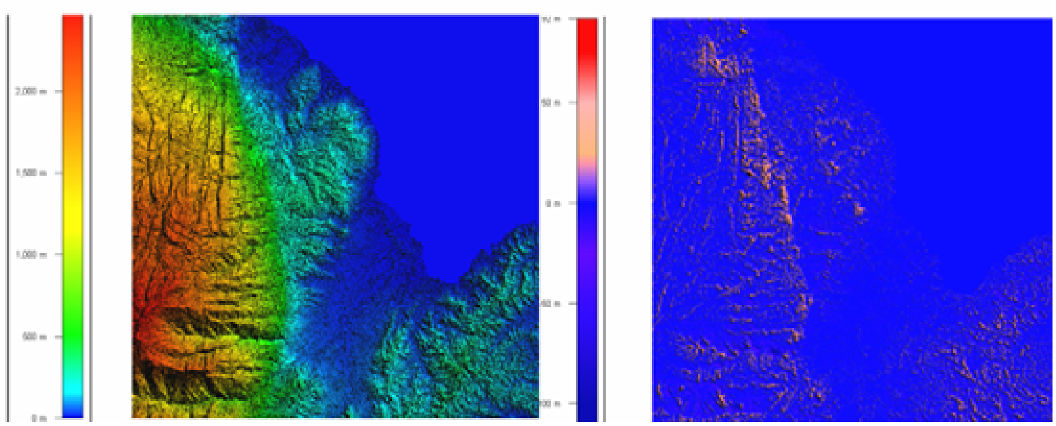


Figure 8. Sulawesi Site (Left) and Difference Image (Right)

Table 9. Sulawesi Site Difference Statistics (SRTM DTED® Level 1 – Resampled STAR-3*i* DSM)

	Flat	Hilly	Mountainous	Whole Site (difference image)
Terrain relief	6 m ~ 31 m	713 m ~ 985 m	1726 m ~ 1895 m	0 m ~ 2560m
Area	1.2 km x 1.3 km	1.0 km x 1.1 km	1.2 km x 1.2 km	28 km x 28 km
Number of elevations compared / Image dimension	58, 985	43, 818	55, 225	304 x 308
Mean difference	-0.6 m	0.7 m	0.2 m	0.2 m
Maximum difference	-16.9 m / 6.4 m	-16.1 m / 23.2 m	-15.3 m / 32.7m	-113 m / 92 m
RMS difference	2.0 m	4.9 m	5.6 m	7.8 m

5.4 Discussions and Observations

By analyzing the above test results, we have come up with the following observations:

- When using highly accurate ground control points as the reference data, Lidar data demonstrate the highest accuracy among all the test datasets with a 30-cm RMSE. On the other hand, it is also the more expensive dataset due to the nature of the technology. The airborne bare-earth DTM (1.5m RMSE) is more accurate than the DSM (2.9 m RMSE) and are both more accurate than the SRTM DTED® Level 1 and 2, which validates the subsequent difference analysis between the Intermap DEMs and SRTM DTED® 's.
- Although SRTM DTED® Level 1 product (3" x 3") was derived from the Level 2 product (1" x 1"), there is no obvious accuracy difference between the two SRTM DTED® levels, which is expected due to the nature of the derivation process.
- Both airborne DSM and SRTM DTED® are first-surface DEM, which is clearly demonstrated when compared with the GCPs and the bare-earth counterpart – positive mean differences of the statistics.
- There is no obvious mean difference or systematic error between the airborne and spaceborne DSMs. Generally, the two datasets agree to a high level. However, the RMS differences are ranging from 2 to 8 m. Difference images show that big elevation differences are typically located in the radar shadow areas. The RMS differences get larger when the terrain condition changes from flat to hilly and to mountainous. Extreme elevation differences between the two datasets are caused by terrain change as well as the voids in the SRTM data (see Figures 9 and 10 for examples). Furthermore, elevations of rivers and lakes are sometimes not set to the same values at the same location. The delineation of shoreline is also different, which might be caused different data acquisitions dates and thus different tide.
- Terrain features (lakes, rivers, highways and overpasses) are much better represented in the airborne DEMs than these in the spaceborne data due to the higher spatial resolution of the airborne data. It can also be found that most first-surface features (e.g. trees and buildings) were successfully removed from the corresponding DSM during the bare-earth process for airborne execution.
- In general, the tested vertical accuracy (3 to 5-m RMSE) of the SRTM DTED® (both Level 1 and 2) exceeds the mission requirement (16-m LE90 which is equivalent to a 9.7-m RMSE) when compared to GCPs and higher accuracy Intermap DEMs.

Figure 9. Cause of Extreme Large Values in Difference Image – Terrain Change

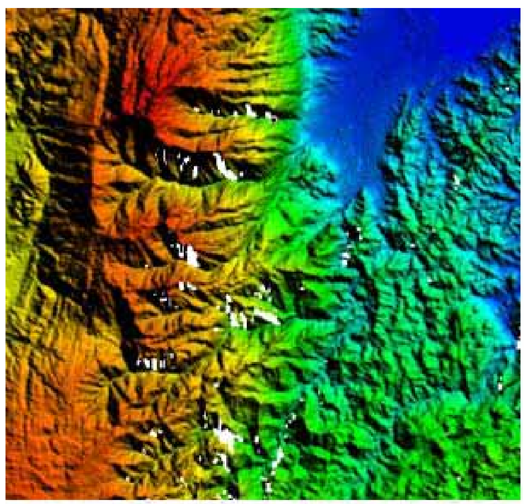


Figure 10. Cause of Extreme Large Values in Difference Image – Data Voids

6. Conclusions and Prospects

While airborne and spaceborne IFSAR mapping technologies are competing with each other and with other mapping technologies for given domains, they are largely complementary for many geospatial applications. Products from both IFSAR implementations are finding applications in many traditional mapping fields and non-traditional markets where geospatial information plays an indispensable role.

Comparing with spaceborne data, airborne IFSAR mapping products provide more accurate and more detailed terrain depiction that are necessary for many applications possible only with such high-quality DEMs. On the other hand, DEM products from spaceborne SRTM — globally available at low cost with medium resolution and reasonable accuracy — can be used cost-effectively for many regional applications where high accuracy and resolution are not paramount.

With the increased awareness of the availability and applicability of IFSAR mapping products, the application list will become longer. Research is underway to study the combined use of medium-and high-resolution DEM for different applications and to investigate the performance difference between the different resolution DEM products.

7. References

Intermap (2005). http://www.intermap.com/images/handbook/producthandbook.pdf

JAEA (1999). http://iss.sfo.jaxa.jp/shuttle/flight/sts99/mis_srtm_e.html (accessed on July 12, 2005).

Li, X., K. Tennant, and G. Lawrence (2004). "Three-dimensional mapping with airborne IFSAR based STAR technology – Intermap's experiences". In: *Proceedings of* XXth ISPRS Congress, July 12-23, Istanbul, Turkey, 2004.

JPL (2005). http://www2.jpl.nasa.gov/srtm/ (accessed on May 20, 2005).

USGS (2005). http://srtm.usgs.gov/ (accessed on May 20, 2005).