ACCURACY ASSESSMENT OF MAPPING PRODUCTS PRODUCED FROM THE STAR-3*i* AIRBORNE IFSAR SYSTEM

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ABSTRACT

Traditional photogrammetric mapping technologies are being challenged by the increasing demands for faster and cheaper digital mapping products. High-resolution airborne Interferometric Synthetic Aperture Radar (IFSAR) systems are starting to penetrate the traditional photogrammetric market due to their operational and economic advantages. Many geo-spatial data, such as Digital Elevation Models (DEMs), Digital Ortho Images (DOIs) and Topographic Line Maps (TLMs), can be derived efficiently and quickly by using the IFSAR system and appropriate processing technologies. These products have proven to be an important data source for Geographic Information Systems (GIS). The main objective of this paper is to examine in detail the positional accuracy and characteristics of these topographic products through a comprehensive test.

1. INTRODUCTION

New mapping technologies are emerging and challenging their conventional counterparts, primarily due to the advances in sensor and georeferencing technologies coupled with the ongoing improvement of digital technologies. These parallel advancements are providing the mapping community with versatile mapping methodologies and products for the new century. Among the new technologies, IFSAR has been a technique of considerable scientific interest for some years due to its three-dimensional (3D) information extraction capability, quick turn-around time, and nearly weather-independent operation. This has been particularly so since data became widely available from the microwave sensor on the ERS-1 satellite (OEEPE, 2000). The Shuttle Radar Topographic Mission (SRTM) gives a further impetus for mapping applications of IFSAR. Compared with their spaceborne counterparts, airborne IFSAR systems have many significant advantages such as flexible system deployment, higher spatial resolution, and less degree of influence from the atmosphere, thus providing greater accuracy. During the last few years, high-resolution airborne IFSAR systems are reaching a wider application base and have begun to penetrate the traditional photogrammetric market. DEM and DOI data components from the Intermap Technologies Corporation STAR-3*i* system are being used to produce value-added products, at scales from 1:20,000 to 1:50,000.

The main objective of this paper is to examine in detail the accuracy of mapping products from the STAR-3*i* system. After a brief introduction of the system, the DEM, DOI and TLM products from the STAR-3*i* data are discussed. The paper then proceeds to describe a comprehensive study where the accuracy of the products are assessed by comparing them with a photogrammetric data set built from 1:24,000 scale photographs. Finally, the conclusions and future prospects of STAR-3*i* mapping are given.

2. STAR-3*i* AIRBORNE IFSAR SYSTEM

2.1 System Specifications and Characteristics

The STAR-3*i* system is an airborne, single-pass IFSAR system. Intermap Technologies, through agreements with the Environmental Institute of Michigan (ERIM) and Defense Advanced Projects Agency (DARPA), has obtained exclusive rights to market and operate this airborne IFSAR system developed by ERIM. The system has been operated commercially by Intermap since January 1997. Approximately 750,000 square kilometers of DEM have been acquired over several continents by the system. The STAR-3*i* system comprises an X-band SAR interferometer onboard a LearJet 36 (Figure 1). The two antennae are mounted to a solid invar frame (pedestal) with a one-meter separation. The positioning and orientation of the radar system are achieved through use of a laser inertial reference platform and Global Positioning System (GPS) that is differentially post-processed. More information on the STAR-3*i* system is reported in Birk and Bullock (1999), Bullock et al. (1997), Mercer et al. (1998), and Tennant and Coyne (1999).

Figure 1. Intermap's LearJet 36 STAR-3*i* System

2.2 Data Workflow

The data collection from the two antennae occurs simultaneously. Generally, the set of acquired raw data are 'interfered' by a digital correlation process to extract terrain height data that are used to geometrically correct the radar image. The STAR-3*i* processor generates three separate data files (Simental et al., 1999):

- A magnitude file: SAR data from which an intensity image of the area can be produced;
- An elevation file: elevation data for each pixel referenced to pre-defined datum;
- A correlation/coherence file: correlation data between the two antennae of the system.

All of these data have extensive use in applications (OEEPE, 2000). The data workflow begins with turning the raw information into strip information, then into map sheet data, and finally a complete and edited map sheet product for final delivery. Strip products are created by ingesting the raw radar phase history data and creating Scan, Cross-scan Height (SCH) elevation, magnitude and correlation strip products. Once the strip products are created, the internal consistency of the data is verified. The data are then merged and mosaicked into 7.5-minute tiles. Any missing data is interpolated. The data are then loaded into a stereo viewer where the operator will remove any obvious blunders and correct any large water features. Birk and Bullock (1999), Tennant and Coyne (1999) give further information on data processing of the STAR-3*i* system.

3. MAPPING PRODUCTS FROM STAR-3*i* SYSTEM

3.1 DSM (Digital Surface Model) and DEM

DSMs and DEMs are the main products produces from the STAR-3*i* system. By nature, the original elevation models provided are of the first surface and not the underlying bald-earth. The active X-band radar sensor responds to the first surface it interacts with. A DSM has its own specific applications, such as surface roughness for signal propagation, air flow simulation over terrain, pollution tracking, commercial and military virtual landscape simulation, tree height estimation, and line-of-sight for transmission signals. A bald-earth DEM is traditionally expected and required for topographic modeling. With proprietary processing technologies, a bald-earth DEM can be derived from the DSM. Currently, STAR-3*i* DEMs are provided as Global Terrain® (GT) series. Table 1 lists the specifications of main GT products. All GT products are in Universal Transverse Mercator (UTM) projection referenced to WGS84 horizontal datum. All elevation data are provided in orthometric heights through the application of the EGM96 geoidal model. The standard post spacing of GT products is 5m.

Table 1. Main Global Terrain® Products

GT Products	**Nominal Altitude**	**Nominal Accuracy (RMSE)**	
		Vertical	**Horizontal**
GT1	6100 m	1 m	2.5 m
GT2	6100 m	2 m	3 m
GT3	9100 m	3 m	3 m

3.2 Digital Ortho Image (DOI)

A DOI is a radar intensity image with 2.5m pixel size, which is orthorectified by using simultaneously generated DEM. It can provide information on the layout of built-up areas, roads, waterways, and lines of communication. As it is orthorectified, relief displacements are removed. The DOI images are registered to a UTM projection and are mosaicked into image maps. STAR-3*i* DOIs can be used as base maps for GIS applications or output as hardcopy image maps at scales as large as 1: 10,000 (Tennant and Coyne, 1999). More recently, they served as a very important data layer for in-house TLM production.

3.3 TLM

TLM is a value-added STAR-3*i* product. STAR-3*i* DEMs and DOIs are the two main data sources for TLM generation. In general, the DOI and DEM are used to generate a 'stereomate' in a digital softcopy photogrammetric environment. The stereomate/DOI pair is then used to create a pseudo stereoscopic viewing/measuring environment to extract the features required to generate TLMs. With this technology, TLMs can be created at scales ranging from 1:20,000 to 1:50,000 solely from STAR-3*i* data. Tighe and Baker (2000) give detailed information about the TLM generation process.

4. ACCURACY ASSESSMENT STUDY

4.1 Study Area and Data Sets

An area of about 10km by 6km south of Denver, Colorado, U.S.A. was selected for study. In addition to the available data sets for this area, the different types of terrain (roads, waterways, residential area, mountains etc.) with about 750m height difference serves as a valid test area due to the rich terrain information. The following data sets are available and were used for the study:

Photogrammetric data

24 black-and-white aerial photographs with 1:24,000 photo scale covering the study area were scanned with 14-microns resolution (Figure 2a). Digital softcopy Aerial Triangulation (AT) was conducted for geo-referencing based on 20 ground-surveyed Ground Control Points (GCPs). The resulting sigma-naught from the AT is about 5 microns and the RMSE residuals on GCPs are 0.20m, 0.17m and 0.09m in X, Y and Z direction, respectively.

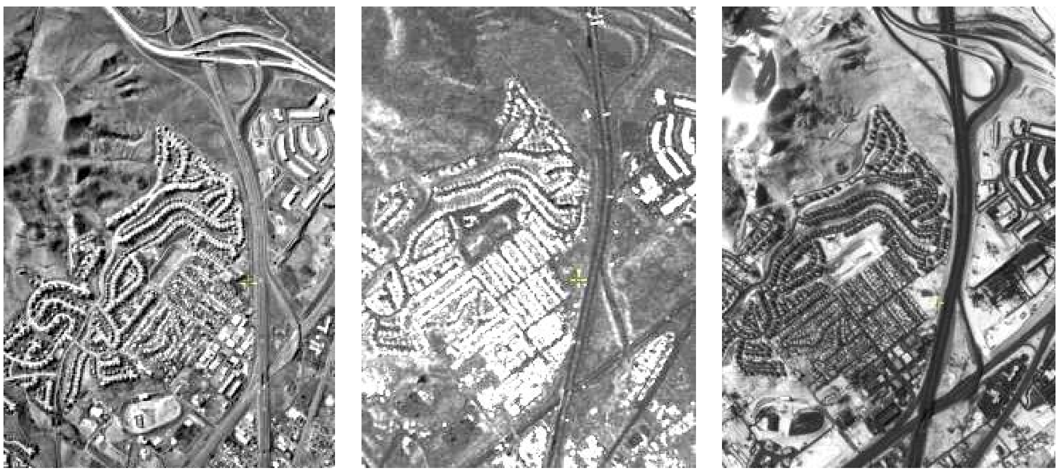
STAR-3*i* DOI, DEM, and TLM data

The GT1 bald-earth DEM with 5m-post spacing, DOI (Figure 2b) with 2.5m pixel size and TLM data compiled at 1:25,000-scale specifications were used for accuracy studies.

IKONOS high resolution imagery

A one-metre resolution black-and-white IKONOS stereo pair from Space Imaging is available for study purposes (Figure 2c).

All the above data sets were geo-referenced to the same datum, coordinate system and map projection.



(a)

(b) (c)

Figure 2. Part of Study Area. (a) Scanned Aerial Photograph (b) STAR-3*i* DOI Image (c) IKONOS Image

4.2 Study Design

In general, a number of checkpoints of specific features were measured on each radar-derived data set. The same points were also collected from the photogrammetric data set, which is used as the comparative 'base data'. The differences between the test data set and the 'base data' will serve as a valid indicator of the accuracy of individual product. In the following sections, the accuracy studies will be described in detail and results analyzed for DOI, DEM and TLM, respectively. Accuracy reporting is generally done with statistical measures, typically the mean offset and standard deviation, or alternatively the RMSE (Mercer 1998). The mean offset generally represents residual systematic error. The standard deviation represents mostly random noise, approximately normally distributed about the mean offset, which can be considered as an internal/relative accuracy indicator of the system/data. The RMSE represents an overall absolute error and corresponds to the external/absolute accuracy of the test data. When the mean offset is small, standard deviation is close to RMSE. In the following described studies, mean offset, standard deviation and RMSE were all calculated and presented.

4.3 DOI Accuracy Study

By nature, a DOI contains only two-dimension information. Therefore, the horizontal accuracy of STAR-3*i* DOI is validated by comparing the geographic locations of a number of well-defined points on the DOI to the corresponding points from the photogrammetric 'base data'. The differences between the DOI readings and the 'base data' were computed in both the X and Y direction. The overall distances between the two readings were also calculated to show the offset between the two data sets. In total, 105 checkpoints were measured and compared. Table 2 gives the statistical results for DOI accuracy study.

It can be seen that there are no obvious accuracy differences between easting and northing directions. The mean offset between the horizontal locations of DOI image points and checkpoints is 2.4m (less than one pixel) with a 1.3m standard deviation. This conforms to the results reported by Birk and Bullock (1999). Points collected along waterway features have slightly reduced accuracy when compared to other types of features.

Table 2. Results of STAR-3*i* DOI Accuracy Test

Type of Point	No. of Points	Mean Difference			Standard Deviation			RMSE Difference		
		X	Y	Dist.	X	Y	Dist.	X	Y	Dist.
Control points	13	0	-0.3	2.3	1.7	2.0	1.2	1.6	2.0	2.6
Waterway points	25	-0.3	2.0	3.2	2.0	2.0	1.4	2.0	2.8	3.5
Road intersections	60	-0.6	0.7	2.2	2.2	1.7	1.1	2.3	1.8	2.4
Transportation line points	7	-1.1	0.4	2.2	1.0	2.1	0.9	1.5	2.0	2.5
Overall	105	-0.6	0.9	2.4	1.6	1.9	1.2	1.7	2.1	2.7

Units: meters

4.4 DEM Accuracy Study

Accuracy of STAR-3*i* derived DEM is evaluated three ways:

- Direct comparison of DEM elevation with photogrammetric ‘base data’.
- Application of the DEM to orthorectify 1:24,000 aerial photographs.
- Application of the DEM to orthorectify IKONOS imagery.

4.4.1 STAR-3*i* DEM vs. photogrammetric data

Elevations of the same 105 checkpoints were collected from the photogrammetric models and were used as the comparative data. The STAR-3*i* elevations of those checkpoints were interpolated from the DEM and were compared against the photogrammetrically collected elevations. The accuracy statistics are listed in Table 3.

Table 3. Results of STAR-3*i* DEM Vertical Accuracy Test

Type of Point	No. of Points	Mean Difference	Standard Deviation	RMSE Difference
Control points	13	0.2	1.1	1.0
Waterway points	25	0	1.2	1.2
Road intersections	60	0.7	1.0	1.3
Transportation line points	7	1.2	0.5	1.3
Overall	105	0.5	1.1	1.2

Units: meters

The results show that the STAR-3*i* DEM is about a half meter higher than the comparative photogrammetric data. There could be some minor uncompensated systematic effect in the DEM data. T he RMSE value of 1.2m is close to the claimed 1m value.

4.4.2 Accuracy of orthorectification of aerial photographs with STAR-3*i* DEM

It is well known that accuracy of orthorectification of aerial photographs is largely dependent upon the DEM accuracy where the georeferencing accuracy of photographs is very high. Therefore, a test was conducted to employ STAR-3*i* DEM to orthorectify the same aerial photographs that were used for the check data set collection. The Ground Sample Distance (GSD) of 0.5m was used and bi-cubic algorithm was applied for orthorectifcation. Planimetric locations of 40 image points were measured from 4 orthorectified aerial photographs for testing purposes. The corresponding points were also measured on photogrammetric models. The differences are statistically summarized in Table 4.

Table 4. Accuracy Test Results of STAR-3*i* DEM for Orthorectification

Image	No. of Points	Mean Difference			Standard Deviation			RMSE Difference		
		X	Y	Dist.	X	Y	Dist.	X	Y	Dist.
Aerial photographs	40	0.3	0.6	1.1	0.9	0.8	0.8	0.9	1.0	1.2
IKONOS image	64	-2.4	-0.9	3.7	2.6	2.1	2.0	3.5	2.2	4.1

Units: meters

The average offset between the image points on the orthophoto and the checkpoints is 1.1m (about 2 photo pixels) based on 40 checkpoints with a 0.8m standard deviation. It can be estimated that the STAR-3*i* GT1 DEM can be used for orthorectifying aerial photographs with

1:5,000 or smaller scale in order to meet the National Mapping Accuracy Standard (U.S. Bureau of the Budget, 1947). Further studies are ongoing to verify the findings.

4.4.3 Accuracy of orthorectification of IKONOS image with STAR-3*i* DEM

This test was carried out to study the possibility and accuracy of orthorectifying one-meter high-resolution IKONOS images by using STAR-3*i* DEM. The same DEM data set was used for orthorectifying an IKONOS image with the GSD being one metre as that of the original IKONOS image. Planimetric locations of 64 image points were measured on the orthorectified IKONOS image and were compared with X and Y coordinates collected from the photogrammetric models. Table 4 lists the results of this test.

The mean offset between the orthorectified IKONOS image points and check points is 3.7m, which is close to the 4m value claimed by Space Imaging for its CARTERRA Precision® products. This demonstrates the feasibility of applying STAR-3*i* generated DEM for orthorectifying IKONOS images. More studies are being conducted by Intermap to further verify this.

4.5 TLM Accuracy Study

A TLM data set with 1:24,000 map scale specifications was compiled for the study area with the technologies described in Section 3.3, which contains 10m contour lines, linear hydrological features and cultural features, i.e. roads, building footprints etc. A certain number of well-defined checkpoints for different features were randomly measured from both the TLM and the photogrammetric data set and compared in order to evaluate the accuracy of different TLM features collected from the STAR-3*i* data.

4.5.1 Contour line accuracy

10 contour lines (5 index and 5 intermediate contour lines) were tested with 10 randomly sampled data points on each contour line. Figure 3 shows the contour lines overlaid onto an aerial photograph. The statistically calculated elevation differences were tabulated in Table 5.

Table 5. Results of STAR-3*i* TLM Contour Line Accuracy Test

Contour Line	Elevation	Mean Differences	Standard Deviation	RMSE Differences
No. 1	1710	0.8	2.2	2.3
No. 2	1740	1.0	1.2	1.5
No. 3	1750	-0.3	1.4	1.4
No. 4	1770	1.4	0.7	1.6
No. 5	1790	0.6	1.3	1.4
No. 6	1800	0.4	1.2	1.2
No. 7	1850	0.4	2.0	1.9
No. 8	1870	0.3	2.4	2.3
No. 9	1900	1.0	2.3	2.4
No. 10	1950	0.1	1.7	1.6
Overall		0.6	1.7	1.8

Units: meters

Figure 3. TLM Contour Lines Overlaid onto an Aerial Photograph

Generally, the contour lines on the TLM are a very good characterization of the surface. Again, the STAR-3*i* DEM is slightly higher than the check data. The 1.8m RMSE is largely attributed to the interpolation process of the contour lines from the DEM and the breaklines. Even so, it is still well within one-third of the 10m contour interval specified by ASPRS (1988). Smaller contour intervals are also possible based on the test results.

4.5.2 Horizontal accuracy of other TLM features

The horizontal accuracy of transportation features (3 heavy-duty highways, 5 light duty roads, and 2 unimproved dirt roads), hydrographic features (50 checkpoints) and 7 building footprints of the TLM data was assessed by comparing with corresponding features/points from the photogrammetric models. Table 6 lists the results. Only the overall distances between the TLM feature points and the photogrammetric 'base data' points are listed.

Table 6. Results of TLM Horizontal Accuracy Test (overall distances)

Type of feature	No. of Points	Mean Difference	Standard Deviation	RMSE Difference
Heavy duty highway	31	2.6	2.1	3.3
Light duty roads	48	4.6	3.3	5.6
Unimproved dirt roads	12	5.2	4.3	6.7
Overall roads/highways	91	4.0	3.2	5.1
Buildings	48	4.3	3.2	5.3
Hydrographic points	50	2.9	3.2	4.3
Overall	189	3.8	3.2	5.0

Units: meters

According to well-adapted NMAS standard (U.S. Bureau of the Budget, 1947), 90% of points tested shall be in error not more than 1/50 inch for maps on publication scales of 1:20,000 or smaller. For tested 1:24,000 TLM data, it is transferred to 12m on the ground. The results show that the TLM data is well within specifications (only 5 of 189 tested points were out of tolerance). If 1:12,000 scale were considered, the tolerance would be 10m (1/30 inch on the map). For the tested data set, 10 out of 189 (5%) tested points are out of specification. This indicates that, from an accuracy point of view, TLMs with scale larger than 1:20,000 are also possible. However, the interpretation limitation of radar image data would apply some constraints on the compilation process.

4.5.3 Vertical accuracy of other TLM features

As the TLM data was compiled in 3D, the vertical accuracy can also be evaluated for TLM features, except for building footprints. This is because the 3D compilation for these features is difficult and these data would not be used for the subsequent contour generation. Table 7 gives the statistical results of this test.

Table 7. Results of TLM Vertical Accuracy Test

Type of feature	No. of Points	Mean Differences	Standard Deviation	RMSE Differences
Heavy duty highway	31	1.3	1.5	2.0
Light duty roads	43	0.7	1.6	1.7
Unimproved dirt roads	12	-1.6	2.5	2.9
Overall roads/highways	86	0.6	1.9	2.0
Hydrographic points	50	0.3	1.9	1.9
Overall	136	0.5	1.9	2.0

Units: meters

Mean offset between the two data sets is again approximately half a meter. Both the standard deviation and RMSE are slightly larger than those of the DEM test, which indicates that additional errors were introduced during the radar image interpretation and compilation process. However, the results are still encouraging considering the 1:24,000 map scale. From the test results, we realize that the unimproved dirt roads are difficult to digitize compared with other features.

5. SUMMARY OF STUDY

Using 1:24,000 photogrammetric data set as 'base data' and for the given terrain situations, the findings from the accuracy assessment studies are as followings:

- DOI accuracy
  The mean offset between the horizontal locations of DOI image points and checkpoints is 2.4m (less than one pixel) with a 1.3m standard deviation.
- DEM accuracy
  STAR-3*i* DEM is about a half meter higher than the comparative photogrammetric data. There could be some minor uncompensated systematic effect in the DEM data. The RMSE value of 1.2m is close to the claimed 1m value. STAR-3*i* GT1 DEM can be used for orthorectifying aerial photographs with 1:5,000 or smaller scale in order to meet the National Mapping Accuracy Standard. The feasibility of applying STAR-3*i* generated DEM for orthorectifying IKONOS images is also well demonstrated.
- TLM accuracy
  Generally, the contour lines on the TLM are a very good characterization of the surface. The interpolation process of the contour lines from the DEM and the breaklines introduce extra error budget. Even so, it is still well within one-third of the 10m contour. Smaller contour intervals are also possible based on the test results. The results show that the TLM data is well within specifications of 1:20,000 map scale.

6. CONCLUSION AND PROSPECTS

IFSAR technology is becoming increasingly important in the advancement of the overall spatial information industry associated with mapping, GIS and remote sensing. Intermap's STAR-3*i* system is the first commercial implementation of a high-performance, single-pass interferometer. This technology is providing high quality mapping products addressing the ever-increasing needs of the worldwide imaging and mapping community. The system-generated DEMs and DOIs are already making contributions to many applications. Value-added products, such as TLM data with 1:20,000 to 1:50,000 scales are satisfactorily produced from the DEM and DOI. The accuracy assessment studies described in this paper show that mapping products produced from the STAR-3*i* system can meet pre-designed goals. Some new applications are also feasible, such as the orthorectification of one-metre high-resolution IKONOS optical satellite imagery as well as medium to large-scale aerial photography.

Currently, Intermap's STAR-3*i* system is undergoing an upgrade in order to provide a higher resolution image component (up to 1.25m pixel size) and higher accuracy DEM (with 0.3m RMSE accuracy) to support more demanding applications. It is envisioned the production of larger scale TLMs, e.g. 1:10,000 will be practical once the upgrade is complete.

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