STAR-3*i* INTERFEROMETRIC SYNTHETIC APERTURE RADAR (INSAR): SOME LESSONS LEARNED ON THE ROAD TO COMMERCIALIZATION

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ABSTRACT

Intermap's across track interferometric synthetic aperture radar, called STAR-3*i*, entered commercial service in August, 1996. Even though the research phase was highly successful, considerable effort was still required to transform STAR-3*i* into a system that produced data that were of consistently high quality. Consideration has to be given to first surface and motion issues, as well as to the special problems associated with benign, moderate, and severe terrain. Other issues related to the handling of the data. These required administrative as well as technical solutions and were effectively dealt with when Intermap became ISO 9001 certified. The ISO processes have improved the quality of mission planning, calibration, and data acquisition. Examples are given of problematic data sets and the improvements that were achieved as STAR-3*i* matured as a commercial system. This information may be of use in evaluating or planning an INSAR collection. It may also be helpful for the scientific community as an overview, and perhaps as a guide to future research requirements in the INSAR field.

Keywords: SAR, IFSAR, interferometric, DEM, and DTM STAR-3*i*

1.0 INTRODUCTION

The paper begins with a very brief history of INSAR development and the type of output Intermap generates for commercial consumption. It then describes basic INSAR performance issues as manifested in the STAR-3*i* system. This is followed by a description and qualification of the some of the phenomena present in INSAR data and how Intermap has addressed these difficult issues. As with any engineering process, a review of the failures is often more useful than review of the successes. With this in mind, project examples are presented which highlight the improvements learned from process failures as well as a brief overview of some of the success achieved by applications of the lessons learned.

2.0 DEVELOPMENT

The Environmental Institute of Michigan (ERIM) and the Jet Propulsion Laboratory (JPL) in California developed STAR-3i (formally IFSARE) under DARPA funding. Several papers are available that describe the system and the development program (Sos, *et al*). This development effort culminated in several successful demonstration programs conducted under the review of the Topographic Engineering Corps, Army Corp of Engineers. After the demonstration programs were completed in 1996, the system was transferred to Intermap Technologies for commercialization. Since then, Intermap has made a significant investment to bridge the gap between a successful demonstration system to a successful commercial system. In doing so, we are able to deliver a consistent and defined product to the user in a timely manner, and reduce our associated costs. The following table outlines the standard product levels offered by Intermap Technologies Ltd. from the Star-3i system:

Table 1. Global Terrain DEM products based on STAR-3*i* output

Global Terrain Level	Horizontal (RMSE)	Vertical (RMSE)
GT-1	1.5 m	1 meter
GT-2	2.5 m	2 meter
GT-3	5 m	3 meter

3.0 STAR-3*i* SYSTEM DESCRIPTION

The STAR-3*i* system is an X-band SAR interferometer, with the antennae mounted to a solid INVAR frame (pedestal) with a 1-meter separation. This frame is steerable in the azimuth dimension thus allowing for the two antennae to collect from either the left or right side of the aircraft. The motion measurement data is provided by a Honeywell H770 Inertial Reference Unit (IRU), which is tightly coupled, in post processing, to an Ashtech Z-12 GPS receiver and it's complementary GPS base station. The IRU is co-mounted on the INVAR frame with the antennae to eliminate lever arm errors between the aircraft and the antenna phase centers. The interferometric channels share a single receiver chain and operate in a "ping-pong" mode providing an effective doubling of the baseline length.

The system specifications are listed below followed by a brief outline of the Star-3i process flow.

Table 2. STAR-3*i* System Specifications

Frequency	9.5675 GHz	**Real Baseline**	0.9205 m
Bandwidth	67.5 MHz	**Effective Baseline**	1.841 m
Pulse Width	22.6 microsecs	**Slant Range Swath**	7500 m
Chan PRF	600 Hz	**Ground Swath**	10 km nom. at 30,000 ft.
Range Res.	2.5 m	**Data Rate**	13.75 Mbytes/sec
Azimuth Res.	2.5 m		

The phase history is digitized by the control computer and recorded to Ampex DCRsi 107 tape recorders. The motion and ancillary information is recorded separately onto an Exabyte 8mm-tape drive. The navigation data and ancillary information is post-processed to provide the final navigation solution and the required information for the field QC process. These are combined with the raw phase history at the processing center by an array of up to twelve workstations to provide the intermediate strip image and DEM products. These intermediate strip products are combined to form the final map products required by the customer.

4.0 INSAR PHENOMENA

The RMSE product specification that is normally quoted provides only a first order statistical characterization of the elevation measurements based on the 1-sigma variance and the mean error. Users desiring to understand applications and utility of the elevation data set must consider both the systematic issues and limitations associated with INSAR. This should include understanding the contributors to the variance below and above the 1-sigma bound. It has been well documented in the literature that the performance of the INSAR is greatly dependent on the scene characteristics. Some of these issues are summarized below.

4.1 FIRST SURFACE

As with most remote sensing systems the INSAR system responds, in the first order, to the first surface it interacts with. Thus the elevation models provided are of the land coverage and not a bald earth DEM. It is also important to note that the elevation measured for any individual pixel is a function of the integral of all scatterers within the sample area. Thus, volume scatter can result in an elevation measurement that represents some depth into the foliage and not the height of the tree. Because of this, vegetated areas are subject to more height measurement noise than specular scatterers. Further, the surface area sampled by one pixel may not be homogeneous and the interaction of the different scatterers could result in a misinterpretation of the height.

4.2 MOTION ISSUES

In order to have reasonable throughput performance, SAR image formation and interferometric algorithms use model approximations at every stage of processing. In general, these approximations break down when platform motion exceeds the limits of the model. When this occurs, performance is reduced and possibly discrete motion artifacts occur in the output product. Many phenomena witnessed by the user in INSAR data can be related to these failures.

4.3 BENIGN TERRAIN

Benign terrain provides the most favorable application of INSAR technology. Unlike stereo methods it is not dependent on image matching technology (which is difficult in homogeneous terrain). For this reason the interferometer provides excellent performance in flat to rolling terrain, where many phase unwrap issues are not present. However, any systematic errors in height measurements become immediately apparent in flat terrain. Thus, calibration errors and model mismatches are best evaluated in these circumstances. Some of the items to be aware of are:

- Lakes and shorelines: Lakes offer either low return (no data) or a displaced return due to wave motion. Thus the interferometer may provide confusing height data in water body regions.
- Islands: The phase unwrap problem is well documented (Ghiglia and Pritt). All INSAR processors must solve both internal phase ambiguities as well as the initial ambiguity to the first target. This information is then integrated throughout the process. An isolated point such as an island may be completely lost. In other cases, the ambiguity to the start of the island may be incorrect and the island displaced.
- Airports: motion of large aircraft and weather radars around airports can degrade the performance of the measurement.
- Calibration Errors: To provide consistent performance, the unmodeled differential phase errors between he two antennae must be accounted for though a calibration process. Errors in this effort will result in height troughs are hills running systematically in the azimuth dimension. These are best evaluated in very flat terrain.
- DEM Seams: The interferometers will create elevation models in a strip parallel to the aircraft track. These strips must be merged to complete an elevation model for the client. Small errors in attitude, atmospherics, and so on, can result in these models have discernible seams at the edges of the strips after they are merged.
- Rivers: Rivers provide a unique challenge to phase unwrap algorithms because they represent areas of discontinuous phase.
- Saturation: Bright targets will saturate the radar and thus corrupt the measurement of all targets within the affected region. For STAR-3*i* this can result in errors that extend for a nominal 400 meters in azimuth and up to 2 Km in range. Height errors within the vicinity of bright targets are common. Further, if the system is equipped with an Automatic Gain Circuit (AGC) to minimize saturation, you will have SN variation as well as loss of low return target height during the transition.

4.4 MODERATE AND SEVERE TERRAIN

The largest problems in severe terrain are radar shadow and foreshortening and layover. In shadow regions no data are present, thus no heights can be determined. Any steep gradient situation poses additional problems for the phase unwrap algorithms where the phase function can become severely undersampled or worse, discontinuous (layover). Volume scatter issues in vegetated regions can further corrupt this. In general, mountainous terrain poses the largest challenges for INSAR technology. The positive news is that the lower level errors, calibration and motion induced phenomena and to a large extent saturation issues are hidden within the larger problems discussed above. As a result an INSAR system will not be able to achieve the same accuracy specifications in severe terrain as on flat areas. The following summarizes the issues associated with this type of terrain:

- Shadow Holes: No data areas.
- Steep Slope Displacement: Failure of the INSAR algorithms due to undersampling of the phase signal results in height displacement of steep slopes. Unfortunately this phenomenon is well understood but is highly dependent on the target type and very difficult to model (Rodriguez and Martin and Li and Goldstein).
- Isolation Towers: As the phase function is becomes discontinuous, it is highly likely that the phase unwrap will not propagate and isolated areas can occur. Thus the area becomes displaced during orthorectification.
- Drainage: Trees and valley's can cover drainage sites, making it difficult to accurately represent the drainage. Elevation models may not be an accurate representation of the water flow.
- Cycle Slips: Most INSAR processors determine the phase ambiguity at the start of the process and bootstrap the phase from process cycle to process cycle. If this bootstrap function fails due to lower correlation, the balance of the strip would be in error by one or more phase cycles.
- DEM Seams (detilt): As mentioned previously, the height error is a function of terrain slope and incidence angle. With differing slopes and incidence angles between the near and far range, the height match in overlapping areas will vary along the strip. This will induce transition seams when the strips are combined in the map product.
- Saturation: If the scene includes large rock faces sloping towards the sensor, there is a possibility that the response will saturate the receiver cause artifacts similar to those in bright cultural areas.

4.5 URBAN ISSUES

An urban area presents another difficult challenge for the INSAR system. An urban environment has similar height gradients and shadow regions as in mountain situations. Saturation problems and multipath within the same range cell compound these. For these reasons INSAR performance will be degraded in urban areas. The good news is the issues are most prevalent within the dense urban core, which represent only 10% of most cities. Mercer and Gill concluded that INSAR elevation data, while being affected by the problems discussed above, could be used effectively for most applications.

5.0 PROCESS TO ACHIEVE PERFORMANCE

INSAR performance is affected by many factors, from design through to terrain type. These issues must be fully understood and addressed with consistent processes if customer requirements are to be met in a timely, cost-effective manner. For this reason, Intermap's data acquisition and production process are fully ISO9001 certified. Some of the key processes are outlined below.

5.1 MISSION PLANNING

Mission Planning involves the translation of users' accuracy and coverage requirements into detailed flight planning and the logistics required to complete the mission. The beginning of the planning process involves review of the terrain within the coverage area and determination of the best flight line positioning to meet the user requirements. There are many factors that must be considered in this process including:

- The accuracy of the required data will set the flying altitude of the aircraft; lower collections provide higher accuracy due to improved signal to noise and shorter lever arm errors. However, lower collections also provide less terrain coverage per swath leading to the requirement of more flight lines (with correspondingly higher costs).
- Large areas are more efficient than smaller coverage areas[1] thus per square kilometer costs can be reduced by appropriate selection of the coverage area.
- Benign Terrain, if a GT1 level product is being attempted, tie lines will be required to check for internal consistency. Orthogonal coverage will also be required in order to determine the relative performance of the sensor. As range and azimuth errors are to a first order independent, comparing orthogonal tie lines can provide significant insight into the relative performance of the sensor.
- Moderate to severe terrain poses planning difficulties, as the shadow and layover issues must be mitigated. Opposite look data is often required, in many cases a shadow area in the first look will be a layover region in the second. For this reason a full orthogonal look is often a good idea.
- Urban areas in North America tend to be orientated North South, thus it is best to plan off cardinal coverage in these areas to avoid the saturation issues discussed in Section 4.
- GPS and aircraft support logistics. To support the highest accuracy requires a short GPS baseline[2]. However, in remote areas this may not be possible. Aircraft support facilities will dictate the amount of collection time is available on any mission, directly effecting cost.

In order to provide a consistent product, the STAR-3*i* mission planning is supported with unique tools and a well defined process. The primary tool is the Mission Planning software that is built on top of a commercial GIS package. With the assistance of an existing DEM it provides full modeling of the planned radar coverage, thus assisting the operator in the decision making process. The use of mission planning software is a controlled process with enforced review requirements. Further, the logistics are controlled to ensure compliance with all logistics issues.

5.2 CALIBRATION

Calibration is a key component in providing consistent performance in an environment of the ever-increasing performance demands from the user. To the credit ERIM and JPL, the system is very stable and capable of exceeding the design goal of 3-meter RMSE accuracy. The primary tool used to exceed this design is the calibration process. Calibration is the attempt to measure the differential phase errors between the two channels in order to support their removal from the final product. The differential phase errors within the STAR-3*i* system have proven to be time invariant. With the improvement of the antennae point circuitry, variance of the differential phase errors is consistent to the level of better than 0.5 meters from acquisition to acquisition.

The ISO process used to maintain system calibration is tied to maintenance events that will affect the system’s calibration status. The process involves collection of elevation data over a site where an accurate elevation surface is available and radar corner reflectors have been deployed. As the radar collects at various

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[1] The aircraft requires 15 minutes per turn, thus on projects with short lines much time is spent in positioning the aircraft for collection.

[2] GPS Baseline is the separation of the rover GPS receiver on the aircraft and the GPS base control station.

fixed azimuth angles through the radome[3] each of these angles must be collected during the calibration. In addition these cases must be collected at aircraft altitude of 20,000 feet and 30,000 feet. The requirement for calibration of two altitudes is not fully understood. The differential phase errors should only be linked to the incidence angle (through the radome), multipath issues within the radome and path length differences for the two channels. However, the historical data indicate second and third order variance in the differential phase errors as a function of altitude. The use of process controls for these issues and the use of orthogonal lines internal consistency during any project can also be monitored.

5.3 ACQUISITION PROCESS

The acquisition process is both logistical and operational. Although the controlled logistical aspects are key to successful data acquisition, they have less impact on the quality of the data. For this reason, only the key operational issues are discussed here. As the fundamental accuracy of the program is tied to the GPS control point used for INS/DGPS processing, it is a critical item. The survey of the GPS base station is strictly controlled in both North America, where highly accurate survey monuments are readily available, and in remote areas where more extensive survey techniques are required to establish the control. In most cases multiple GPS base stations are installed to minimize the GPS base line[4].

The data need to be certified prior to the aircraft leaving the acquisition site so that lines can be flown again if necessary. This certification is broken down into evaluation of the radar ancillary data for failures of the radar system and evaluation of the navigation and motion performance of the aircraft during the acquisition. Once the radar ancillary data have been reviewed and no radar errors found, the navigation data are reviewed for absolute accuracy. Finally, data are passed through a process that estimates the performance of the resulting product against model errors. Model errors are caused by failures of the processor to handle large squint or motion situations.

5.4 PRODUCTION SCENARIO

The production process turns the raw information into strip information, then into map sheet data, and finally a complete and edited map sheet product for final delivery. Strip products are created using the JPL IFPROC processor which ingests the raw phase history data and creates Scan, Cross scan Height (SCH) elevation, magnitude and correlation strip products. Once the strip products are created, the internal consistency of the data is verified to insure no calibration issues have arisen. If no issues are identified, the data are then merged and mosaicked into 7.5 minute tiles. These tiles will incorporate all available information including second look data in an attempt to "complete" the information within that tile. At this point, any missing data is interpolated. The data are then loaded into a stereo viewer where the operator will remove any obvious blunders and correct any large water features, including 2-line drainage. These steps are necessary to provide a consistent product to a user interested in the elevation content and not in the phenomena in the data. All of these processes are strictly controlled via the ISO system. For 1-meter RMSE collections, ground control will be acquired to verify the absolute performance of the system. A bias adjustment may be performed based on the ground control data. All other specifications have no requirements for a ground control effort.

6.0 PROJECT EXAMPLES

Several problematic phenomena are illustrated below, with descriptions of the changes implemented to improve data quality. A project in Indonesia provides an excellent example of the failure of phase un-wrap

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[3] Angles are chosen based on the local upper winds to try and maintain the antenna point across track, thus minimizing the processed squint and resultant model errors. Present angles supported or left and right 80, 85, 90, 95 and 100 degrees (zero at aircraft nose).

[4] Intermap's INS/DGPS software can support simultaneous processing of multiple base station.

techniques in severe terrain as well as loss of data due to shadow and layover. There were calibration and motion phenomena present in data from California, although the project was still well within user specifications. Nonetheless these problems affected the presentation of the data. A scene from a region from around the Red River is included because it incorporates the lessons learned in California.

6.1 INDONESIA

One of Intermap's first acquisition projects with Star-3i, the Indonesian project well demonstrated the INSAR phenomenology that occurs in severe terrain. The line of discontinuity in the image chip on the right indicates the seam between processor batches where the absolute phase is incorrectly "bootstrapped" from the previous batch. In these cases, the error in absolute phase cause the entire region to be displaced. These areas are extremely difficult to process and require manual intervention at every stage.

In regions of forested slopes in the near range where in interferometer is more sensitive, the phase becomes de-correlated due to volumetric scattering or motion within the trees. This results in a patchy or "Swiss cheese" phenomena. In general, this artifact is minimized by increased overlap in the mission planning stage.

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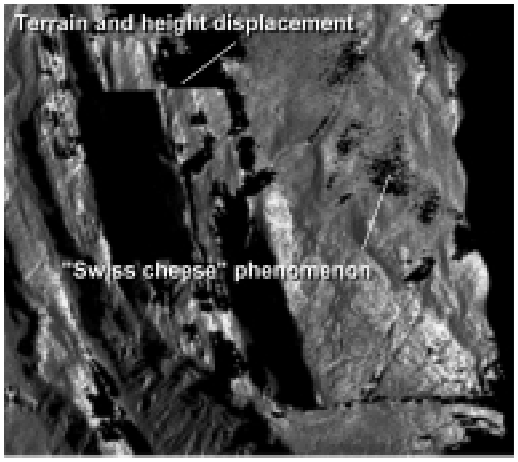

Figure 3 Irian Jaya, Indonesia magnitude

6.2 CALIFORNIA

The California data have proven to be very accurate and from an RMSE specification the clients needs were well met. However, certain phenomena limit the usefulness of these data. Mainly, calibration motion and seam artifacts. Figure 3 illustrates the worst artifacts before correction measures were taken. The Calibration artifacts are the 20 to 50 cm troughs in the elevation models running NNW. Strip alignment issues are very similar to the calibration artifacts and again are witnessed in the NNW troughs. The motion artifacts are witnessed as the troughs running orthogonal to the larger artifacts. These artifacts are also at the 0.5-meter range. The motion error estimation was not in use at the time of collection of these data. It is important to note that all illustrated phenomena are well within the RMSE specification, none exceed the 50cm level.

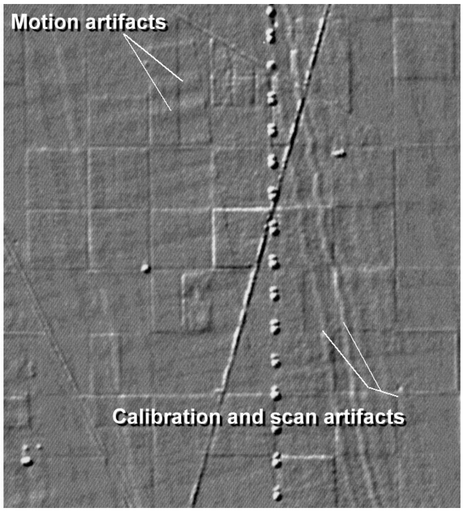

Figure 4 California Shaded Relief DEM

6.3 RED RIVER

The process used for the Red River project incorporated the lessons learned in California. The calibration-performed prior to Red River used techniques that allowed consistency to the 20-cm level. In addition strip to strip model errors were maintained to below 10-cm level. The fine drainage features visible in the Red River DEM shaded relief DEM data is at the 10-20 cm level. Red River demonstrated the possibilities of the system with GPS base station in-scene and careful system calibration. The Army Corp of Engineers collected extensive ground control in the region. Blind testing of this ground control vs. the unedited strip DEM's directly from the processor where consistent to a 5-cm. bias and 50-cm RMS. Only 5% of points were outside of 3 sigma. All were related to target issues.

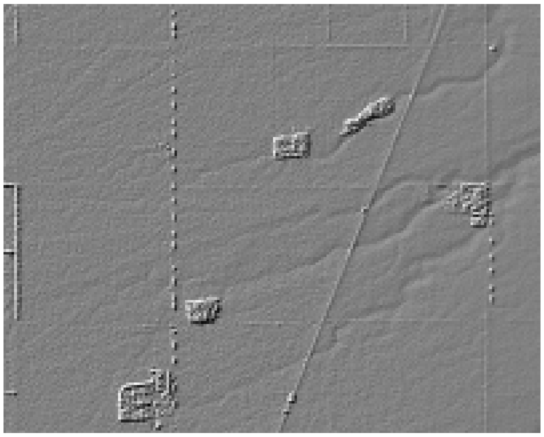

Figure 5. Red River Shaded Relief DEM

7.0 CONCLUSION

This discussion is timely as the primary focus of across track interferometry systems is vertical accuracy performance. STAR-3*i* data have many applications, with proven vertical accuracy in the 1-3 meter RMSE. At present, however, standard elevation mapping techniques are primarily based on older stereo air photo technologies, whose quirks are well understood by users. Because it is newer, users are not as familiar with interferometric SAR phenomena. Further, dealing with these issues in a consistent manner to deliver elevation information is not discussed in the scientific literature. There is a standard process in place for presentation of phenomena in air photo data, but this is not yet the case with INSAR data. This can lead to user dissatisfaction—even though data may be well within the RMSE specification.

Notwithstanding the above, we hope we have demonstrated to the reader that the technology can generate highly accurate DEMs for clients in a reliable and ongoing manner. But this has only come about because of the implementation of an effective process for collecting and handling the data. The gap from experimental to commercial was effectively filled. Using the same methodology makes it possible to continually push the limitations of the technology for the customer – while ensuring the final product always meets those more stringent specifications.

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