Generation of Fine Resolution DEM at Test Areas in Alaska Using ERS SAR Tandem Pairs and Precise Orbital Data*

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ABSTRACT

The ASF Science division has released the world's first free end-to-end interferometric digital elevation model (DEM) generation system. This software, which processes from raw signal data through to a map-projected, ground-range 20m DEM, is completely automated. Preliminary comparison with differential gobal positioning system (GPS) indicates that over a 100km swath, horizontal position errors are less than 120m, and comparison with the 2x3 arc second United States Geological Survey (USGS) DEM indicates an average vertical error of 7m, 25m RMS. This result was obtained from an ERS tandem pair over Delta Junction, Alaska. 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 computationally intensive nature of these algorithms was minimized through the creation of a parallel SAR processor and a linearized ground rectification procedure.

1. INTRODUCTION

Spaceborne synthetic aperture radar (SAR) satellites have given rise to sar interferometry, one of the most exciting remote sensing techniques of the twentieth century. Satellite radar interferometry has been applied successfully to topographic mapping, to detecting, surface motion of earthquakes, volcanoes, glaciers, ice streams, and to applications of forestry and agriculture. In this paper, recent advances are discussed in the development of satellite radar interferometry user tools at the Alaska SAR Facility in support of the NASA Mission to Planet Earth (MTPE). The Alaska SAR Facility (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-1, ERS-2, JERS-1, and RADARSAT data. 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 SAR user community. The initial focus was to support SAR products provided by the Alaska SAR Facility. This interferometric software package is a direct result of that direction.

The European Space Agency (ESA) operated two 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 global coverage. During this period, ESA performed orbital maintenance sufficient to achieve over 70% success in obtaining baselines which were suitable for SAR interferometric mapping. A sizable collection of tandem mission data was acquired at the Alaska SAR Facility and at McMurdo Station, Antarctica. To take advantage of this, 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 production capability was released. This prototype used ERS-1 and ERS-2 complex image products produced at ASF. Since that time, facility staff have established strong working relationships with engineering experts in the field including Howard Zebker of Stanford University, and researchers at the Jet Propulsion Laboratory. To process ASF computer compatible signal data

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(CCSD) requires a software correlator, i.e., a matched filter image signal processor code which compresses the extended ground echo returned by the radar. Based on a Fortran code of Howard Zebker, [Zebker, 94] a C implementation of a software correlator was developed. This new code, which we call AISP, is capable of producing full framed complex products. Interferometry algorithms used in our first prototype were enhanced in several areas in order to process the resulting full frame complex products. Full ERS-1 raw telemetry data was used to insure maximum accuracy and to measure and compare precision timing, orbit and other critical processing parameters needed for accurate ground rectification. C.K. Shum [Kozel, 94] of the University of Texas at Austin provided precision orbit data for tandem pairs over Delta Junction, Alaska. This paper describes the algorithms used to produce a geocoded digital elevation model of the Delta Junction area. Error analysis was also performed.

2. BACKGROUND

Synthetic aperture RADAR (SAR) is a remote sensing technique with a number of useful peculiarities. It works by emitting a coherent (completely in phase) radar pulse toward the ground and listening for the echo of objects on the ground. Objects which scatter the incoming radar pulse better show up as brighter pixels. One of the most widely touted benefits of this technique is that these radar waves travel through cloud cover. In addition, because the SAR provides its own illumination, imaging is not dependent on the daylight. But possibly the most useful aspect of SAR coherence is that the return signal contains information not only about the amplitude of the echo, but also its phase. Recall that for a periodic wave, the maximum height of a wave is its amplitude. The relative position, or amount of shifting, is the phase (usually measured in angular units of degrees or radians).

The field of interferometry concerns itself with extracting information from phase differences. From a set of two SAR images, it's possible to determine elevation, find the velocity of slow-moving objects, or detect minuscule surface changes. The basic technique used is to take one SAR image of an area, then take another SAR image of the same area, and subtract the phase at each pixel. An intensity plot of the phase difference shows contours at multiples of one phase cycle (360° or 2π radians). These are referred to as fringes. Since the radar's phase changes regularly as it propagates, the phase at any particular pixel then shows the difference in round-trip path length between the two images (see Fig. 1). The resulting "interferogram" can be analyzed to determine a variety of characteristics of the imaged area. This interferogram analysis is complicated by several factors, such as the fact that phase information can only be obtained between 0 and 360 degrees (modulo 2π), and is hence ambiguous. Finding a discriminant to resolve this ambiguity is called phase unwrapping.

If the two images were taken from exactly the same place, any change in the interferogram can be attributed to a change of the surface. Because the radar waves used in typical SARs such as RADARSAT have a wavelength of about 5 centimeters, it is possible to detect surface movements of 1 cm or less. By creating an interferogram from SAR images taken before and after the 1992 Landers earthquake, the French Centre National D'Etudes Spatiales (CNES) was able to create an image of the elastic deformation of the ground caused by the earthquake [Messonnet, 92]. By interfering images of a glacier taken several days apart, we can determine the velocity and velocity profile of the glacier [Fatland, 94].

Because they are taken from space, the two SAR images are almost never taken from exactly the same place. When the two satellites are separated by some distance (this distance is usually separated into along-look and across-look components, and then referred to as a baseline), the resulting interferogram contains a rather unexpected effect. Since the interferogram is extremely sensitive to total path length changes, and since the path length depends on the elevation of the imaged point (see Figure 1), we can invert to solve for the elevation of each imaged point from the interferogram. The geometry works out such that the smaller the distance between the satellites (the smaller the baseline), the smaller the effect of elevation on phase. For longer radar wavelengths (employed, for example, by the Japanese JERS-1), the effect of elevation on phase is also smaller, because one cycle of phase represents more path distance.

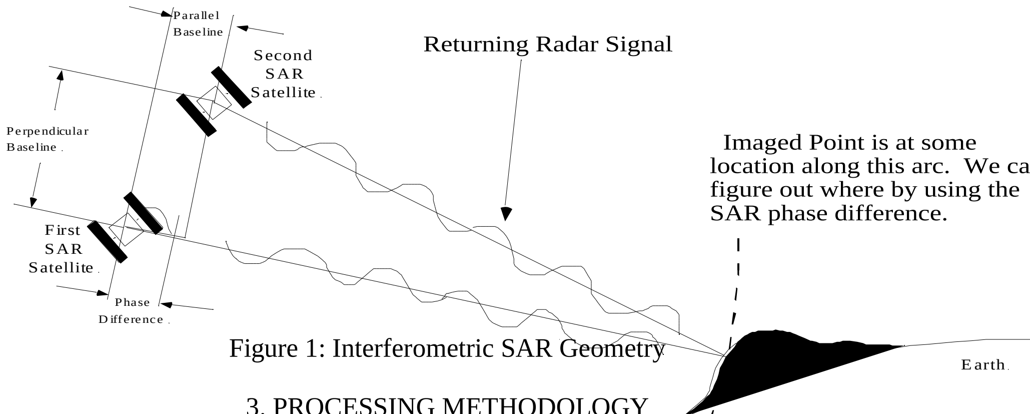

Figure 1: Interferometric SAR Geometry

3. PROCESSING METHODOLOGY

The overall processing scheme is shown in Figure 2. The input SAR scenes are processed and registered with one another, then an effective baseline is found using ground control points. The baseline is used to create and map the unwrapped phase into a DEM, which is finally map-projected.

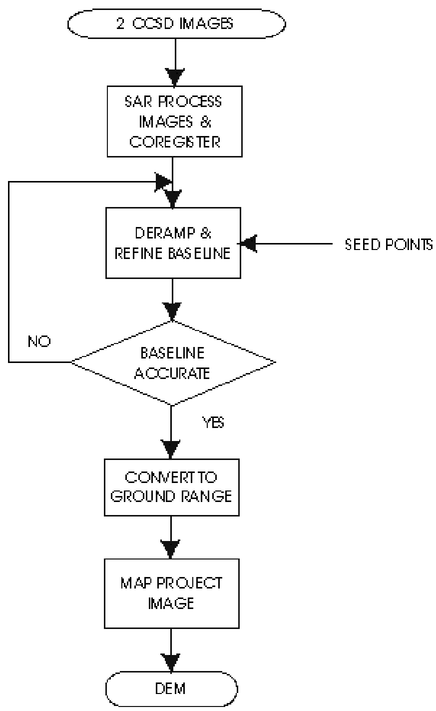

Figure 2: Software Flow Diagram

The CCSD products provided by ASF include decoded and byte aligned data which come from the raw 5-bit I and 5-bit Q signal data. These products are accompanied by metadata which fully characterizes the product including critical processing parameters such as the slant range to first pixel, precision timing, and satellite ephemeris. AISP performs range compression by a matched filter correlation of the scattered return with the original outgoing radar chirp. It then performs range cell migration correction, and synthesizes aperture by a matched filter correlation of each line of data with the azimuth reference function. As output, we get a single-look complex format image. We can process to constant, linear, or quadratic approximation of the doppler shift and rate. The procedure supports both automatic parameter generation from metadata 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 [Madsen, 1989]. The first image is then 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 coregistered to sub-pixel accuracy. The information thus obtained is then used to reprocess the second image. The result is two complex format images which are registered to sub-pixel accuracy. Because SAR processing is so computationally intensive, this is the slowest part of our interferometry process. On our Sun Microsystems SPARCserver 1000, processing one full frame 5,120 sample by 24,000 line image using our processor (AISP) takes 3 hours. To speed this up, we have developed a parallel implementation of our SAR processor (PAISP). Running on 56 processor elements of the University of Alaska Arctic Region Supercomputing Center's Cray T-3E massively parallel supercomputer, we can process the same image in under 2 minutes.

Once the two full frame complex images have been accurately co-registered, they can be interfered with one another and vector-averaged (i.e. multilooked). During co-registration, our software produces an estimate of the satellite baseline through use of the satellite state vectors supplied in the CCSD metadata. While these state vectors are accurate to a few meters, interferometry is extremely sensitive to the baseline distance - to as little as a few centimeters - which is not yet feasible with current tracking data. Hence, we must use geographic tie-points to indirectly determine the true baseline. Thus the user creates a file of seed points of known position and elevation picked from the amplitude image (see fig. 3A). The unwrapped phase information is then compared with these user-input parameters, and the baseline is refined according to the difference. This process usually converges within three iterations to less than millimeter-scale differences in baseline parameters.

The unwrapped phase [Goldstein et al. 1988] and correctly refined baseline are then used to generate an elevation image. Each pixel of the 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 (i.e. not geolocated). The look angle skew 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, "holes", where we have no information about the elevation. The phase coherence and phase unwrapping masks shown in figure 3c and 3d give visual indicators of how well the unwrapping process should, and did, go (respectively).

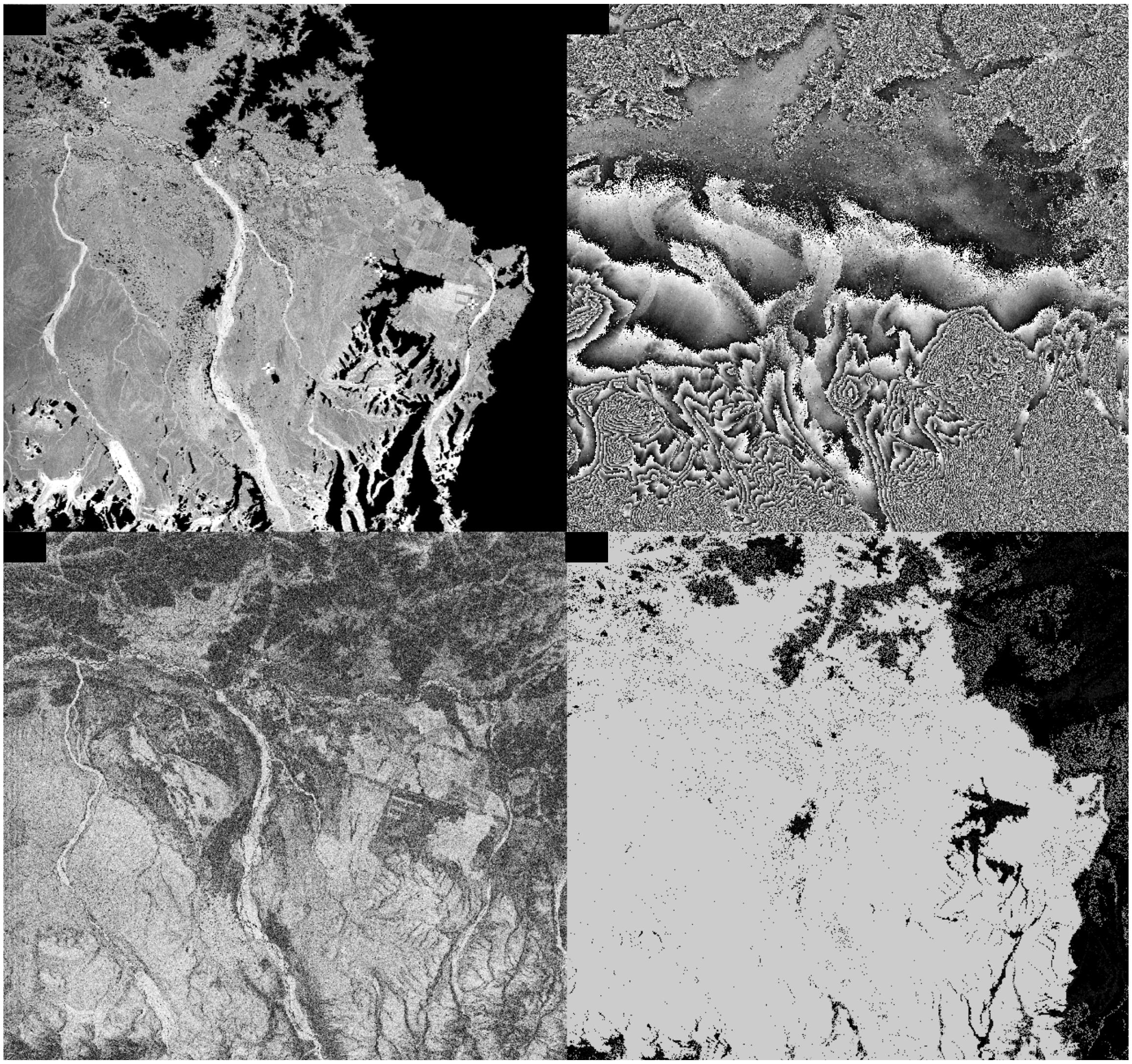

Figure 3A: Tie point locations 3B: phase image 3C: phase coherence image 3D: phase unwrapping mask

The straightforward approach to terrain-correcting geometric distortion 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 for the Delta Junction scene, and a result of linearization, our SPARC 1000 converts a 100 MB, 5120x4800 pixel slant-range height image into a pseudo-ground rectified DEM in about two minutes.

Having removed the elevation effects from a SAR DEM 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), as shown in figure 4. 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 the SPARC 1000.