Automated DEM Production Using ESA Tandem Mission Data for the Caribou-Poker Creek LTER Watershed, Alaska

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Abstract

The Alaska SAR Facility has developed an automated procedure for production of a digital elevation model (DEM) from ESA tandem mission data. This software processes from ASF Computer Compatible Signal Data (CCSD) or Level Zero (raw) products to a map-projected, ground-range 30m DEM. Several advanced techniques have been integrated into the procedures to improve accuracy and to allow full automation. This spring, a test site at the Caribou-Poker Long Term Ecological Research (LTER) watershed was analyzed in collaboration with Larry Hinzman (Principal Investigator) and the Arctic Region Supercomputing Center. An accuracy assessment of the results for four ESA tandem pairs showed average differences ranging from approximately 4 to 8 meters in elevation when compared with field measurements using differential GPS. The final mosaic had an average difference of 4.68 meters in elevation. Point target analysis of existing 3x6 and 2x3 arc-second USGS digital elevation data showed an average difference of 19.97 and 10.04 meters in elevation, respectively. These advances in accuracy are due to use of precision timing and orbital data in an interferometric SAR processor using an average Doppler, precise baseline refinement, and direct ground rectification. The Alaska SAR Facility continues to refine its interferometric SAR processor in support of NASA-approved users.

Introduction

In this paper, recent advances are discussed in development of satellite radar interferometry user tools at the Alaska SAR Facility (ASF) in support of the NASA SAR user community. ASF was established by NASA as a satellite receiving, processing and analysis facility located at the Geophysical Institute, University of Alaska Fairbanks. ASF is responsible for scheduling all the U.S. data requests for ERS-2 and RADARSAT. ASF is one of NASA's Distributed Active Archive Centers with large data holdings including ERS-1, ERS-2, JERS-1, and RADARSAT. In the fall of 1994, the Polar DAAC Advisory Group (PoDAG) charged the Science Division of the Alaska SAR Facility with the responsibility of developing and supporting SAR user tools for the NASA SAR user community. The initial focus was to support SAR products provided by the Alaska SAR Facility. Recent changes to the system now provide capabilities to process from Flight Agency format level zero data including ERS-1, ERS-2, JERS-1, and RADARSAT.

The European Space Agency (ESA) operated two, identical polar-orbiting SAR satellites, ERS-1 and ERS-2 during the period of August 1995 through May 1996 in a one-day trailing tandem orbit to map extensive land surfaces. Each satellite imaged the same land surface in a 35-day repeat orbit to obtain near global coverage. During this period, ESA performed orbital maintenance sufficient to achieve over 70% success in obtaining baselines that were suitable for SAR interferometric mapping. A sizable collection of tandem mission data was acquired at ASF and at McMurdo Station, Antarctica. To maximize scientific return from this data, ASF has been working to develop and promote scientific applications of SAR interferometry.

In the winter of 1996, the first version of a digital elevation model processing capability was released. This prototype used ERS-1 and ERS-2 complex image products produced by ASF (Lawlor, et al. 1997). Since that time, facility staff have collaborated with SAR engineering experts including Howard Zebker of Stanford University and Paul Rosen at the Jet Propulsion Laboratory. In the summer of 1998, a study was conducted over Delta Junction, Alaska, to characterize and enhance the topographic mapping procedures using point target data from ASF corner reflector array. Results were presented at IGARSS'98 in Seattle showing a composite DEM generated from eight tandem pairs. Results showed reasonably good vertical accuracies could be obtained using lower resolution topographic data as automatic seed points for baseline refinement (Guritz et al. 1998).

Processing Methodology

The ASF Computer Compatible Signal Data (CCSD) products include decoded and byte aligned data which come from the raw 5-bit I and 5-bit Q signal data. The newer ASF level zero product follows the flight agency CEOS (raw) product format. Both products are accompanied by metadata that fully characterizes the product including critical processing parameters such as the slant range to first pixel, precision timing, and satellite ephemeris.

The ASF SAR User Toolkit encompasses a full range of algorithms required for SAR processing, generation of interferograms, coherence maps, estimated height error maps, and height maps. It includes shell scripts that automate execution of individual programs. Each program is modular in design, written in ANSI C, well documented, and accompanied with a Unix style manual (man) page. The code has been developed under Sun Solaris and ported to SGI Irix. A large portion of the code has also been ported to run under the Linux operating system for use on high-end personal computers. A graphical user interface (GUI) display tool written in TCL/TK allows graphic display of intermediate and final results.

The preprocessor converts the CCSD or CEOS level zero data to an internal level zero format. This conversion minimizes metadata dependencies, extracting critical processing parameters from accompanying metadata or deriving them directly from the binary data. The binary data is corrected for missing lines, changes in window position, and auto gain control if applicable. The Doppler centroid is determined by cross correlation (S.N. Madsen, 1989). The Alaska Interferometric SAR Processor (AISP) performs range compression using a matched filter correlation of the scatter return with the original chirp replica. It then performs range migration, and synthesizes aperture by a matched filter correlation of each line of data with the azimuth reference function. As output, a single-look complex image is produced. It can process to constant, linear, or quadratic approximation of the Doppler shift and rate. The procedure supports both automatic parameter generation as a preprocessing step or will use an externally specified set of processing parameters.

For interferometric processing of a tandem pair of SAR images, the Doppler value for each image should be estimated and then averaged. The first image is processed to the average Doppler without any offsets being applied in the image formation. Portions of the top and bottom of the second image are processed to the same average Doppler frequency, and then co-registered to sub-pixel accuracy with the first. The co-registration produces offsets that characterize the azimuth and range mapping between the two images. The second image is then reprocessed using these offsets in the image formation producing an image co-registered with sub-pixel accuracy to the reference image (Zebker et al., 1994). Because SAR processing is so computationally intensive, this is the slowest part of our interferometry processing. On our Sun Microsystems SPARC Server 1000, processing one full frame 5,120 sample by 24,000 line image using our AISP processor takes a little over an hour. On an SGI Origin 2000, processing one full frame complex product takes about 15 minutes. To speed this up, we have developed a parallel implementation of our SAR processor (PAISP). Running on 56 processor elements of the Arctic Region Supercomputing Center's Cray T-3E massively parallel processor, we can process the same image in less than 90 seconds.

Once the two full frame complex products have been co-registered, an interferogram can be generated and vector-averaged (i.e. multilooked). During co-registration, a baseline is estimated from satellite ephemeris contained in the metadata. Azimuth and range phase trends expected for a flat Earth are then removed from the interferogram. Optionally, phase filtering can be applied to the interferogram before phase unwrapping (Goldstein and Werner, 1997). Phase unwrapping is then performed on the interferogram using the branch cut method to mask areas of low coherence or where residues are identified and avoided (Goldstein, et al.

1988, Rosen, et al. 1994). A mask image is produced identifying residues, branch cut lines, areas that integrated, and areas that were masked.

When a user supplied DEM is available, an elevation-induced phase can be determined and subtracted from the interferogram before phase unwrapping is performed. Upon completion of the phase unwrapping, this elevation-induced phase can be added back to obtain the desired result. This technique improves the percentage of integration for areas of moderate to steep sloped terrain. Baseline refinement is then performed using either a user-supplied set of known elevation points or a lower resolution digital elevation model. When a DEM is supplied, points of minimal local slope are chosen while maximizing point distribution within the image frame. A refined baseline estimate is derived iteratively using a least squares fit to the points of known elevation. In most cases, baseline convergence occurs within three or four iterations.

The unwrapped interferometric phase together with the precision baseline are then used to derive the topographic heights based on the geometric relationships (Madsen et al. 1993, Zebker et al. 1994). Each pixel of the elevation image represents the height above sea level, in meters, of each location on the ground. The entire process between interferogram generation and elevation image generation takes about an hour elapsed time. The resulting slant-range height image is not yet corrected for the curvature of the Earth or look angle of the spacecraft and is still oriented with the raw SAR image. The look angle distortion is especially visible in mountains, which lean toward the spacecraft in classic SAR foreshortening. Since layover, shadowing, and lack of phase coherence create unresolvable ambiguities in our slant-range height image, the resulting DEM will have regions where we have no information about the elevation.

The straightforward approach to terrain-correcting geometric distortions in a DEM is to use vector analysis to solve for the arc length from sea level to target and so obtain ground range. Since this approach is very slow, we use a range shift due to earth curvature, combined with a nearly linear shift in range on the basis of the elevation of the target point. This simplified linearized method results in worst-case millimeter-scale differences from the original and the ability to rectify a full resolution height image in about two minutes on a Sun Microsystems SPARC server 1000.

After removal of the elevation effects from a height map or amplitude image, we can now efficiently register this image to a map projection of our choice. We define a mapping function between slant-range image space and the map projection coordinates by defining a uniform grid of geographic tie-points (we use a 10 by 10 grid) on the image, computing the latitude and longitude of each point, converting these coordinates to the map projection, and fitting a polynomial function to the tie-points. The pseudo-ground rectified DEM is then mapped into a ground rectified DEM (or cartographic product). Our tie-point procedure is completely automated and can register a SAR derived DEM to any of 20 map projections in approximately three minutes on a Sun Microsystems SPARC Server 1000.

Caribou-Poker Creek Watershed Study

Researchers at the Institute of Northern Engineering, Dr. Larry Hinzman and Dr. Matt Nolan, have been comparing soil moisture estimates derived from terrain rectified SAR imagery with a spatially distributed hydrologic and thermal model. The accuracy of existing topographic information did not allow for complete rectification of the SAR data. There were also noticeable discontinuities in the DEM at quadrangle boundaries. Temporal animations of SAR imagery showed inconsistencies that were attributed to errors in correlation due to elevation errors in the existing USGS topographic data.

In collaboration with the Arctic Region Supercomputing Center, a new composite DEM was constructed from four tandem pairs. Each pair was processed using the ASF interferometry software producing a rectified DEM for the study area. The accuracy of each DEM was compared to existing topographic data and available ground control. A composite DEM was then constructed from the four individual DEMs from the most accurate data. A complete statistical assessment was performed on the results (see figure 1). Using the composite DEM, the accuracy of the SAR image rectification was significantly improved.

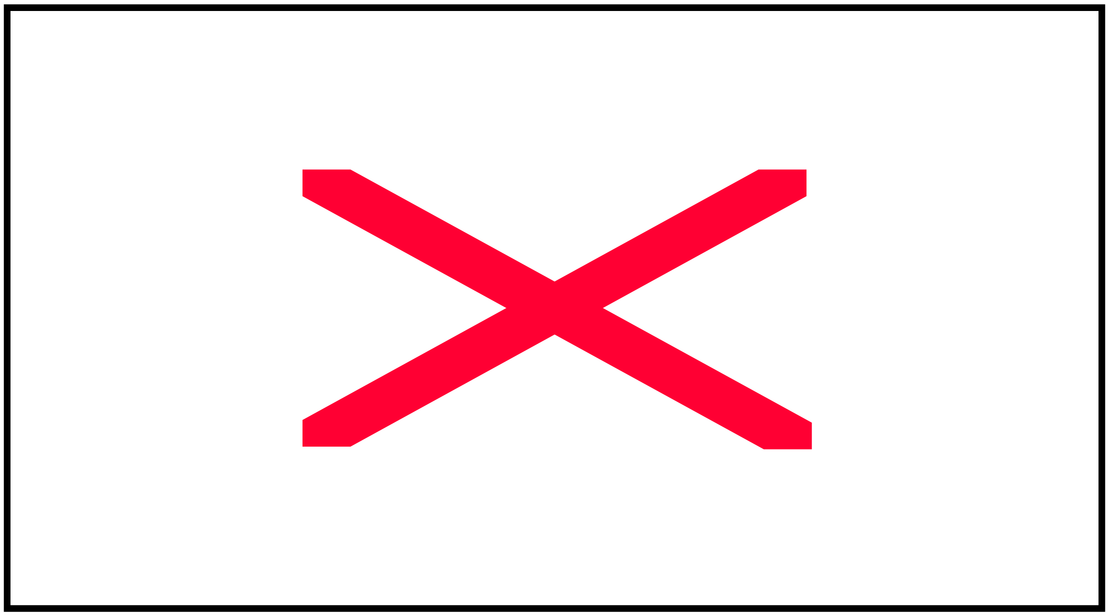

Figure 1: Accuracy Assessment Spreadsheet

A comparison of the interferometric derived DEM with the USGS topographic data derived from 250,000 scale maps show significantly more detail in high frequency information (see figure 2). This is especially noticeable as banding at certain contour intervals in the USGS data due to the methods used to convert contour maps into gridded data.

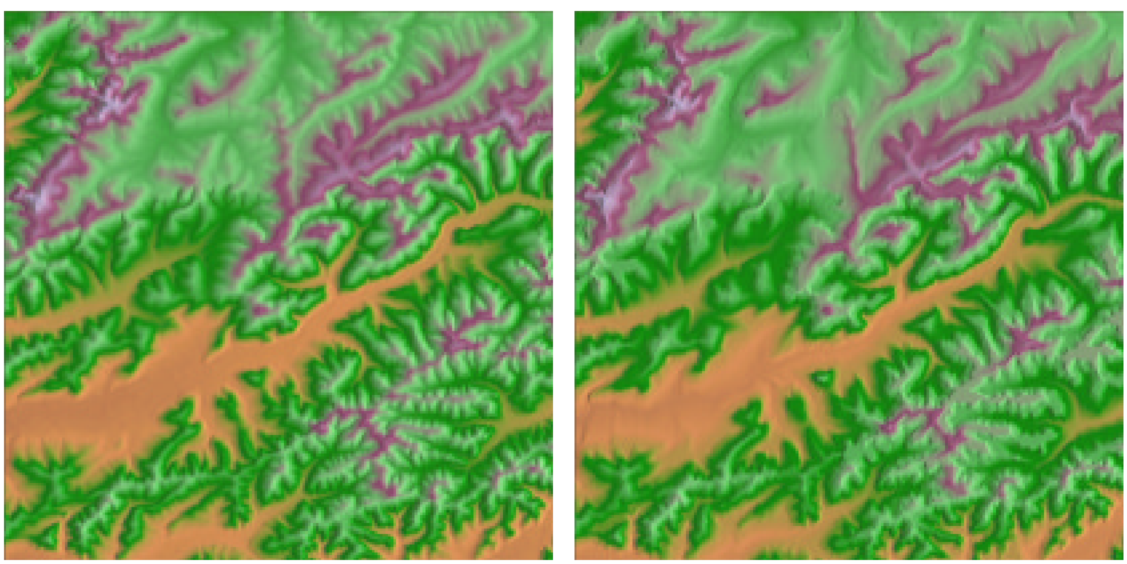

Figure 2: Interferometric Derived DEM (left), USGS 3x6 arc-second DEM derived from 250,000 scale maps (right).

A comparison of the interferometric derived DEM with the USGS topographic data derived from 63,000 scale maps is more difficult to evaluate (see figure 3). Major ridge features appear consistent although there is a noticeable difference for hydrographic features visible in the USGS data.

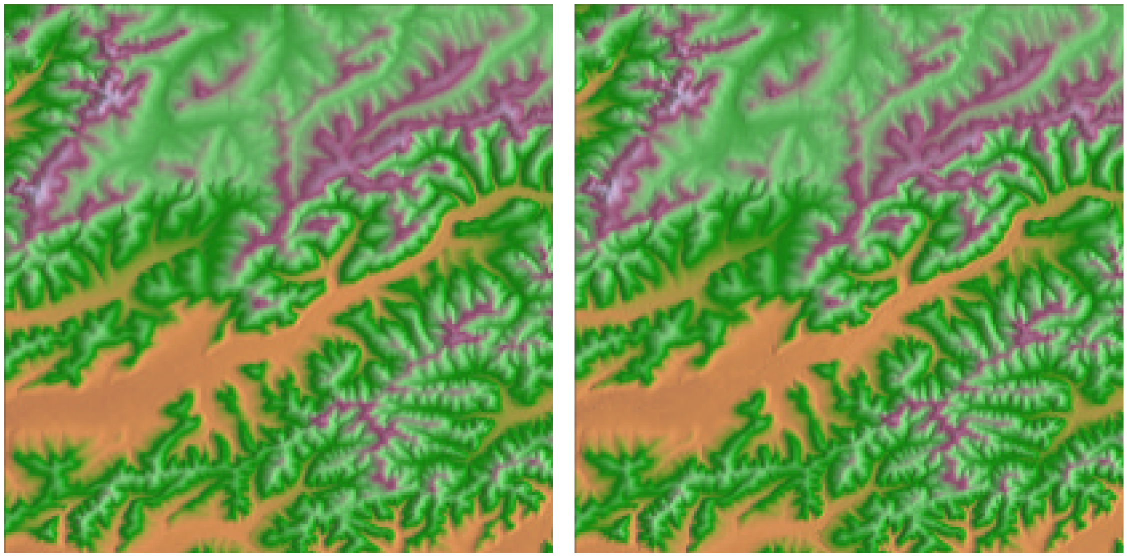

Figure 3: Interferometric Derived DEM (left), USGS 2x3 arc-second DEM derived from 63,000 scale maps (right).

Results and Discussion

Over the past few years, the Alaska SAR Facility has refined its SAR processing and SAR interferometry tools to meet NASA investigator requirements for topographic mapping. Through a number of enhancements, topographic maps can be derived from repeat pass SAR data as a fully automated process. In this study, results from four tandem pair were analyzed using existing ground truth data. An accuracy assessment of the results for four ESA tandem pairs showed average differences ranging from approximately 4 to 8 meters in elevation when compared with field measurements using differential GPS. The final mosaic had an average difference of 4.68 meters in elevation and a root mean squared difference of 5.39 meters in elevation. Point target analysis of existing 3x6 and 2x3 arc-second USGS digital elevation data showed an average difference of 19.97 and 10.04 meters in elevation, with a root mean squared error of 18.11 and 5.12 meters in elevation, respectively. ASF plans to continue refining its SAR toolkit to include other interferometric analysis methods. These will include differential interferometry for surface change studies for glacier motion and ice streams, volcano deformation, subsidence, etc. Please refer to our web site (www.asf.alaska.edu) for additional information.

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