TOPOGRAPHIC LINE MAP PRODUCTION USING HIGH REOLUTION AIRBORNE INTERFEROMETRIC SAR

M. Lorraine TIGHE
Intermap Technologies, Canada
Ltighe@intermap.ca

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ABSTRACT

The production of 1:20,000 topographic maps similar or identical in nature to photo derived maps are being successfully generated from interferometric SAR data. Interferometric SAR 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. Intermap Technologies is taking advantage of this state-of-the-art technology. STAR-3*i* interferometric SAR system is shown, in some applications to replace traditional photogrammetry. Creating and updating topographic maps with STAR-3*i* data provides an economical means of maintaining a country's topographic database while improving accuracy and data content within the topographic maps. In the fall of 1998, Intermap collected interferometric SAR data for the entire island of Puerto Rico just under 13 days, marking the first time that an entire state/region had been mapped by STAR-3*i*. This data is part of an on-going project to generate 1:20,000 topographic maps for the whole island. One such map sheet, Central Aguirre, is the focus of this paper. High-resolution orthorectified SAR imagery and digital elevation models were used within a photogrammetric workstation to interpret the data in synthetic stereo. STAR-3*i*'s sensitivity to surface roughness, soil moisture, and topography made it an excellent medium to successfully map land use, land cover, cultural features, and hydrography. The final results are very promising and confirm that STAR-3*i* data is successful in generating 1:20,000 topographic maps comparable in standards to USGS photo derived 1:20,000 topographic maps.

1   INTRODUCTION

For many years, topographic maps have been created almost exclusively from aerial photography by traditional photogrammetric methods. The efficiency of data collection, has, however, been limited in many places around the globe due to cloud cover, economic constraints, and/or congested airspace. Interferometric SAR (INSAR) is providing an alternative means to conventional aerial photography methods. INSAR systems have advanced to the point of accuracies in the centimeters and are now gaining increasing credibility as a promising tool for deriving high-resolution digital elevation models (DEMs) and therefore topographic maps (Feller *et al*., 1995; Graham, 1994; Zebker and Goldstein, 1986; Zebker *et al*., 1994). Intermap is taking advantage of this state-of-the-art technology by using in-house STAR-3*i* INSAR system to create and update topographic maps. INSAR systems are not impeded by cloud cover, which becomes problematic in the cloud belt region within 15° of the equator and near the poles (Graham, 1974). Moreover, INSAR systems are not restricted by sunlight allowing for data collection day or night, which combats areas of congested airspace. STAR-3*i* has an added bonus over other airborne platforms in that the INSAR system is mounted on a LearJet allowing for high-speed data collection of up to 100 km² per minute. This allowed Intermap to acquire high-resolution DEMs and Ortho-Rectified Images (ORIs) for the entire island of Puerto Rico in less than two weeks. Central Aguirre Quadrangle was chosen from this data set to demonstrate the capabilities of STAR-3*i* data to successfully generate TLMs comparable in standards to 1:20,000 USGS photo-based TLMs, without the assistance of auxiliary data. This methodology is similar in nature to that of TLMs derived from aerial photography methods. Planimetric information such as shoreline, lakes, rivers, roads, railways, transmission lines, vegetation cover, urban areas were easily compiled from the INSAR data within a photogrammetric workstation to comply with 1:20,000 mapping specifications adapted for STAR-3*i* data (Michael and Tighe, 1999). The paper provides a brief review of STAR-3*i* sensor characteristics, data products, data acquisition, and processing techniques. More attention is placed on the interpretation of the INSAR data and the generation of the TLMs. Finally, the results are discussed and compared to the preexisting 1:20,000 USGS photorevised 1982 TLM created by photogrammetry methods from aerial photography.

2 STAR-3*i* INSAR SYSTEM

2.1 Overview

STAR-3*i* was developed by the Environmental Research Institute of Michigan (ERIM) under contract to the U.S. Defense Advanced Research Projects Agency (DARPA). In August of 1996, STAR-3*i* became the world's first commercial implementation of a single pass across-track interferometer managed by Intermap Technologies. STAR-3*i* sensor characteristics are outlined in Table 1. It is an X-band dual antenna interferometer separated by a ~1-meter baseline in the across-track plane operating at an incidence angle range of 35°-55°, centered on 45°. The INSAR sensor is mounted on a LearJet 36A aircraft capable of high-speed data collection, imaging up to 100km^2 per minute (Figure 1). Under ideal conditions, high-resolution DEMs and ORIs geometrically co-registered and fully Geocoded can be acquired for approximately 30,000 km^2 of terrain in one day of operation. The system operates independent of day/night and therefore is not hampered by cloud cover, tropical haze, or congested airspace. Accurate positioning of the STAR-3*i* system is achieved through post-processing GPS data, precise inertia measurement data, and careful calibration of the baseline. 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 GT2/3 data collection. STAR-3*i* is a coherent imaging system that records both amplitude and phase of the radar backscatter signal from the two antennae during a single pass. It exploits this coherence using phase measurements to infer differential range and range change on the two SAR images. The phase differences, representing phase variations are due to changes in topography, are recorded as an interferogram used to calculate the elevation of the terrain. Height measurements from INSAR are well developed in the literature (Graham, 1974; Zebker and Goldstein, 1986; Li and Goldstein, 1990; and Zebker et al., 1992) and are best explained with the aid of a diagram shown in Figure 2. Given two antennas A$_1$ and A$_2$, surface topography is given by z(y), altitude *h* above the ellipsoid, the baseline B, range to the target ρ, the look angle at target location θ, and the angle of the baseline with respect to the horizontal α, antenna 1 transmits and receives while antenna 2 receives at the same time as A$_1$ is defined by:

$$z(y) = h - \rho \cos(\theta) \qquad [1]$$

Based on the law of cosines, we can state that:

$$(\rho + \delta\rho)^2 = \rho^2 + B^2 - 2\rho B\cos(90-\theta+\alpha) \qquad [2]$$

where δρ is the difference on the two slant ranges and δ is the orientation of the baseline with respect to the horizon. Solving equation [2] for ρ and substituting into equation [1] gives:

$$z(y) = h - \left\{ \frac{\delta\rho^2 - B^2}{2B\sin(\alpha-\theta) - 2\delta\rho} \right\} \cos(\theta) \qquad [3]$$

Equation [3] reveals an obstacle when trying to determine δρ which is given by:

$$\delta\rho = \frac{\lambda\phi}{2\pi} \qquad [4]$$

PARAMETER	X-HH
Operational Speed	750 km/hr
Frequency	9.5685 Ghz
Bandwidth	67.5 MHz
Pulse Width	22.6 microsecond
Chan PRF	600 Hz
Nominal Resolution	3 m
Pixel Spacing	2.5 m
Depression Angle	35°-55°
Real Baseline	0.9205 m
Effective Baseline	1.841 m
Slant Range Swath	7500 m
Ground Swath	10 km nominal at 9100m
Data Collection Rate	13.75 Mb/second 100 km^2/minute

Table 1. STAR-3*i* Sensor Characteristics
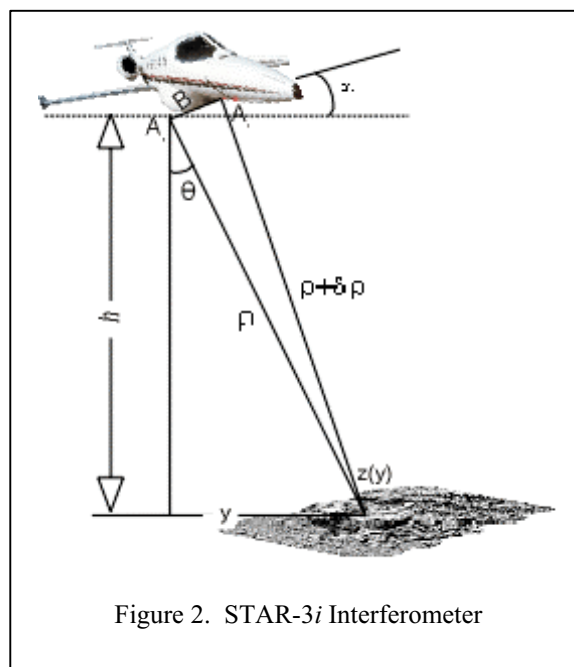

Figure 1. STAR-3*i* LearJet

Figure 2. STAR-3*i* Interferometer

where λ is the radar wavelength and φ is the absolute phase difference between the two returns. ɸ Can not be directly measured by the radar (the radar can only determine fractional component $0 - 2\pi$) leading to ambiguities. The process of phase unwrapping is used to determine the integer portion of ɸ.

2.2 STAR-3*i* Products

STAR-3*i* data is classified as Global Terrain™ products consisting of standardized high resolution DEMs and ORIs that meet varied mapping criteria (see Table 2). These products are generated as 7.5' by 7.5' (latitude by longitude) tiles in UTM projection and WGS84 horizontal Datum. The naming convention for the products begin with the prefix GT and then a number which indicates the maximum root-mean-square error (RMSE) inherent in the vertical data. For example, GT3 data is comprised of a

DATA SOURCE	NOMINAL ALTITUDE	NONIMAL VERTICAL ACCURACY	NONIMAL HORIZONTAL ACCURACY	MAPPING SCALE
GT1	6100m	1m RMSE	2.5m RMSE	1:5,000 - 1:10,000
GT2	6100m	2m RMSE	3m RMSE	1:10,000 - 1:12,000
GT3	9100m	3m RMSE	3m RMSE	1:12,000 - 1:50,000
IM1	both	N/A	2.5m RMSE	1:5,000 - 1:50,000
Information from Global Terrain Product Handbook				

Table 2. Global Terrain™ STAR-3*i* product Classification

DEM with a nominal vertical error of 3 meters RMSE or less and an ORI with a nominal horizontal error of 2.5 meters RMSE. GT3 data is recommend for 1:12,000-1:50,000-scale mapping. STAR-3*i* system's accuracy has been independently validated by blind tests conducted by the U.S. Army Topographic Engineering Corporation, NASA Stennis Space Center, and the Institute of Navigation, Stuttgart University (Mercer, 1998).

3 STUDY AREA

3.1 Data Acquisition

On November 21, 1998, Intermap undertook a large flight campaign to collect INSAR data for the island of Puerto Rico, marking the first time that an entire region/state has been mapped by the STAR-3*i* system. The data was collected in less than 13 days despite mid-afternoon tropical weather conditions of rain, cloud, and turbulence. The LearJet flew at an altitude of approximately 10,000-meters with south look direction and an incidence angle range of 35°– 55° centered on 45°. This configuration produces high-resolution GT3 DEM and SAR data with a ground range cell of 2.5-meters range and 2.5-meters azimuth, and a 3-meter vertical accuracy for the DEM. The DEM is provided in orthometric heights (above mean sea level) through the application of EGM96 vertical datum. The SAR data was orthorectified and registered to WGS84 UTM coordinate system along with the DEM.

3.2 Test Site

One map sheet, Central Aguirre, representing one 7.5' tile (approximately 145 km^2) was selected from the flight campaign to demonstrate Intermap's ability to generate 1:20,000 topographic maps from high resolution INSAR data, without the assistance of auxiliary data. Central Aguirre is located in the southern portion of Puerto Rico island between l18°00' - 66°15' and 17°52'30" - 66°05'30"
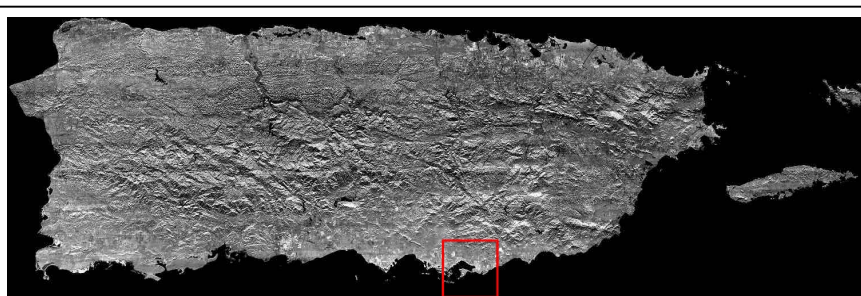

Figure 3. Study area location outlined in red

latitude and longitude coordinates (Figure 3). The test site was chosen for its diverse landscape (elevation range of 300 meters) ranging from tropical forest covered mountains in the north to the flat terrain of mangrove forests along the coast. The study area contains a well-developed infrastructure of urban, residential, and industrial environments linked by major highways and extensive railroad networks. The land cover contains fringe, basin, and channel mangroves, subtropical dry forest, complex systems of lagoons and channels interspersed with salt and mudflats, corel reefs, and sea grasses. A large portion of the original tropical dry forest has been cleared for plantation agriculture, settlements, and industry. The climate is subtropical, warm, and humid with an average yearly temperature of 26° Celsius.

4   STAR-3*i* DATA PROCESSING FOR TLMS

STAR-3*i* data processing flow for the creation of TLMs consists of SAR, INSAR, and cartographic processing modules (see flow chart in Figure 4, *modified after* Sos *et al*., 1994). Prior to and during data acquisition, GPS data is collected and preprocessed to produce highly accurate aircraft antennae position data. Once in flight, the aircraft passes over the terrain transmitting microwaves pulses simultaneously, from two antennae separated by a ~1 meter baseline. Phase and amplitude data resulting from ground reflectivity is recorded for each antenna. Acquisition geometry and sensor system parameters are then used to create two pixel phase and amplitude SAR images, one from each antenna. Highly accurate navigational data is combined with in flight and ground GPS data to generate the necessary information to co-register radar signals. The phase history information of the STAR-3*i* images is processed to create pixel phase difference, called an interferogram. The interferogram phase is a measurement of STAR-3*i* path length difference, which is related to elevation. Coherence information is computed and recorded. Phase unwrapping technique is applied to remove phase ambiguities. Height calculations are then derived from the phase information. The data is in the SCH (Scan, Cross-scan, Height) coordinate frame that is oriented along the actual aircraft flightline. A de-tilting algorithm is applied to the data to remove the tilts in the model caused by geometry (non-nadir look). A SCH to UTM coordinate system conversion is applied to transform the image and DEM data into real world coordinates. Image strips are mosaicked and radiometrically balanced. The DEM data is processed using in-house software to merge all the data acquired (i.e. data from all looks) and to interpolate in order to fill in any holes within the data. Seven and a half-minute tile are then generated for both the DEM and ORI. The DEM data is then processed in the 3-D LH

Figure 4. STAR-3*i* Processing Data Flow

Systems where blunders and the water are edited to meet production specifications. The DEM and ORI are viewed in the third dimension within a photogrammetric workstation where the operators compile the TLM features (refer to Table 3, Section 6.1). Cartographic processing of the TLM layers result in topographic map that is comparable in standards to TLMs derived from photo-based methods.
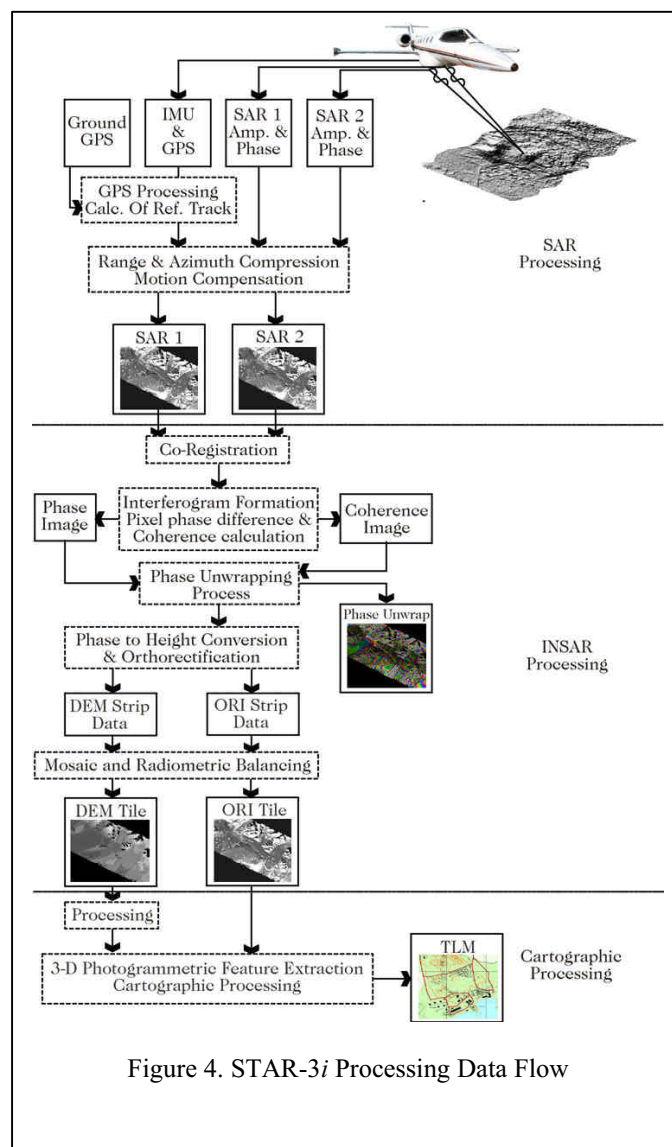
5   METHODOLOGY

5.1   Background

INSAR data have certain characteristics that are fundamentally different from aerial photography of comparable resolution. These specific characteristics are the consequence of the INSAR imaging technique and related geometry and radiometry (texture, speckle). STAR-3*i*'s sensitivity to surface roughness, land and water boundaries, soil moisture, and topography is what makes it an excellent medium used to identify and map tropical deforestation, drainage networks, soils, and vegetation. STAR-3*i* is responsive to man-made features such as roads, bridges, and to a lesser extent buildings, and is therefore, used to discriminate targets and assess urban development. Water features, shorelines, lakes, reservoirs, and double line rivers are easily interpreted from the STAR-3*i* imagery. Primary and most secondary roads are readily interpreted from the STAR-3*i* imagery. Dirt roads, tracks, and some cultural features are sometimes problematic from the standpoint of interpretation, but are improved by auxiliary data such as existing maps, or photos. As with most INSAR systems, the data represents "first surface" it interacts with. In addition, rolling

topography interaction with the slope could 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.

5.2   Methodology

An important caveat with respect to radargrammetry is that only features that can be detected and interpreted properly in the SAR imagery are compiled as a component of the map. Intermap has adapted 1:20,000 map specifications to properly qualify and quantify TLMs based on STAR-3*i* data (Michael and Tighe, 1999).   The detection and interpretation of these features (listed in Table 3, Section 6.1) is performed in synthetic stereo. Viewing the data in three dimensions greatly enhances the interpretation of the imagery.   The hydrographic layer is compiled first, copied and merged with the DEM and used to create breaklines in the DEM. LH Systems internal TIN package is used to model the surface and to produce cartographically acceptable contours based on the STAR-3*i*'s "first surface" of return. The land use, land cover, culture, and transportation features are interpreted and transformed into TLM layers. Finally, all TLM layers are combined in a cartographic workstation. Place names, river and lake names, taken from the existing 1:20,000 USGS topographic map, are added and the surround is generated. Each map sheet undergoes extensive quality assurance to comply with our ISO9001 standard.   In the example presented here (Figure 5), a partial TLM map sheet of the study is depicted with a portion of the TLM replaced by the DEM, and ORI. It is clear to see how the STAR-3*i* products present the interpreter with data that easily depicts the study areas topography (DEM) and land cover and land use categories (ORI).
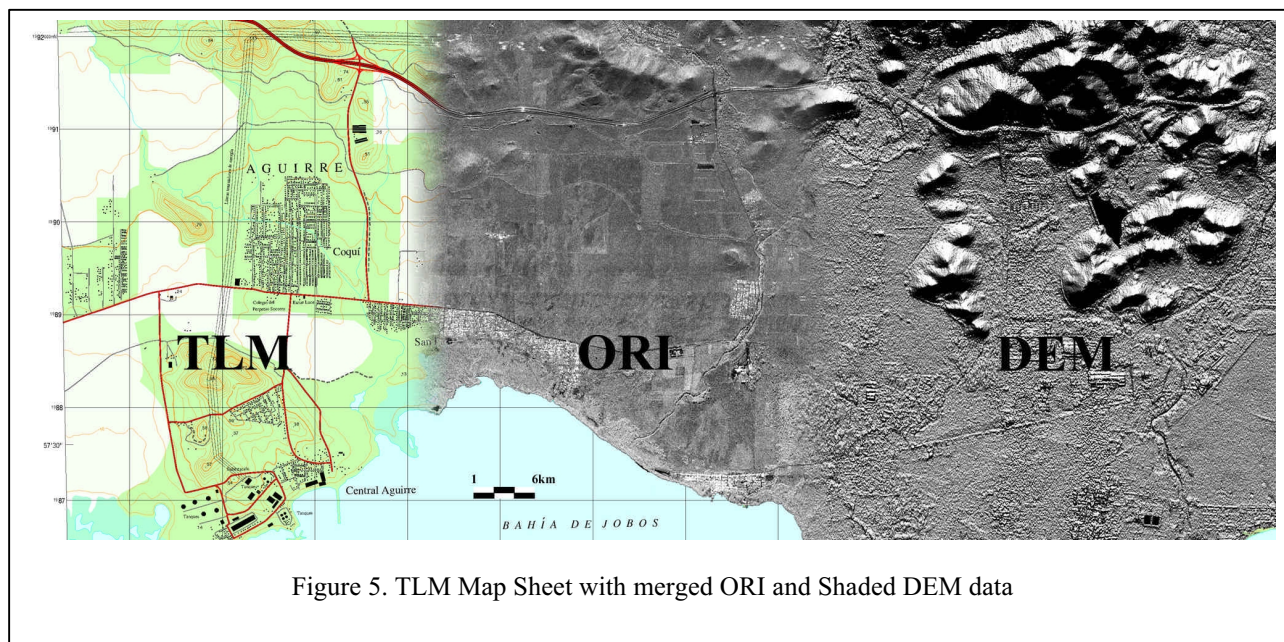

Figure 5. TLM Map Sheet with merged ORI and Shaded DEM data

6   RESULTS AND DISCUSSION

6.1   Comparison to Existing 1:20,000 USGS Map Sheet

The INSAR-base TLM is compared to 1:20,000 USGS topographic map. Table 3 provides a list of the STAR-3*i* TLM features compiled from the INSAR data and an ORI percentage value. This value represents the percent or amount of information that was blindly (no reference was made to the existing map) interpreted from that SAR when compared to the existing TLM. For example, mangroves 95%, indicates that 95% of the mangrove class, as outlined on the existing map, could be blindly interpreted from the INSAR data.   Accordingly, the following discusses the results presented in Table 3.   Approximately 85%-95% of hydrography features (lakes, shoreline, and rivers) are easily detected due INSAR's sensitivity to dielectric changes in soil moisture and water boundaries. Hydrographic features can become obscure in areas of shadow created by tree lines. 90% of Man-made features such as roads and railways are readily detected on the ORI; however, the classification of roads and railways is sometimes difficult as a radar signature for a railway can be similar to a major highway. Transmission lines are seen 70% of the time on the ORI as bright spots, representing the supporting structures equally space along a cleared corridor of land, they tend to follow survey lines rather than the terrain. Mangrove vegetation may be mapped 95% of the time. Mangrove forests have a strong radar backscatter signature related to environmental conditions such as salinity, soil moisture, topography, and the presence

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. Percentages of TLM Feature Classes extracted from the INSAR data alone

of water moisture. Forests, comprised of individual trees of varying heights and diameters of tree trunks, branches and leaves, are subjected to multiple and volume scattering as the radar penetrates the canopy. In addition, physiognomic differences between forested and non-forested land cause significant changes in radar backscatter; this coupled with volume/multiple scattering allows for the delineation of tropical forest 85% of the time. Difficulties were encountered in establishing the transition from forest to savanna, particularly in hilly and rolling terrain, where the radar signature of the vegetation is accentuated by that from the topographic aspect. INSAR's sensitivity to soil moisture allows for the interpretation of swamps and marshland at least 80% of the time; however, the differentiation between the two is difficult without auxiliary data. Cleared land usually consisting of grasses, agriculture, or exposed soil is identified 95% of the time on SAR imagery from their geometric shape and homogeneous tone and texture. Residential and urban environments are easily spotted on SAR imagery as bright regular patterns resulting from the buildings acting as corner and dihedral reflectors and therefore 95% of this class can be identified on the ORI alone. Individual buildings are sometimes difficult to interpret if they are spaced too close together, or become over saturated due to multiple bounces. Tanks, due to their geometric shape and nature, are easily identified at no less than 85% of the time. Auxiliary data must be consulted 100% of the time for features commonly not represented on SAR data, such as place names and river and lake names. The result is a digital TLM containing 85% or more of the features commonly found on comparable maps. Of course Table 3 percentages can be greatly improved with the use of auxiliary data, and this is Intermap's preferred method of TLM production. However, in many places around the world, accurate topographic information is not available, thus this study provides a promising tool to capture topographic data at reasonable costs for these regions. Figure 8 (located at the end of the paper due to its size) provides an illustration of a decimated 1:20,000 scale map of the study area. Although it is impossible to read most of the text on this map, the point of the diagram is to give the reader an impression of what state-of-the-art INSAR data is capable of.

6.2   Contours

Generation of contours from the INSAR data is similar or identical in nature to the process used in stereo photo. 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. The values and shapes of the contour lines are in good agreement with those of the 1:20,000 USGS preexisting topographic map for the study area. Figure 6, is an image chip of the study area representing a section of the TLM data draped over the INSAR DEM. The contours are an accurate depiction of the terrain in open areas (Figure 6, A), whereas in areas that are heavily treed (Figure 6, B), the contours should be regarded as form lines. Contours in obscured

Figure 6. Merged DEM and TLM illustrating Contours

areas are designated as approximate in radargrammetric mapping as they are based on the compiler's estimate of the height of the trees. There is considerably more variability (noise) in the DEM over vegetated areas since the radar does penetrate 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 manually removed from the DEM.
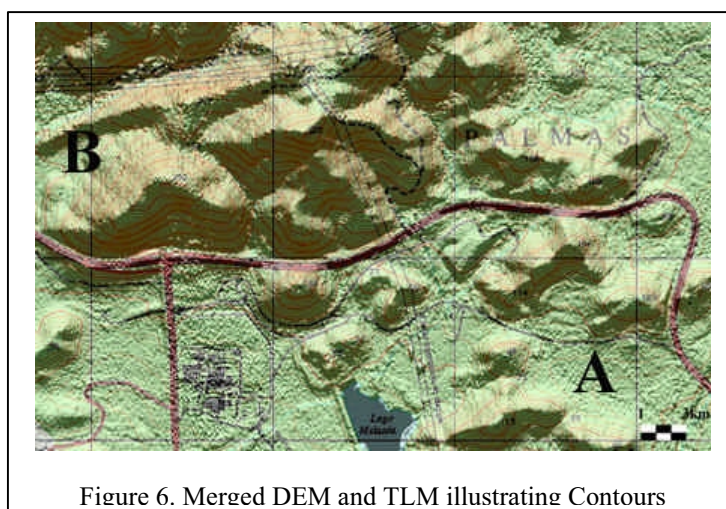
6.3   Example of STAR-3*i* Interpretation

The high-resolution data provided a superb 1:20,000 INSAR-base for collecting topographic map information. In Figure 7, the TLM data is merged with the ORI data this time; again the TLM is providing the feature classes and the ORI is providing the tone and texture of the SAR image. Referring now to the diagram, the letters A through to G are defined below. In areas of exposed soil, the tonal differences can aid in the detection of soil moisture contrasts and textural units from which vegetation classes can be inferred. Tonal variations caused by different degrees of moisture retention in various surficial sediments permit the delineation of cleared land for agriculture. The light toned, circular feature represents pivot irrigation areas with crops that have much higher moisture content than surrounding vegetation (A). Areas of dry tropical forest (B) having a higher relief were identified by the mottled pattern caused by volume scattering characteristic of full canopy. Due to the geometry of INSAR data, man-made features are easily detected on the bases of shape, size, and bright tones due to high radar reflectivity.   Residential areas (C) consisting of buildings that act as dihedral corner reflectors and sloped roofs that have a strong radar backscatter create a high contrast and aid in the detection of streets. An oil refinery (D) is readily interpreted on INSAR data merely due to the geometric shape of the tanks that

Figure 7. Image chip of a section of the TLM

house the oil. Again, the geometric shape of large warehouse buildings return large portions of the radar backscatter to the sensor resulting in bright regular patterns on the SAR imagery, which allows for quick identification of an industrial park at (E). Transportation network of roads and railways are seen on the SAR imagery at (F). Mangroves (G) appear bright on INSAR data due to the increased surface roughness caused by the canopy and increased moisture content resulting from the submerged tree trunks. In addition, each mangrove tree trunk forms a right angle with the water and act as corner reflectors. Combine all these effects and you will get bright tones that correspond to coastal and channel mangrove forests.
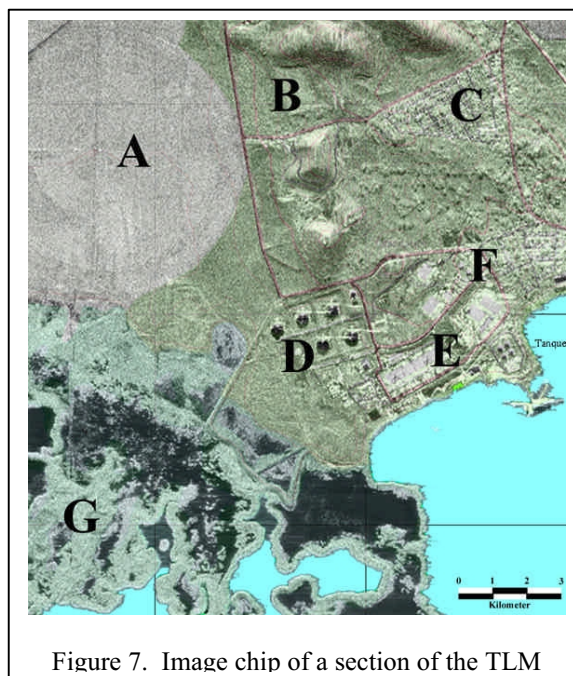
7   CONCLUSIONS

The generation of topographic line maps from high resolution airborne INSAR data has been described. Topographic maps with relative errors of 3m RMS or less can be derived from INSAR data collected by the STAR-3*i* system, providing a cost effective means to generating DEM over regions where little topographic data is available. 85% of land use and land cover, transportation, cultural features, and hydrography features were efficiently mapped from the ortho-rectified radar image (ORIs) without the use of auxiliary data. This is a promising since existing maps are not available in many places around the globe. TLMs as large as 1:20,000 from STAR-3*i* INSAR are being successfully generated and are currently being offered commercially by Intermap.

ACKNOWLEDGMENTS

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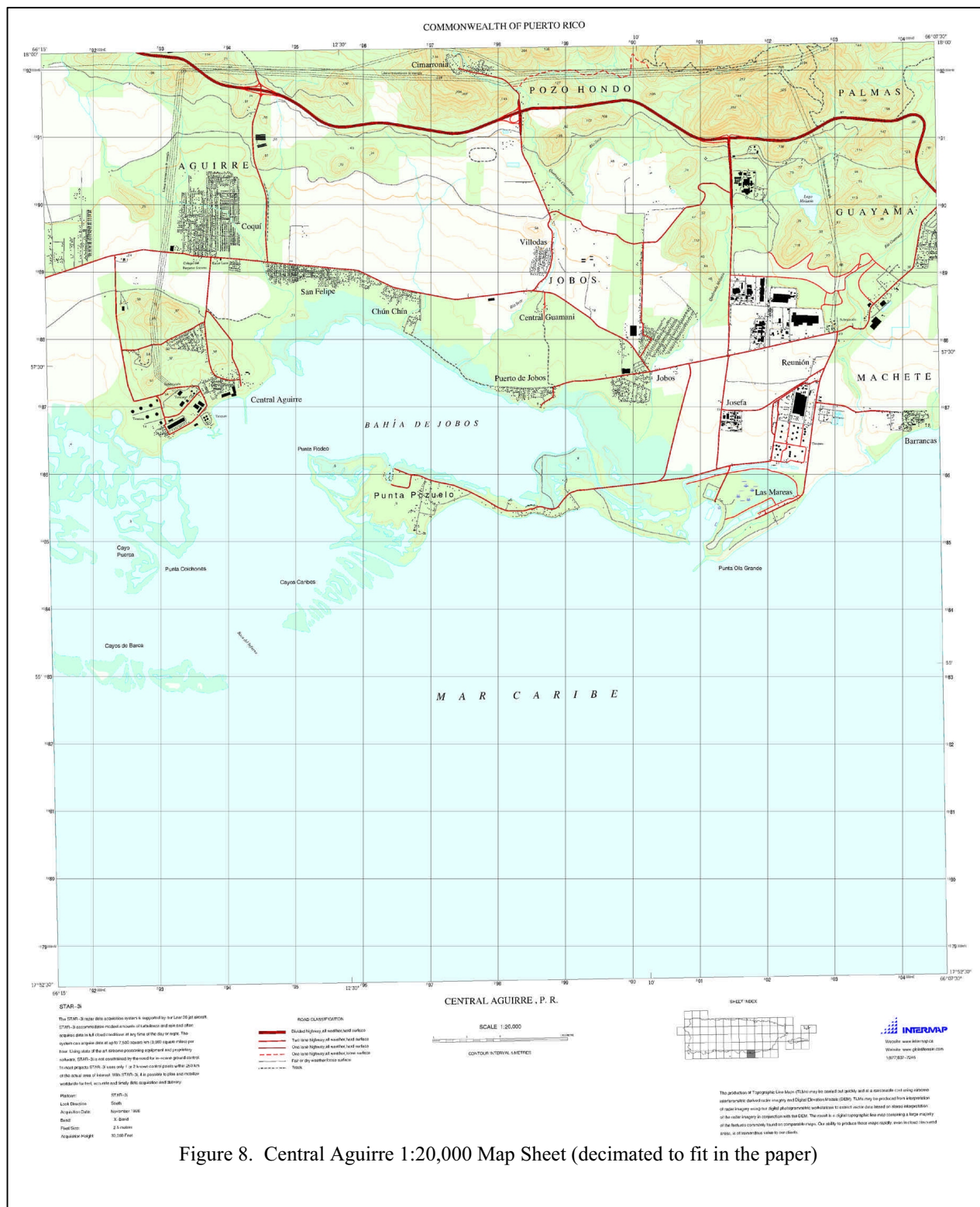
Figure 8. Central Aguirre 1:20,000 Map Sheet (decimated to fit in the paper)