An Innovative Approach Using a Digital Photogrammetric Workstation to Generate Topographic Line Maps from Airborne IFSAR

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ABSTRACT

The production of 1:20,000 topographic maps similar in nature to photo derived maps are being successfully generated from interferometric SAR (IFSAR) data. IFSAR has advanced to the point where airborne systems are capable of accuracies in the centimeters. These high-resolution systems are making their way into aerial photography niches, especially in areas inaccessible by photo due to cloud cover or congested airspace. STAR-3i airborne IFSAR data from three test sites, two in Puerto Rico and one in Alaska, were used to demonstrate topographic line map production. High-resolution orthorectified SAR imagery and digital elevation models were used within a digital photogrammetric workstation to interpret the data in synthetic stereo. STAR-3i's sensitivity to surface roughness, soil moisture, and topography make it an excellent medium to successfully map land use, land cover, cultural features and hydrography. More than 85% of the TLM features were extracted from the IFSAR data alone. Where ancillary data were available, the percentage of TLM features extracted increased to 95-100%. Creating and updating high quality 1:20,000 TLMs with STAR-3i data provides an economical means of maintaining a country's topographic database, especially in regions with persistent cloud cover. The final results are very promising and confirm that IFSAR data was successful in generating 1:20,000 topographic map comparable in standards to USGS photo derived 1:20,000 topographic maps.

INTRODUCTION

For many years, topographic line maps (TLMs) have been created almost exclusively from aerial photography by traditional photogrammetric methods. However, data collection has been limited in many places around the globe due to cloud cover, economic constraints, congested airspace, or combinations of all three. Interferometric synthetic aperture radar (IFSAR) is providing an alternative to conventional aerial photography. TLMs compiled in a stereo environment from IFSAR data are gaining momentum in today's mapping community (see, for example, Feller N. P. and Meier E.H., 1995; Graham, 1994; Li and Baker, 2000; Tighe, 2000; Zebker and Goldstein, 1986; Zebker *et al*., 1994). Intermap is leading the way in this state-of-the-art technology after it acquired an IFSAR system developed by DARPA and ERIM in 1996. Renamed STAR-3*i* is the world's first commercial implementation of a single pass across-track interferometer. STAR-3*i* collects high resolution orthorectified radar images (ORRI) from which digital elevation models (DEMs) are derived. This data is used in conjunction with ancillary data in a traditional map compilation environment to generate and update TLMs. Where no ancillary data exists, approximately 85% of TLM features collected from small scale photogrammetric methods are compiled to effectively generate 1:20,000 - 1:50,000 maps that meet rigorous mapping standards. The percentage of TLM features collected increases to > 95% with the use of ancillary data.

There are fundamental differences in the physical principles underlying SAR imaging and conventional aerial photography. SAR remote sensing is executed by systems that use an antenna positioned below the aircraft and point to the side (side-looking). Side-looking SAR systems introduce geometric distortions such as relief displacement that differ from those of aerial photography and must be understood by map compilers to effectively extract topographic information from the SAR data. Photogrammetric compilers with years of experience working in stereo photo are able to understand these differences through SAR interpretation training. Then map compilation function is akin to that of traditional mapping from aerial photography. In this paper we examine the value of STAR-3*i* IFSAR data for 1:20,000 TLM mapping over different types of topographic environments in Puerto Rico and Alaska. Our goals here are to demonstrate the feasibility of producing topographic maps from high resolution

IFSAR data as an alternative means to conventional aerial photography and to introduce an operational methodology that successfully takes the TLM products to the commercial market.

BACKGROUND ON STAR-3*i* SENSOR

STAR-3*i* is a high-resolution single pass across-track IFSAR mounted in a Learjet 36 (Figure 1), previously described by Ellis (2000), Tighe (2000), and Tennant and Coyne (1999). Data recorders collect return radar pulses from an X-band twin antenna interferometer (separated by a 1-meter baseline) and positioning information from differential GPS (DGPS) and inertial systems. Note the large dome on the underside of the aircraft; this structure houses the radar antennae and positioning equipment. STAR-3*i* can "see" through clouds and obscurants (smoke) and is not restricted to daytime operation. The Learjet is capable of high-speed data collection (up to 100km^2/minute) and can collect 13,000 km^2 in a 24 hour period. These data are processed to provide high-resolution first surface DEMs with an RMSE 1 to 3-m and ORRIs with a 2.5-m pixel.

STAR-3*i* PRODUCTS

STAR-3*i* products are sold through Intermap's "off the shelf" commercial site, called GLOBAL Terrain™, (www.globalterrain.com). These products are assigned designations based on the vertical RMSE accuracy of the product (GT1, GT2, GT3 see Table 1) (Global Terrain Product Handbook, 2000). All GT and TLM products are in Universal Transverse Mercator (UTM) projection referenced to WGS84 horizontal datum. All data are provided in ortho-metric heights (that is, heights above mean sea level) through the application of the EGM96 vertical datum. These products are cut to 7.5 minute by 7.5-minute tiles (quadrangles) for latitudes between 56N to 56S and 15 minute by 7.5-minute tiles for latitudes north and south of 56 degrees latitude. GT1 products require in-scene ground control to yield DEMs with a RMSE 1-m vertical accuracy and 5-m posting specification. A GPS ground station is established within

200 km of the study area being mapped so that in-scene ground control is not required for GT2 or GT3 data collection. These products collected at a higher altitude than GT1 deliver DEMs with a RMSE of 2-m and 3-m, with a 5 and 10 m posting, respectively. The pixel size of the ORRI has an RMSE of 2.5-m for all GT products.

STUDY AREAS

Three test sites, two in Puerto Rico and one in Alaska, representing different type of topographic environments (urban and mountainous) and two STAR-3*i* product types (GT3 and GT1) were used to demonstrate the capability to generate 1:20,000 TLMs from IFSAR. The study sites are described below.

Test Site 1. San Juan, Puerto

Most of the topographic base mapping (using 1940's aerial photography) in Puerto Rico has been untouched in 50 years. In November 1998, Intermap was contracted by Caribbean Pictometry Inc. to acquire and process STAR-3*i* data of the Commonwealth of Puerto Rico to generate new TLMs. GT3 STAR-3*i* data were collected at flying height of 9100 m to generate a 2.5-m resolution ORRI and a DEM with RMSE 3-m vertical accuracy. Approximately 9,200 km^2 of STAR-3*i* data were collected over a 5-day period, despite mid-afternoon tropical weather conditions of rain, cloud, and turbulence. The San Juan quadrangle was selected from this flight campaign for two reasons: there were existing aerial photographs available for comparison and the land cover is comprised mainly of urban areas, which tend to be problematic for interferometric SAR sensors (Tennant J. K. and Coyne T., 1999). The high concentrations of buildings in downtown cores can result in radar shadow, foreshortening, and layover effects. These effects can be minimized to some degree at the flight planning and data processing stages. San Juan is located in the northeastern portion of the island of Puerto Rico between 66°07'30"W - 18°30'00"N and 66°00'00"W - 18°22'30"N (see, Figure 2). San Juan has a well-developed infrastructure of urban, residential, and industrial environments linked by major highways and extensive railway networks. The area is relatively flat with little variation in relief (< 30 m).

Test Site 2. Corozal, Puerto Rico

Corozal quadrangle was selected for its mountainous terrain not present in the San Juan test site. Corozal offers a different topographic environment characterized by mountainous terrain of 700-m maximum relief. Corozal is located in the eastern-central portion of Puerto Rico island between 66°22'30'W - 18°22'30"N and 66°15'00"W - 18°15'00"N (Figure 3). 50% of the tropical forests have been cleared for plantation agriculture and settlements.

Test Site 3. Fairbanks, Alaska, USA

Intermap collected GT1 STAR-3*i* data on contract to Alaska Science and Technology Foundation (ASTF), which provided the data to Fairbanks Gold Mining (Ellis, 2000). On October 15-20, 1999, the Learjet flew at an altitude of 6100 m over Fort Knox, Alaska at night collecting approximately 1,380 km^2 of DEM data with a 1-m RMSE vertical accuracy (a posting of 5 m) and ORRI data at 2.5-m pixel. Image resolution remains 2.5-m, regardless of altitude; however, the lower altitude provides a better signal-to-noise ratio resulting in DEMs with a higher accuracy. Ground truth information, as required by GT1 specifications (and not GT2 or GT3), was supplied by Fairbanks Gold Mining. Fairbanks quadrangle was selected from the Fort Knox campaign because GT1 data with ground truth information were available. The Fairbanks is located between 65°00'00"W- 147°00'00"N and 64°30'00"W - 146°30'00"N (Figure 4). The overall relief varies from sea level to 300 m. The land cover is made up of urban, residential, and forests.

TLMs FROM STAR-3*i* DATA

Producing TLMs from STAR-3*i* elevation and image data are intricate. The data are processed in a UNIX environment using custom software as well as commercial LH Systems LLC Digital Photogrammetric Workstation (DPW) software and hardware. UNIX systems (to date) have been the only ones powerful enough to handle the data volume and demanding graphics requirements of the STAR-3*i* –to-TLM process. The process flow consists of the following steps: STAR-3*i* data processing, TLM data capture, and TLM cartographic process, as described below (Figure 5).

STAR-3i Data Processing

The STAR-*3i* processor generates STAR-3*i* image (magnitude), DEM (height), and correlation data for each input segment. The data are in the SCH (Scan, Cross-scan, Height) coordinate frame that is oriented along the actual aircraft flightline. Primary and secondary look image data are radiometrically balanced. A SCH to UTM coordinate system conversion is applied to transform the data into real world coordinates. The image data is mosaicked into map sheets at a 2.5-m pixel size. The DEM data is processed at 5-m postings in Helava format using in-house software. Both image and DEM are cut into map sheets. In areas where relief displacement effects like layover or shadow persist (in both looks) and result in missing DEM data, the data is interpolated to ensure a fully populated DEM. Flight planning is designed to minimize any loss of data so that interpolation is only over small areas. A vigorous editing process checks for radar anomalies such as layover and shadow. Stereo models and DEM for each map sheet are delivered to the TLM cartography department for use in TLM data capture.

TLM Data Capture

Preparing topographic maps from IFSAR data within a digital photogrammetric workstation uses the art and science of radargrammetry in much the same fashion as photogrammetry is used with aerial photography. Stereo models, however, are generated differently. In traditional photogrammetry this is done with a stereo pair and ground control. The stereo model is then used to collect DEM and TLM data. Intermap developed a similar method using STAR-3*i* IFSAR data. In this case, the DEM already exists and is used in conjunction with the ORRI to derive an artificial second image called a stereomate. This stereomate/ORRI pair is then used to create the stereoscopic viewing/measuring environment as in softcopy photogrammetry. Radargrammetry techniques are then used to collect TLM features. The hydrographic features are compiled and merged with the DEM to generate breaklines in the DEM. LH Systems internal triangular irregular network (TIN) package is used to model the surface, generate the final stereomate, and to produce cartographically acceptable contours based on the STAR-3*i*'s "first surface" of return. TLM features are captured in synthetic stereo using the following information: new stereo-mate/ORRI pair, contours, ancillary data (aerial photo, maps, and charts), and feature tables generated from project specifications. The ancillary data are used as interpretation, classification, and compilation guides. Where the features depicted on the existing map are visible on the radar imagery they are compiled from the imagery. All TLM features are processed through commercial software to ensure a proper topological structure and to adherence to client specifications. Once these QA/QC procedures are carried out, the data are ready for cartographic processing.

TLM Cartographic Process

The general TLM cartographic conventions are those described in U.S. Defense Mapping Agency Product Specifications for 1:50,000 Scale Maps of Foreign Areas (1980) and in the Topographic Line Maps From Interferometric Synthetic Aperture Radar Product Definition (1999). The features collected for test sites 1 and 2 in Puerto Rico were compiled from 1:20,000 specifications supplied by the client. In-house specifications adapted from USGS mapping standards for 1:20,000 mapping scale were used in test site 3 in Fairbanks (Topographic Line Maps From Interferometric Synthetic Aperture Radar Product Definition, 1999). 5-Meter contours were produced semi-automatically from the DEM within the photogrammetric workstation with an accuracy +/- one half of the contour interval 90% of the time. Contours are an accurate depiction of the terrain in open areas, whereas in areas that are heavily treed, the contours should be regarded as form lines. There is considerably more variability (noise) in the DEM over vegetated areas because the radar penetrates the canopy in unpredictable ways. The drainage is digitized as physical breaklines that are added to the DEM. Points causing small contour isolations such as tree stands and isolated buildings are automatically removed from the DEM using proprietary software. Toponymy (name keys and font guides) and administration boundaries are provided by the end user and integrated with the files in accordance with normal cartographic practice. The production of TLMs is necessarily dependent upon an acceptance test procedure. The acceptance test is based on two iterations of inspections. The first inspection is comprehensive. A “first inspection” product is provided to the end user. The end user annotates required changes on the first inspection product and provides a written description of the required changes to Intermap. Intermap makes the required changes and returns the newly edited product to the end user for a “second inspection”. The purpose of the second inspection product is only to verify that all the required changes from the first inspection were made. The final product is a TLM map sheet, scales as small as 1: 20,000, in digital format.

DISCUSSION AND RESULTS

Table 2 provides a comparison of the three test sites described here. IFSAR’s sensitivity to surface roughness, soil moisture, and topography and its viewing geometry (analogous to low sun-angle photo) make it an excellent medium to successfully map a diverse range of vegetation that includes scattered trees, scrub, mangroves, plantation, orchards, and mixed woodland. It is also well suited for mapping topography (land cover, hydrography, and contours). IFSAR is responsive to cultural features such as roads, bridges and, to a lesser extent buildings. It can therefore be used to discriminate targets and assess urban development. Water features, shorelines, lakes, reservoirs, and double line rivers are easily interpreted from the IFSAR imagery, as are primary and most secondary roads. Successfully interpreting features such as dirt roads, tracks, and some cultural features is sometimes problematic but using ancillary data such as existing maps, or photos enhance this process. Land cover classes represent the most significant compilation challenge for IFSAR systems because these data are “first surface” collections. In addition, the varying slope of the rolling terrain can impair the ability to separate the land cover types. Interpretation in the third dimension helps to reduce the effects from first surface and rolling topography.

Approximately 85% - 90% of TLM features collected from smaller scale photogrammetric methods were compiled from the STAR-3*i* data alone to effectively produce 1:20,000 maps that meet rigorous mapping standards (Table 3). Where ancillary data were available, 100% of TLM features were extracted. Data for GT1 products are captured from a much lower altitude than for GT3 products. Therefore there is considerably more variability (noise) in the GT3 DEM over vegetated areas as compared to the GT1 DEM. The great advantage of IFSAR is that the observations are acquired with virtually complete spatial coverage, rather than the sparse observations inherent in conventional photography.

The IFSAR-base TLMs were compared to 1:20,000 USGS topographic maps on a grid cell by grid cell bases. Table 3 provides a list of the STAR-3*i* TLM features and a percentage value that relates to the amount of TLM features that were collected from the STAR-3*i* alone. For example, mangroves 95% indicates that 95% of the mangrove class, as outlined on the existing map, could be blindly interpreted from the IFSAR data. 85%-95% of the hydrography features (lakes, shoreline, and rivers) were collected. Approximately 90% of cultural features such as roads and railways, were extracted, however, the classification of roads and railways required some assistance of ancillary data. 95% Residential/urban environments are easily spotted on SAR imagery as bright regular patterns resulting from the buildings acting as corner and dihedral reflectors; percentage decreases for scattered settlements. IFSAR sensitivity to vegetation allowed for the delineation of 85% tropical forest; 95% cleared land usually consisting of grasses, agriculture, or exposed soil, 80% interpretation of swamps and marshland.

Test Site 1: San Juan, Puerto Rico

GT3 STAR-3*i* ORRI is compared with aerial photography in Figure 6 and Figure 7. As previously discussed, urban areas (like that of San Juan shown here) can present a challenge for IFSAR systems. However, proper flight planning and processing of the data minimizes these challenges to generate a

SAR image that is comparable to aerial photography. A decimated version of the 1:20,000 TLM map product of San Juan is shown in Figure 8. It was generated from GT3 SAR data (3-m RMSE vertical accuracy DEM and 2.5-m pixel ORRI). Ten-meter contours were produced semi-automatically from the DEM within the DPW with an accuracy +/- one half of the contour interval 90% of the time. This TLM product was based on specifications outlined by the end user and adaptations of the USGS topographic map specifications.

Test Site 2: Corozal, Puerto Rico

Corozal differs from San Juan in that it has little urban development, 75% vegetation canopy, and is characterized by mountainous terrain with a maximum relief of 700-m (Table 2). A view (not to scale) of the 1:20,000 TLM is shown in Figure 9. It was generated from GT3 STAR-3*i* DEM (3-m RMSE vertical accuracy) and ORRI (2.5-m pixel). An average of 90% of TLM features typically collected from aerial photography using photogrammetric processes were collected from the STAR-3*i*'s DEM, ORRI and ancillary data. 10-m contours were produced semi-automatically from the DEM within the DPW with an accuracy +/- one half of the contour interval 90% of the time.

Test Site 3: Fairbanks Alaska

The Fort Knox's STAR-3*i* flight campaign, which included Fairbanks, was collected at GT1 specifications (6100m altitude, 1-m RMSE vertical accuracy DEM, 2.5-m pixel ORRI), Table 2. The ORRI shown in Figure 10 is one of the first products of the STAR-3*i* system. GT1 data provided a superior image to that of GT3, which enabled 90% of TLM features to be extracted from the ORRI alone. Fairbanks has been cartographically enhanced in a fashion similar to USGS line base map sheet. Five-meter contours were produced semi-automatically from the DEM with an accuracy +/- one half of the contour interval 90% of the time. A quantitative comparison of this line work with the scanned USGS quad sheet of the same area show where differences have occurred in both cultural and natural features. Notable differences were seen in the road network on hillsides immediately north of the city. A traditional vector map

(Fairbanks) and SAR image (Fort Knox Region), Figure 11 portrays the TLM data that is easily extracted from the IFSAR data. A portion of the map is presented with full cartographic enhancement to clearly illustrate the capabilities of this TLM process.

The GT1 IFSAR data offered an image with considerable less noise than that of GT3 IFSAR data. The reduction in noise provides a medium that is easier to interpret resulting in increased detail on many cultural features. A combination of the smooth terrain (result of previous glaciers) and sparse full forest canopy provided optimal conditions for X-Band IFSAR data collection lending to better TLM feature identification. For example, railways can be difficult to differentiate from major highways due to similar radar backscatter characteristics, however, that was not the case for GT1 data in Alaska. Most of the railways exhibited a high radar backscatter return as compared to that from highways.

CONCLUSIONS

We presented the method for the production of TLMs from STAR-3*i* IFSAR data. Using the IFSAR data within a digital photogrammetric workstation to produce a 3-D viewing/measuring environment is highly successful for generating and updating the 1:20,000 TLMs. More than 85% of TLM features typically collected from small-scale photography were efficiently mapped using only 7.5 by 7.5-minute DEM/ORRI tiles, over three test sites. The percentage of TLM features collected increased to 90-100% when ancillary data was used in conjunction with the DEM/ORRI data. Three new TLMs were produced for San Juan and Corozal in Puerto Rico, and Fairbanks in Alaska.

IFSAR systems can play a practical role in the generating TLMs. High-resolution IFSAR data are making their way into aerial photography niches. They are not impeded by cloud cover, which becomes problematic in the cloud belt within 15 degrees of the equator and near the poles. Moreover, IFSAR systems are not restricted by the absence of sunlight, which means data collection can occur day or night. This flexibility males it much easier to work in congested airspace.

The STAR-3*i* DEM and ORRI data are already making important contributions towards topographic mapping at 1:20,000 scale. Creating and updating TLMs with STAR-3*i* data takes advantage of a state-of-the-art technology to economically maintain a country's topographic database. The combination of low cost and high performance will not only meet the military need, but promises to have significant impact on civil and commercial users of such data, especially in cartographic applications where an advanced civil capability will mutually benefit the Department of Defense (DOD).

FURTURE RESEARCH

Our next step is to validate an automatic DSM generated by algorithm's underdevelopment by Intermap as well as to assess interpretability of a 1.25m-pixel product to be released soon. Intermap is currently updating the STAR-3*i* system to RMSE 30-cm DEM to produce a DSM (first surface DEM) and DTM (Bald earth DEM). A comparison of the DSM and DTM contours will be considered.

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FIGURES and TABLES in the order as they appear in the text.

Figure 1. STAR-3*i* Learjet

Global Terrain Product	Nominal Altitude (meters)	Nominal Accuracy (RMSE, meters)		Mapping Scales
		Vertical	Horizontal	
GT1	6100	1	2.5	5,000 - 10,000
GT2	6100	2	3	10,000 - 12,000
GT3	9100	3	3	12,000 - 50,000
IM1	both	N/A	2.5	5,000 - 50,000

Table 1. GLOBAL Terrain Products

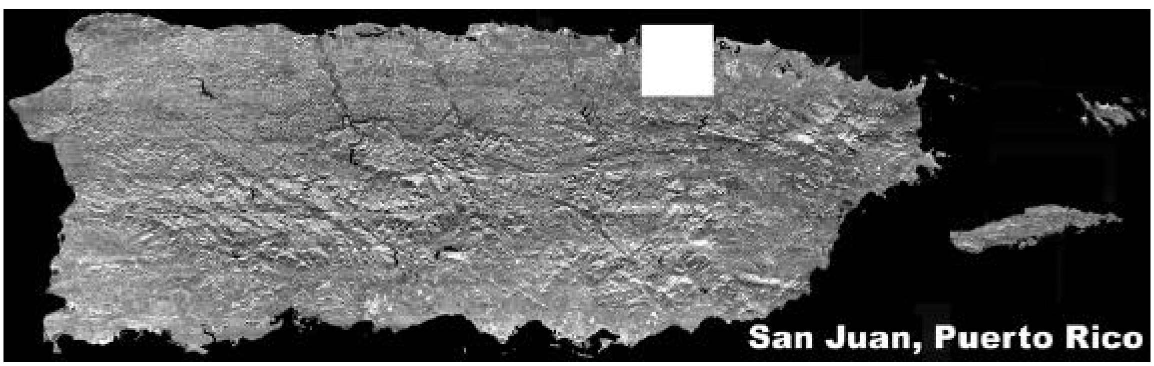

Figure 2. Test Site 1, San Juan, Puerto Rico Quadrangle

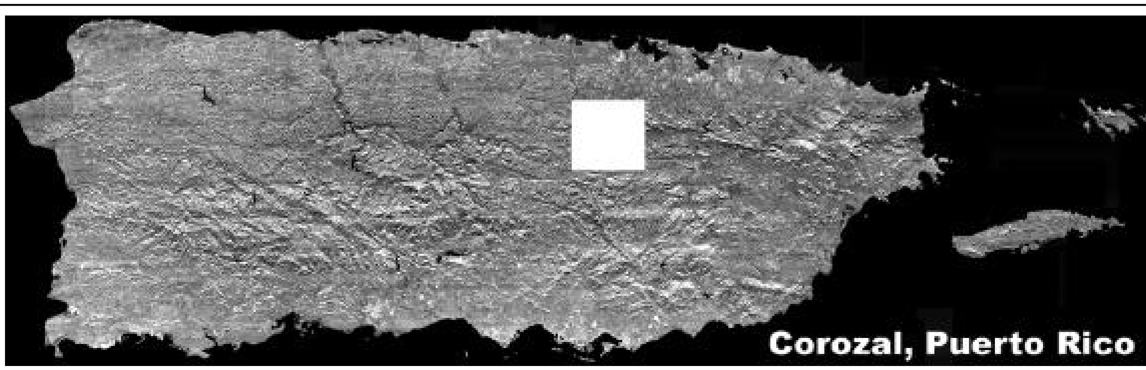

Figure 3. Test Site 2, Corozal, Puerto Rico Quadrangle

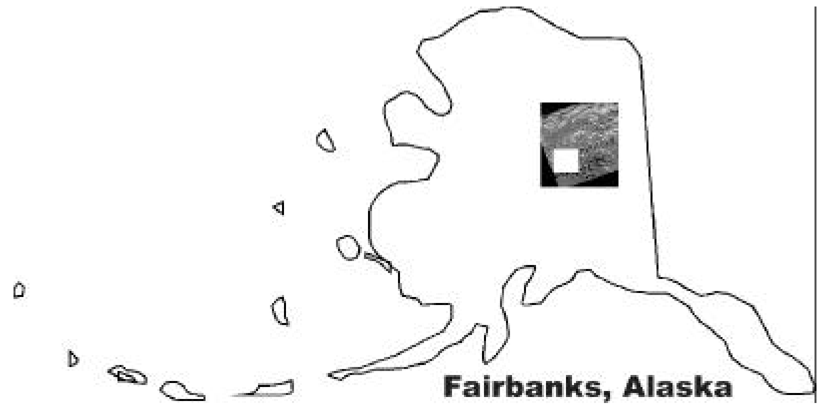

Figure 4. Test Site 3, Fairbanks, Alaska Quadrangle

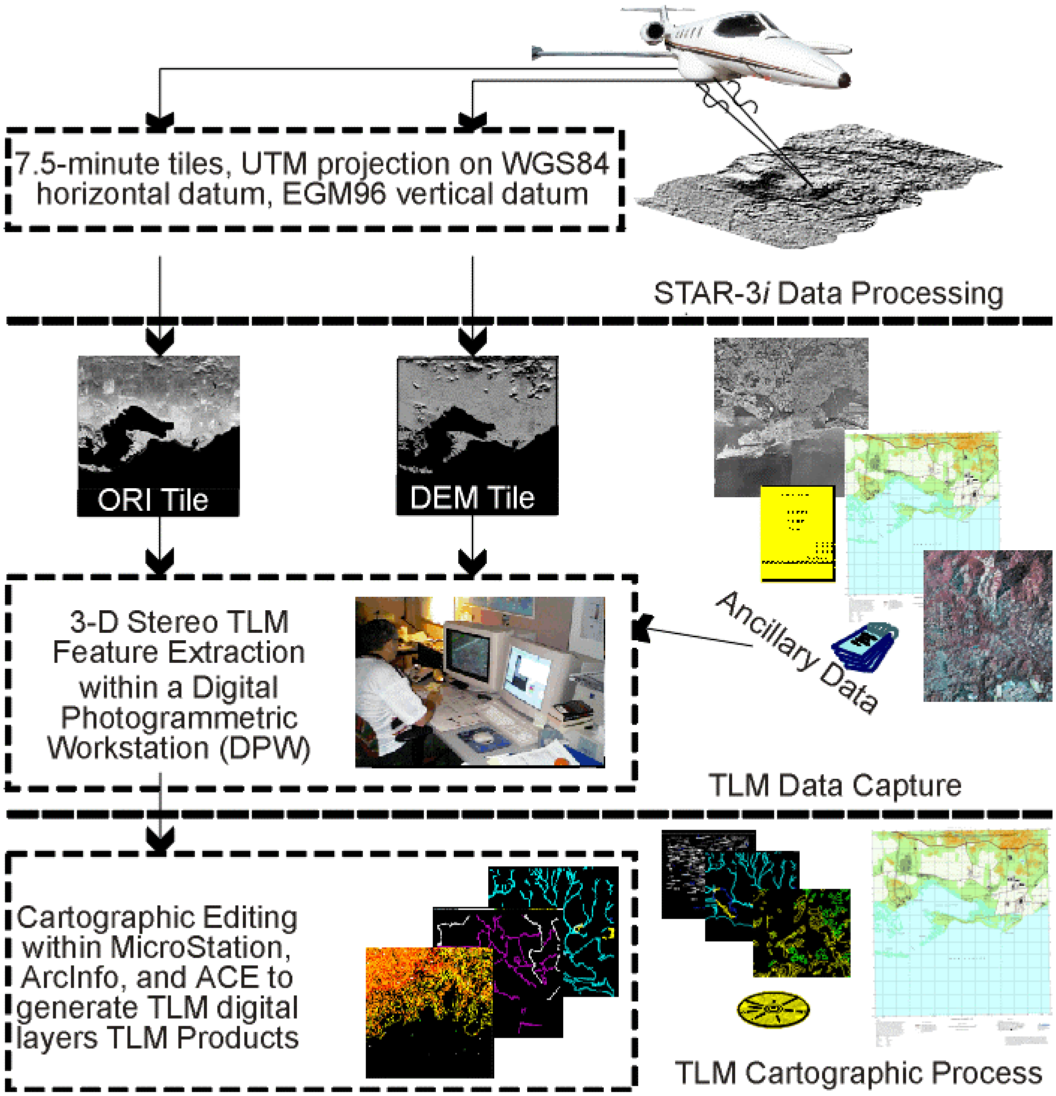

Figure 5. TLM from STAR-3*i* Data Process Flow

Test Site	Terrain/Landform	IFSAR Data	Auxillary Data	Results
1. San Juan, Puerto Rico 7.5" X 7.5" Tile Mapping Scale: 1:20,000 Vegetation Cover: 10% Last Mapped:	Flat Terrain Local Relief 30 meters Beach Ridges/Shore Bluffs Urban Environment	GT-3 Data 9100 m Flying Height 2.5 m pixel ORRI RMSE 3-m DEM Image Date: 21/11/98	94 Photography USGS Quad: (118066D1); Photorevised: 1994	85% TLM Features obtained from SAR data alone, increased to 100% of TLM features collected when combined with existing TLM and Photo
2. Corozol, Puerto Rico 7.5" X 7.5" Tile Mapping Scale: 1:20,000 Vegetation Cover: 75% Last Mapped:	Mountainous Local Relief 700 meters Relief Hummocky Rural Environment	GT-3 Data 9100 m Flying Height 2.5 m pixel ORRI RMSE 3-m DEM Image Date: 21/11/98	USGS Quad: (118066C3); Photorevised: 1994	85% TLM Features obtained from SAR data alone, increased to 100% of TLM features collected when combined with existing TLM
3. Fairbanks, Alaska 15" X 7.5" Tile Mapping Scale: 1:20,000 Vegetation Cover:50% Last Mapped:	Relief Hummocky Local Relief 300 feet Urban/Rural Environment	GT-1 Data 6100 m Flying Height 2.5 m pixel ORRI RMSE 1-m DEM Image Date: 11/04/99	USGS Quad: (164147G7); Photorevised: 1972 & 1975	90% TLM Features obtained from SAR data alone, increased to 100% of TLM features collected when combined with existing TLM.

Table 2. Comparison of the three test sites

TLM FEATURE	ORI*	TLM FEATURE	ORI*	TLM FEATURE	ORI*
lakes, reservoirs, shoreline	>95%	divided highway, all weather, dry surface	>85%	residential	>95%
double line rivers	>95%	two lane highway, all weather, dry surface	>65%	city	>95%
single line rivers tributaries	>85%	one lane highway, all weather, dry surface	>65%	buildings	>70%
mangrove forest	>95%	one lane highway, all weather, loose surface	>55%	tanks	>85%
subtropical dry forest	>85%	fair, dry weather, loose surface roads	>55%	TEXT	
swamp or marsh	>80%	track	>55%	place names	**
cleared land	>95%	railway	>55%	river, lake names	**
		transmission lines	>70%		
*ORI: Percentage of information extracted from the INSAR data alone				** provided by 1:20,000 USGS topographic	

Table 3. Percentage of TLM features compiled from IFSAR data

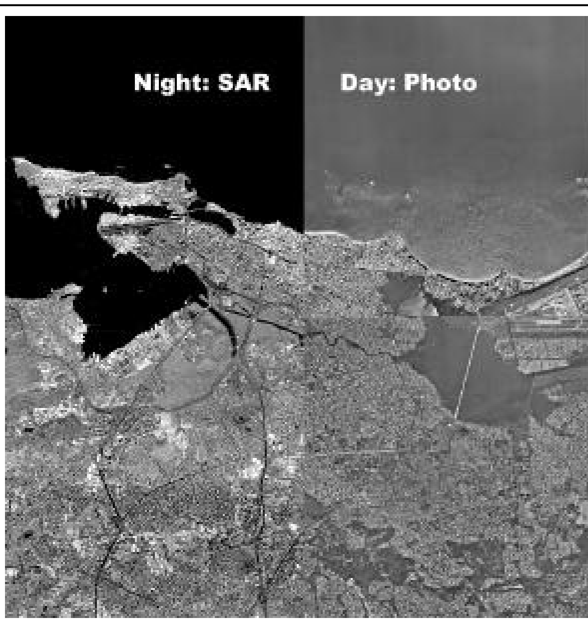

Figure 6. SAR and Photo Comparison

Figure 8. 1:20,000 TLM of San Juan, Puerto Rico generated from GT3 STAR-3i DEM and ORRI

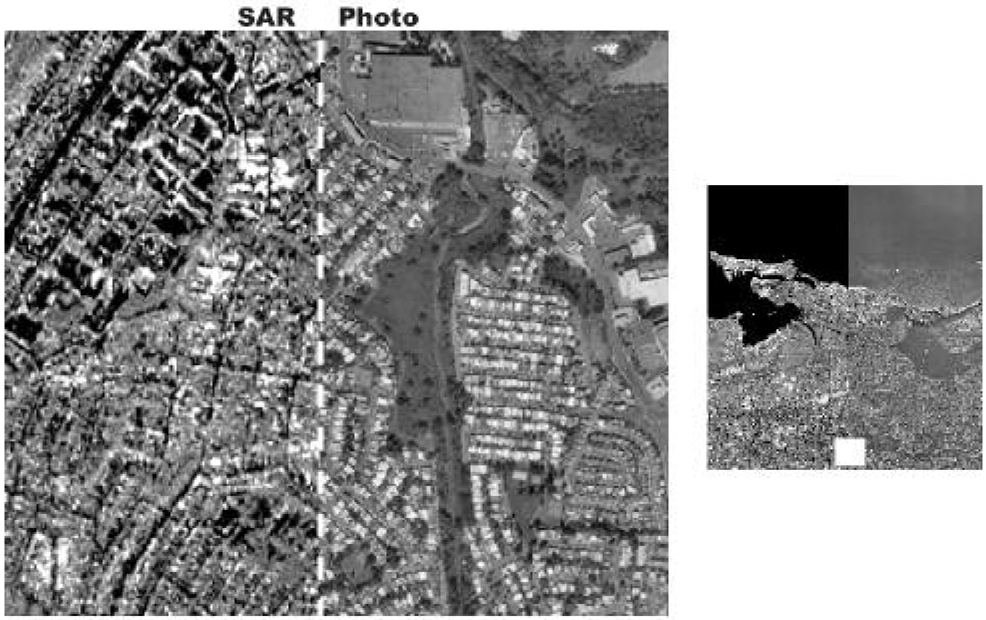

Figure 7. Full resolution SAR and Photo Comparison

Figure 9. 1:20,000 TLM of Corozal, Puerto Rico generated from GT3 STAR-3i DEM

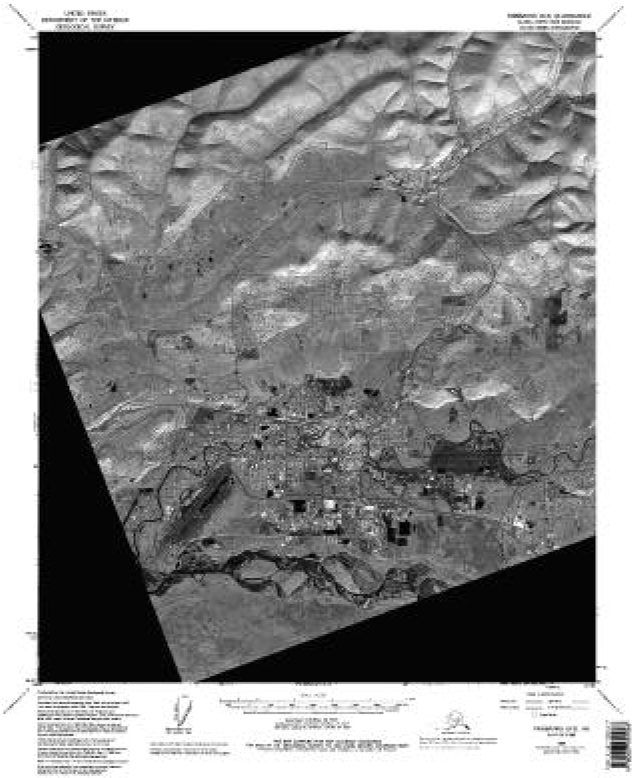

Figure 10. SAR of Fort Knox Flight Campaign (Fairbanks city in the southern portion of the image)

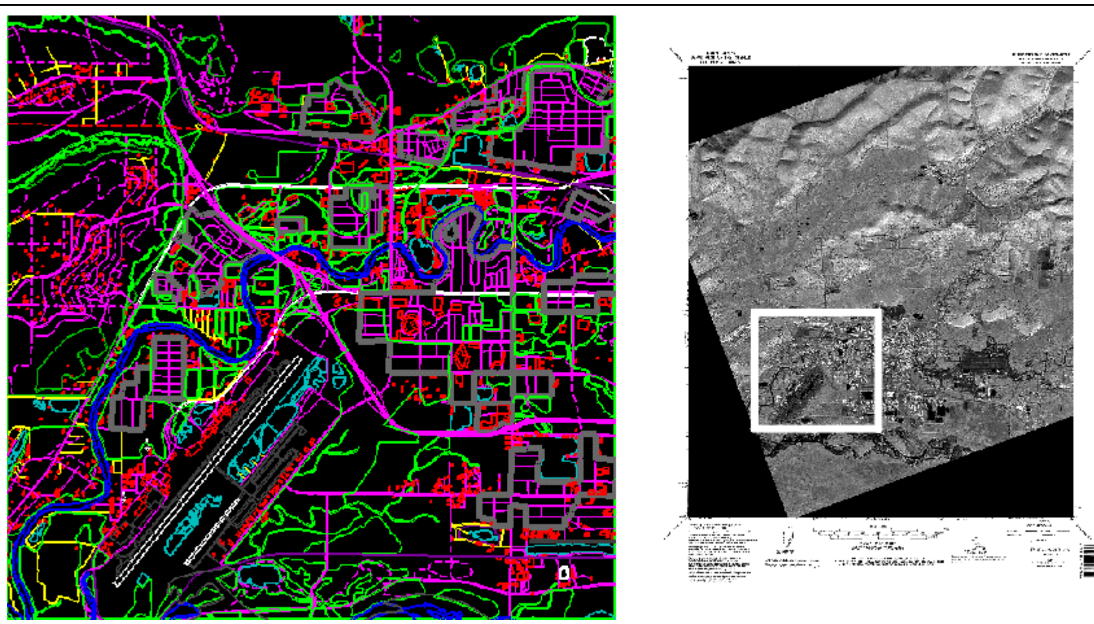

Figure 10. Traditional Vector Map 1:20,000 compiled from GT1 STAR-3i Data