ACCURACY OF AIRBORNE IFSAR MAPPING

Xiaopeng Li, Chief Photogrammetrist
A. Bruce Baker, Technology Manager
Thomas Hutt, Senior Project Manager
Intermap Technologies Corp.
2 Gurdwara Road, Suite 200
Nepean, Ontario, Canada K2E 1A2
Xli@intermap.ca
Bbaker@intermap.ca
Thutt@intermap.ca

ABSTRACT

Airborne IFSAR (Interferometric Synthetic Aperture Radar) mapping is attracting much attention in the geo-spatial community. This attention is due to the flexibility of system deployment, near weather-independent operation, cloud penetrating capability, versatile map products, and quick turn-around time. As a result, high-resolution airborne IFSAR systems are providing data to applications traditionally supported by conventional photogrammetric technology. The three main products are, Digital Elevation Models (DEMs), digital Orthorectified Radar Images (ORRIs), and Topographic Line Maps (TLMs). These products are being produced at Intermap by the STAR-3*i* airborne IFSAR system to support many geo-spatial related applications. The main objective of this paper is to investigate the accuracy performance of airborne IFSAR systems, with a focus on Intermap's STAR-3*i*.

INTRODUCTION

Conventional photogrammetric mapping is being continually challenged by new technologies. Recent advances in sensor development, geo-referencing technologies coupled with the ongoing improvement of digital computing power 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 time due to its high-resolution three-dimensional (3D) information extraction capability, quick turn-around time, and near weather-independent operation. Interest in IFSAR has been growing since data became widely available from the microwave sensor on the ERS-1 satellite (OEEPE, 2000). Also, the Shuttle Radar Topographic Mission (SRTM) which flew successfully in February 2000 provided a further impetus for mapping applications using IFSAR technologies.

Compared with their spaceborne counterparts, airborne IFSAR systems have many 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. During the last few years, high-resolution airborne IFSAR systems are reaching a wider application base and have begun significant penetration of the traditional photogrammetric market. As standard map products, DEMs and ORRIs are also being used to produce value-added products, such as TLMs and thematic maps.

The main goal of this paper is to examine the accuracy aspects of map products created from airborne IFSAR mapping systems. After a brief introduction of the general working principle of airborne IFSAR systems, factors affecting accuracy of resulting map products are discussed. Accuracy of DEM, ORRI and TLM products from Intermap's STAR-3*i* system are demonstrated through a series of evaluation studies.

WORKING PRINCIPLES OF AIRBORNE IFSAR MAPPING

Airborne IFSAR mapping is essentially a process of producing 3D map products by processing and post-processing of raw radar data collected by an airborne IFSAR system. Height information for a scene is obtained from an IFSAR system by using the relative phase difference between two coherent SAR images simultaneously obtained by two antennas separated by an across-track baseline in a single-pass mode (see Figure 1). These systems collect raw radar data based on a pre-determined mission plan. An onboard-integrated Global Positioning System (GPS) and Initial Navigation System (INS) records the sensor position and orientation, together with one or more ground GPS stations for subsequent Differential GPS (DGPS) correction. After the data collection, a series of automated processes are conducted to derive the DEMs and ORRIs. DEMs and ORRIs are the two main map products produced from IFSAR mapping. Other value-added products, such as TLMs and thematic maps can also be generated based solely or in part on the DEM and ORRI components through a well-controlled production chain.

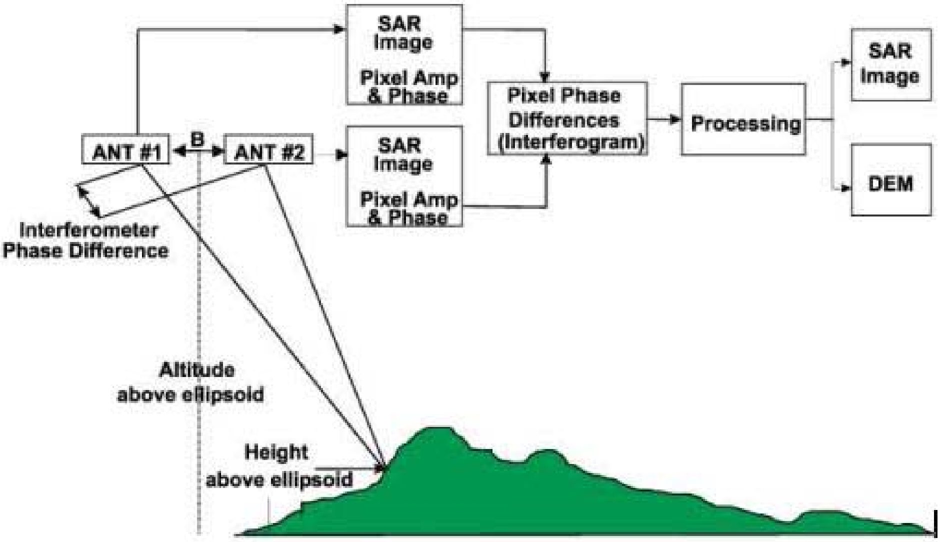


Figure 1. Concept of IFSAR Mapping

Accuracy of the final IFSAR map products depends on many inter-related factors of the mapping process. Understanding the mapping process helps to understand the accuracy performance and limitations of IFSAR map products. A brief description of the basic steps of an airborne IFSAR mapping mission is presented in the following sections. For more detailed information about IFSAR technical background and operations, please refer to Birk and Bullock (1999), Hensley et al (2001), Simental et al (1999), Tennant and Coyne (1999), and Wimmer et al (2000).

Mission Planning and Data Collection

Data collection requirements are determined through a mission planning process that takes into account the mission requirements and terrain conditions. The following are the main components that form a typical mission plan:

- Radar operating modes and instrument/sensor parameters
- Flight altitude
- Number, orientation, length and distribution of flight 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

Raw radar data and platform navigation data are collected by the airborne IFSAR system as pre-determined by the mission plan. Ground GPS data collection is executed simultaneously.

SAR Processing

Once data collection is complete, raw radar data is unloaded from the onboard storage media and de-multiplexed in order to separate the raw data for each antenna. Signals from the two antennae are processed separately to be combined later in the interferometric process. Platform motion information recorded and processed by INS and DGPS technologies, together with the baseline knowledge are used to compensate for perturbation in the data caused by aircraft motion. The position/attitude processor combines the navigation data with airborne and ground based GPS data to generate all the information necessary in order to align the radar signals for proper focusing during the image formation process. For high precision applications, motion compensation procedures must take into account the effects of topography. Single-Look Complex (SLC) image pairs are generated with one image per antenna through an image formation process consisting of: range compression, range curvature correction, range alignment, azimuth compression, depth of focus correction, and azimuth alignment.

Interferometric Processing

Resampling is carried out for one of the SLCs to overlay the other in a sub-pixel precision for subsequent interferometric operation. Multiplying the complex pixel value in one image by the complex conjugate of the corresponding pixel value in the second image on a pixel-by-pixel basis is performed to create an interferogram. An interferogram is a two-dimensional map of phase difference between the two interferometric complex images. The raw interferometric phase, which is represented in slant range geometry, contains artifacts and noise which are inconvenient for the end user (Wimmer et al, 2000). Phase filtering can be implemented to prepare the raw interferometric phase in such a way that the resulting DEMs are as close as possible to the real topography. Both phase spikes and thermal noise can be filtered. 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 3D space, the absolute phase must be determined. Phase unwrapping determines the relative phase between pixels and the connected phase field. After phase unwrapping the data values may still need to be adjusted by an overall constant of 2π through absolute phase determination (Hensley et al, 2001).

An automated approach for phase unwrapping and absolute phase determination can be conducted, for example, in Intermap's STAR-3*i* implementation (Sos et al, 2001). Absolute phase can be determined with the help of elevations of ground control points in the area being mapped or determined by specially developed approach without the use of control points (Birk and Bullock, 1999). Points on the ground are geocoded by geometrically combining the relative range along-track position and depression angle of the radar with the absolute position and attitude of the sensor platform.

Post-Processing

Many aspects of IFSAR post-processing are nearly identical to standard photogrammetric or lidar post-processing. The type and amount of post-processing is application dependent and is tailored to meet specific user requirements (Hensley et al, 2001). Due to the radar's side-looking properties, the above-determined 3D target locations are not evenly distributed in ground plane coordinates. A re-sampling process is applied to generate a regular grid or raster product. These re-sampled flight line products include, the target height or DEM, an ortho rectified SAR image, and a correlation measurement.

These multiple radar images and DEMs are merged into a single image and DEM with a common datum, map projection in a mosaicking process. Data gaps can be filled using an appropriate interpolation method or left undefined. Data editing, primarily for DEMs is conducted to detect and correct potential blunders inherent in the data set, and for quality control purposes. If a bald-earth DEM product is desired, the first surface DEM can be processed to remove objects, such as trees, buildings, towers etc. Other value-added map products can then be produced based on the DEMs and ORRIs.

FACTORS AFFECTING ACCURACY OF IFSAR MAP PRODUCTS

Among all of the quality indicators for a map product, accuracy is one of the most important for many applications. IFSAR mapping is a very complicated process. There are many inter-related factors that affect the accuracy of the final products. These factors encompass the whole process ranging from the design, calibration, stability and practical performance of the sensor system, through to the ground target characteristics, and interaction between the system and targets, as well as processing technologies, editing, and production quality control. In this section, the major factors that influence accuracy of IFSAR map products are presented and discussed.

System Design and Calibration

In any implementation, the system design involves various compromises that determine the overall accuracy and performance. Airborne IFSAR systems must be properly calibrated in order to obtain the desired and consistent accuracy. Mapping with airborne IFSAR requires very accurate measurement of the platform position, range, baseline length and orientation, interferometric phase, wavelength, velocity and Doppler (Hensley et al, 2001). Estimating systematic corrections to these parameters to obtain consistently accurate map products is performed by intensive system calibration.

Bandwidth. Bandwidth is the amount of frequency variation across a radar pulse. Range or cross-track resolution of a SAR magnitude image is directly proportional to the bandwidth; meaning resolution increases as bandwidth increases. This in turn has a direct link to the accuracy of the subsequent map products.

Transmitting frequency. Selection of a transmitting frequency for a particular imaging radar system influences the penetration capability of radar wave and azimuth resolution of radar imagery. A higher frequency system such as X- or C-band will provide little surface penetration and finer image azimuth resolution due to the shorter wavelength. High frequency systems will provide detailed measurements of the first surface that can produce very attractive imagery with an abundance of first surface high frequency detail. Lower frequencies such as P-band or L-band IFSAR systems will penetrate the first surface to a certain degree, provide less detail in the imagery and in forested areas may be able to measure the underlying terrain or ‘bald earth’.

Baseline length. To solve the height, it is critical that the attitude and length of the baseline are known to the highest possible accuracy. An accurate and large baseline is one of three main criteria for an IFSAR system to generate highly precise DEMs (Wimmer et al, 2000). Baseline length is the spatial distance between the phase centers of two IFSAR antennae. Baseline length is obtained by calibration methodologies. Theoretically, the longer the baseline, the higher the sensitivity of phase to height, leading to increased height determination accuracy. However, if the baseline is too long, there is risk of losing correlation between the returns from the two antennae. The baseline length also affects the interferometric scale factor which is the amount of phase shift for a given height change (Sos et al, 1994). When the baseline length is increased, the ambiguity interval will decrease, causing the need for more phase unwrapping to occur, an often-difficult and problematic operation. Errors in baseline determination cause location errors in the final map products in the perpendicular direction to the line-of-sight (Hensley et al, 2001). The magnitude of the error depends on the cross-track location of ground targets within the scene.

Timing offsets and unknown physical delay. IFSAR mapping largely relies upon radar ranging by converting the time that a radar signal takes traveling from the antenna to the target and return. Therefore, hardware timing offsets and unknown physical delays in the transmitter and receiver chain in the radar system are major sources of range errors. Range errors cause the target location in the final map products to be translated along the line-of-sight. Points in the near range are displaced more vertically than horizontally whereas points in the far range are displaced more horizontally than vertically (Hensley et al, 2001).

Data Acquisition

Flying height and speed. Although the image resolution and DEM post-spacing do not change as a result of flight height, some accuracy related quantities scale with platform height. As pointed out by Mercer (2001), for example, the error in the INS-derived roll angle will be converted into an error in two of the recovered ground coordinates (X and Z) of the map products. The IFSAR Signal-to-Noise Ratio (SNR) of the received pulse is also altitude dependent and ultimately is one of the major components of the elevation error budget. At lower altitudes, the SNR is larger and thus the height noise is reduced thereby improving the relative accuracy; however, swath width is also reduced and overall cost increased. Fast flying speed means fast data collection, but with a reduced azimuth resolution for radar imagery.

Platform position/orientation. Both the position and rotation of the antenna structure must be accurately measured to determine the position and the Doppler centroid of the antennae. Processing of the onboard GPS/INS data and ground GPS data produces motion data. Accurate motion data is one of the three main criteria for an IFSAR system to generate highly precise DEMs (Wimmer et al, 2000). Errors in sensor positions (X/Y/Z) will translate directly into the coordinate errors (X/Y/Z) in the direction of the position errors. Sensor position error is the only error source that is completely independent of target location (Hensley et al, 2001).

Topography. Due to the radar side-looking characteristics and certain terrain conditions, foreshortening, layover, and shadow phenomena may appear on the radar imagery and influence the accuracy of final IFSAR map products. Foreshortening, layover and shadow cause correlation between the two interferometric channels to drop below a pre-selected value for a particular pixel, and thus data may be lost for that pixel location. Interpolation can be used to fill small areas of missing data. However, multiple flight lines with different radar look direction may also be required when the situation is severe, typical over areas with significant terrain.

Processing and Post-processing

Image formation. During the process of complex image formation, errors from various sources, such as inaccurate range and azimuth processing will displace the pixel from its theoretical position. This will influence the 3D accuracy of final IFSAR map products.

Filtering. For noise reduction purposes, an operator-selectable filter is normally implemented, which smoothes the phase and may have an effect of averaging over step function height discontinuities in a quasi-liner fashion (Mercer and Gill, 1998). Geometric resolution of radar imagery and accuracy of resulting DEMs may be degraded after the filtering.

Phase errors. Height determination from IFSAR is based on differential phase measurements between two interferometric channels. The differential phase can have unknown delays due to variations in the phase center of the two antennae or from phase delays in the receiver chain (Hensley et al, 2001). Phase errors will translate into differential range errors, and the intersection triangle is thus distorted, which leads to errors in planimetric and vertical dimensions in the final map products. The magnitude of the height error is dependent upon range, and is perpendicular to the line-of-sight. If the phase error is constant, the final IFSAR map products will be shifted and tilted.

Phase unwrapping. The specific implementation of the phase unwrapping algorithm in response to step-function phase changes will impact the derived elevation (Mercer and Gill, 1998).

Datum transformation. Heights determined by IFSAR are WGS84 ellipsoidal heights that may need to be converted to orthometric heights by applying a geoid method. For very accurate DEMs such as the nature of products being produced by IFSAR, the accuracy of the geoid model will have a significant influence upon the overall accuracy of the final DEMs with orthometric heights.

Bald-earth processing. When a bald-earth DEM is desired, the first surface DEMs need to be processed to remove objects such as trees, buildings, towers, etc. Various methods have been developed for bald-earth processing (Wang et al, 2001) with success for certain types of terrain. Bald-earth DEM generation from first surface DEMs is a significant challenge and still a hot research topic. To date, no single method can successfully be applied for all terrain types. Algorithms used in the bald-earth processing will influence the accuracy of generated bald-earth DEM products.

Editing. DEM editing is necessary for the removal of blunders and for quality control purposes. As DEM editing is performed using a combination of manual and automated methods, it is a significant cost component of the IFSAR DEM product. Continued efforts are being made in automation to reduce the amount of manual editing. DEM editing processes contribute to the accuracy of the final DEM product.

MAPPING WITH INTERMAP'S STAR-3*i* AIRBORNE IFSAR SYSTEM

System Specifications and Characteristics

The STAR-3*i* system is a commercial implementation of an airborne, single-pass across-track IFSAR system, owned and operated by Intermap Technologies since early 1997. Approximately 750,000 square kilometers of data 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 2). The two antennae are mounted to a solid invar frame (pedestal) with a 1m baseline. More information on the STAR-3*i* system is reported in Birk and Bullock (1999), Bullock et al (1997), Mercer et al (1998), Sos et al (1994), and Tennant and Coyne (1999).

A major modification was completed recently to allow the Star-3*i* system to support applications which require higher elevation accuracy (~30cm RMS) and produce a higher resolution SAR image (1.25 meter pixel size). The upgraded sensor has begun to operate commercially in the 4th quarter 2001.

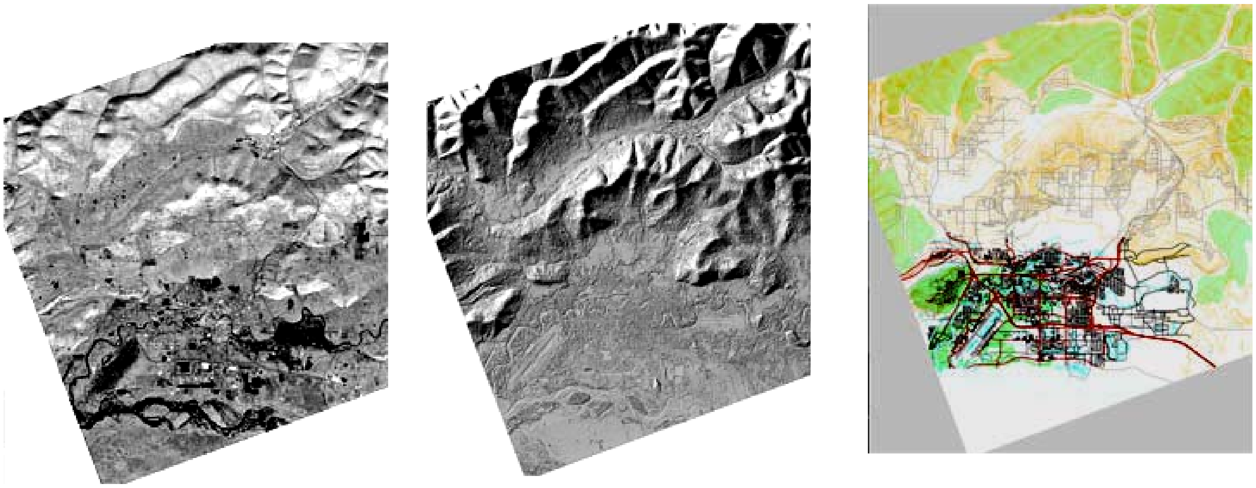
Figure 2. Intermap's LearJet 36 STAR-3*i* System

Products from the STAR-3*i* System

DEMs. DEMs are one of the main products produced by the STAR-3*i* system (see Figure 3a for an example).. By nature of the sensor, the original elevation models provided are of the first surface and not the underlying bald-earth. Although the first surface DEMs have many applications, bald-earth DEMs are traditionally expected and required for many topographic mapping purposes. With proprietary processing technologies, a bald-earth DEM can be derived from the first surface DEMs (Wang et al, 2001) for many terrain types. Currently, STAR-3*i* DEMs are provided as the Global Terrain® (GT) product series in a variety of post-spacing and accuracy. Readers can refer to the *Intermap GT Product Handbook* or www.globalterrain.com website for more details (Intermap, 2002).

ORRIs. ORRIs from STAR-3*i* mapping are radar intensity images with a 2.5 m pixel size (see Figure 3b for an example). ORRIs with 1.25 m pixel size are also provided with the newly upgraded system. These images are orthorectified by the native process using the simultaneously generated DEM. ORRIs provide information similar to black-and-white photography on the layout of built-up areas, roads, waterways, and lines of communication. As the ORRIs are orthorectified, relief displacements have been removed. STAR-3*i* ORRIs 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 are serving as the fundamental base data layer for in-house TLM production.

TLMs. TLMs are value-added STAR-3*i* interpreted map products (see Figure 3c for an example). STAR-3*i* DEMs and ORRIs are the two main data sources for TLM generation. In general, the ORRIs and DEMs are used to create a stereo compilation environment within a commercial off-the-shelf digital softcopy photogrammetric workstation. The digital photogrammetric compilation tools are used as originally designed to extract the features required for the generation of TLMs. With this technology, TLMs can be created at scales ranging from 1:10,000 to 1:50,000 solely from STAR-3*i* data. Tighe and Baker (2000) provide detailed information on the TLM generation process.



(a) Orthorectified Radar Image (b) Digital Elevation Model (shaded relief) (c) Topographic Line Map

Figure 3. Examples of STAR-3*i* IFSAR Map Products (Li and Baker, 2000)

ACCURACY OF STAR-3*i* MAP PRODUCTS

Accuracy of STAR-3*i* map products can be evaluated by comparing the geographic locations of a number of well-defined points to the corresponding ground checkpoints of the 'truth data'. 'Truth data' are usually DGPS determined, map-derived, and photogrammetrically determined coordinates.

Accuracy of DEMs

Many internal studies within Intermap and external evaluations by other mapping organizations have been performed to assess vertical accuracy of various STAR-3*i* DEMs over different terrain conditions. Those accuracy assessments were usually performed on 'bald earth' terrain, i.e. the terrain being comparatively tested should be free of vegetation or other objects that could distort the analysis.

External DEM accuracy evaluation. Mercer (1998) summarizes some of the independent external accuracy evaluations of STAR-3*i* DEMs conducted by different organizations.

Table 1. Results of External Accuracy Evaluation

Report Date	**Terrain Type**	**Flight Height** [1]	**DEM Spacing**	**Size of Test Area (km x km)**	**Author**	**'Truth Data'**	**No. of Check Points**	σ	**Mean Offset**	**RMSE**
Dec. 96	Mixed [2]	12, 000 m	5 m	10 x 16	TEC [3,6]	Photo DEM	6M	**1.7**	**-1.4 m**	**2.2 m**
Dec. 96	Mixed	12, 000 m	5 m	16 x 10	TEC	Photo DEM	6M	**1.5**	**-1.4 m**	**2.1 m**
May 98	Mixed	6, 000 m	2.5 m	8 x 18	INS [4]	GPS	44	**0.9**	**-1.3 m**	**1.6 m**
May 98	Flat	6, 000 m	2.5 m	9 x18	INS	GPS	20	**0.7**	**-1.1 m**	**1.3 m**
May 98	Sloped	6, 000 m	2.5 m	7 x 20	INS	GPS	24	**1.0**	**-1.4 m**	**1.7 m**
May 98	Flat	6, 000 m	2.5 m	8 x 20	INS	Trig Pts	78	**1.3**	**-0.9 m**	**1.5 m**
June 98	Mountains	7, 000 m	10 m	2.9 x 1.3	NASA [5]	Photo DEM	40K	**0.8**	**0.2 m**	**0.8 m**

Notes:

1. Flying height is At Ground Level (AGL).
2. Mixed terrain refers to a mixture of flat and moderately sloped terrain, with slopes up to +/- 35 degrees.
3. TEC is the US Army Topographic Engineering Center - Ray Norvelle was report author. Carling and Davis wrote a separate report on this data set, with similar results.
4. INS is the Institute of Navigation at the University of Stuttgart, Germany - A. Kleusberg and H. G. Klaedtke were authors.

5. NASA Stennis Space Center did the evaluation. Ground truth DEM supplied by USDA-ARS for the San Pedro Watershed Sub-Basin 11.
6. Norvelle's report was very detailed and in it he noted a number of anomalies in certain situations (ravines, slopes, trees).

Results from the above cited independent evaluations are mutually consistent and provide a performance envelope over a range of conditions. The RMSE values represent the absolute accuracies to be expected in the absence of ground control. If ground control is available, the standard deviation represents the ultimate limiting accuracy. At lower acquisition altitudes, the accuracies are superior. These results demonstrate that for acquisition at the lower flight altitudes (near 6,000 m AGL), and with adequate Ground Control Points (GCPs) available, absolute accuracies better than 1 m (RMSE) are obtainable for bald-earth DEMs with 5-m post-spacing in moderate terrain. At higher altitudes (e.g. 12,000 m AGL) and without ground control, absolute RMSE accuracy levels better than 2.5 m have been demonstrated in moderate terrain.

Internal DEM accuracy evaluation. Many internal accuracy studies were carried out within Intermap. Birk and Bullock (1998) compared 10-m post-spacing STAR-3*i* DEMs with photogrammetrically generated 'truth data'. They found that for acquisitions at the lower flying height (6,000 m AGL), absolute vertical accuracies were in the range of 0.8 m to 1.7 m (RMSE) in moderate terrain without the use of ground control. This accuracy may be improved to less than 1 m with the use of GCPs. At higher altitude (12,000 m AGL), absolute vertical accuracy better than 2.5 m (RMSE) were obtained without the use of ground control, which may be improved to less than 2 m with the use of GCPs.

Mercer and Schnick (1999) compared the 5-m post-spacing STAR-3*i* DEMs with laser-derived 'truth data' for three application areas of interests:

- Bald-earth performance for flood-plain risk analysis
- Building height extraction in urban areas
- Forested and agricultural areas with respect to vegetation issues

Their main findings are summarized as follows:

- In non-urban areas, with a 6,000 m flying height, STAR-3*i* DEMs exhibit an elevation noise floor of about 30 cm (1 sigma). Systematic errors in the STAR-3*i* DEMs, which manifest themselves over larger areas and are usually project-specific, can be removed to some level by the use of GCPs. In their studies, the systematic error component was at the 50 to 70 cm levels, although in some projects it is higher.
- In the urban areas, it was demonstrated that in non-core areas, building heights can be extracted using STAR-3*i* with an uncertainty of about 10% of the building height over a height range of 10 to 45 meters.

Li et al (2001) evaluated accuracy of 5-m post-spacing STAR-3*i* DEM data (6,000m flying height) over a mixed terrain in three ways:

- Direct comparison of DEM elevation with photogrammetric 'truth data' (105 checkpoints).
- Application of the DEM to orthorectify five 1:24,000 aerial photographs with 0.5-m ground sample distance.
- Application of the DEM to orthorectify one black-and-white 1-m high-resolution IKONOS image with 1-m ground sample distance.

The main findings from the study are:

- The mean difference in elevation between the STAR-3*i* DEMs and photogrammetric 'truth data' was 0.5 m, with a 1.1 m standard deviation.
- The average offset in X/Y between the image points on the five orthorectified aerial photos and the checkpoints was 1.1 m (about 2 photo pixels) based on 40 checkpoints with a 0.8 m standard deviation. It can be estimated that the STAR-3*i* GT1 (1-m nominal RMSE accuracy) DEMs may be used for orthorectifying aerial photographs with 1:5,000 or smaller scale. Further studies are ongoing.
- Planimetric locations of 64 image points were measured on an orthorectified IKONOS image and then compared with X and Y coordinates in the 'truth data'. Results were: mean difference, 3.7 m; standard deviation, 2.0 m. This demonstrates the feasibility of applying STAR-3*i* generated DEMs for orthorectifying IKONOS images. More studies are being conducted by Intermap for IKONOS and other high-resolution satellite sensors.

Accuracy of ORRIs

Birk and Bullock (1999) used 15 DGPS determined ground checkpoints as 'truth data'. The RMSE from their evaluation were 1.5 m and 1.0 m in X and Y direction, for STAR-3*i* ORRIs produced at a flight height of 6,000 m AGL. In Li et al (2001), 105 photogrammetrically determined checkpoints were used as 'truth data' to evaluate the STAR-3*i* ORRI accuracy for same flight height data. The RMS errors were 1.6 m, 1.8 m in X and Y direction. Results from the two above cited tests show that there are no obvious accuracy differences between easting and northing directions for STAR-3*i* ORRIs. The offsets between the horizontal locations of ORRI image points and checkpoints in the 'truth data' are within 2.5 m pixel size of the ORRIs.

Accuracy of TLMs

A comprehensive study of STAR-3*i* TLM accuracy was reported in Li et al (2001). In these studies, accuracy of TLM data compiled with 1:24,000 map scale with 10 m contour interval, was evaluated based on photogrammetrically collected 'truth data'. A number of well-defined checkpoints for different features were randomly measured from the TLMs and compared to the photogrammetric 'truth data' in order to evaluate the accuracy of different TLM features collected from the STAR-3*i* data. Results of the study are summarized as follows.

Contour line accuracy. Ten contour lines (5 index and 5 intermediate contour lines) were tested with 10 randomly sampled data points on each contour line. Mean difference was 0.6 m with a 1.8 m RMS difference. Generally, the contour lines on the TLM are a very good characterization of the surface. The STAR-3*i* DEM elevation was found to be slightly higher than the check data. The 1.8 m RMS value was well within one-third of the 10 m contour interval specified by ASPRS (1988). Smaller contour intervals could also possible based on the test results.

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 to the 'truth data'. The mean difference between the TLM feature points and the photogrammetric 'truth data' points was 3.8 m with a 5.0 m RMS difference.

According to National Map Accuracy Standard (NMAS) (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. This means that for TLMs produced at 1:24,000 scale, 90% of the test points must be positioned within 12m on the ground. The test results show that the TLM data was well within NMAS specifications (only 5 of 189 tested points were out of tolerance). If TLMs at 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 were outside of this specification. This indicates that, from an accuracy point of view, TLMs derived from STAR-3*i* IFSAR mapping with scale larger than 1:20,000 are also possible. It is important to note limits in the interpretation of some features using radar image data constrain the compilation process.

Vertical accuracy of other TLM features. As the TLM data was compiled in 3D, the vertical accuracy was also evaluated for TLM features. Building footprints were excluded, as compilation of these features is difficult and would not be used for the subsequent contour generation. The overall mean difference was 0.5 m with a 2.0 m RMS value. Mean offset between the two data sets is again approximately half of a meter. The RMS value was slightly larger than that 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, it can be seen that the unimproved dirt roads are difficult if not impossible to digitize compared with other features.

CONCLUSION AND PROSPECTS

It can be concluded that IFSAR technologies are becoming increasingly important in the advancement of the overall spatial information industry associated with mapping, GIS and remote sensing. Airborne IFSAR mapping is a cost-effective mapping technology due to its many inherent advantages compared with other technologies.

Accuracy of map products from IFSAR mapping is one of the main concerns for many geo-spatial related applications. Many interleaved factors have direct or indirect influences upon the accuracy of the final IFSAR map products.

Intermap's STAR-3*i* system is the first commercial implementation of a high-performance, single-pass interferometer. This technology is providing high quality map products addressing the ever-increasing needs of the worldwide imaging and mapping community. Under the well-planned mission and well-controlled production chain, accuracy of map products from STAR-3*i* IFSAR mapping meets pre-designed goals and are being used efficiently for many applications. Some new applications are also feasible, such as the orthorectification of high-resolution satellite imagery as well as medium to large-scale aerial photography.

Recently, a major upgrade of the STAR-3*i* system was undertaken and completed. The upgraded system will offer 1.25 m image resolution with a DEM product specification to be ~30cm for certain terrain types. Accuracy of the resulting map products is expected to improve using the data from the upgraded system. Accuracy evaluation of the map products from the upgraded system is under way and will be reported in future publications.

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