Synthetic Aperture Radar (SAR) Image Processing Technique for Large Scale Terrestrial Applications

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ABSTRACT: *Researchers at the Alaska SAR Facility (ASF) have developed a hybrid package of YMP and T3D based SAR processing algorithms using the Arctic Region Supercomputing Center (ARSC). The capabilities include; radiometric calibration, low-pass filtering, creation of simulated SAR images, image-to-image correlation, terrain correction, incidence angle normalization, and large scale mosaicking. Using these tools, a SAR mosaic was constructed mapping the entire state of Alaska. A 3-D video fly-by of the mosaic was made to showcase the result. This paper discusses additions to the parallel terrain correction package, SAR processing techniques, and the realities of creating the largest SAR mosaic created to date.*

Introduction

Spaceborne SAR systems are providing scientists with a great deal of information on the phenomena associated with surface processes. SAR data have proven useful in studies of sea ice, volcanology, geology, glaciology, vegetation cover, soil moisture, surface hydrology, and oceanography. The utility of SAR derives from its all-weather and day-night capability, its fine resolution, and its sensitivity to changes in the Earth's surface characteristics. This is especially true in remote regions of Alaska where darkness and cloud cover limit the application of optical sensors.

Background

While spaceborne SAR instruments have their unique capabilities, there are certain issues which have to be addressed in order to create products which can be used for scientific investigations. It is well known that SAR images have severe geometric and brightness distortions over rugged terrain due to the nature of its peculiar slant range mapping. According to SAR principles [1], when both the satellite orbit position and the slant range act as functions of time, and the mathematics model for a reference earth surface (e.g. sea level surface) is known, SAR can depict a very accurate picture of features on the reference plane. In fact, as a routine product, a standard ASF image maps the ground to a reference surface with a constant elevation [2].

However, most land features, e.g., rivers, hills, and mountains, run through varying terrain which introduces some geometric distortion. This distortion is a function of both the terrain elevation and the incidence angle of the radar beam to the geoid surface (global incidence angle). The larger the relative elevation, the larger the geometric distortion. Also, the smaller the incidence angle, the larger the distortion. The result is foreshortening and layover for rugged terrain. For the European satellite ERS-1, the global incident ranges from 19.5 to 26.5 degrees, introducing a position offset about 2.3 times as large as the relative elevation. This order of position error is critical to most land applications.

Once this problem is overcome, the all-weather capability and fine-ground resolution available from the satellite SAR instruments will provide scientists in land applications with a unique tool for accurate surface mapping and change detection.

However, geometric correction of SAR imagery is a computationally intensive task, requiring on the order of 10^5 operations per pixel. The correction of a 64 MB full-resolution SAR image to a 2 MB 90-meter resolution image will take more than 6 hours using a SPARC2 workstation at the ASF Interactive Image Analysis System (IIAS) lab. Due to effort in the previous two years, this technical problem has been solved very nicely by porting the original code [3] to the Cray T-3D and YMP at the ARSC. In 1994, code porting, debugging, and customizations were completed [4][5]. Using this code, a 90 meter resolution SAR image can be terrain corrected in about 7 minutes.

Corrections Applied by the ASF Code

The ASF software applies several standard SAR image corrections. Each creates a scientifically more viable product.

The first correction is *radiometric calibration*. Ideally, this process will adaptively compensate for spatial and time dependent variations in the radar system transfer characteristics. Included here are cross-track and image to image intensity inconsistencies due to signal attenuation by distance. This conversion from echo received to mean surface backscatter establishes a common basis for all pixel intensities, giving backscatter values that are independent of positioning in an image or of the particular image viewed [6]. Since SAR images are taken at varying satellite swath angles, directional orientation changes between passes. To standardize orientations, SAR images are resampled to a spatial representation with known geometric properties through a process known as *geocoding*. For this code, the Universal Transverse Mercator (UTM) mapping was chosen because it offers simple x,y coordinate to image line,sample conversion. Geocoding requires rotation and scaling of an image into UTM coordinate space using scene geolocation data. Thus, each geocoded product contains an approximately square rotated SAR image inside it, with empty pixels set to black.

The final standard correction applied is *geometric rectification.* This process resamples an image to remove the terrain induced geometric distortions. It is accomplished by applying adjustments that compensate for the difference between actual and estimated terrain height on a pixel by pixel basis. The results are undistorted images in the sense of orthographic maps. Therefore, these images are suitable for use in geographic distance calculations and size measurements. Final images appear with correctly spaced and placed land marks, and mountains that have properly sized slopes.

Current Code Configuration

The parallel terrain correction package work continued through 1995, with algorithm optimizations, expanded capabilities, process refinement, and metaprograms for increased automation. A flow diagram for the process is given in figure 1. The

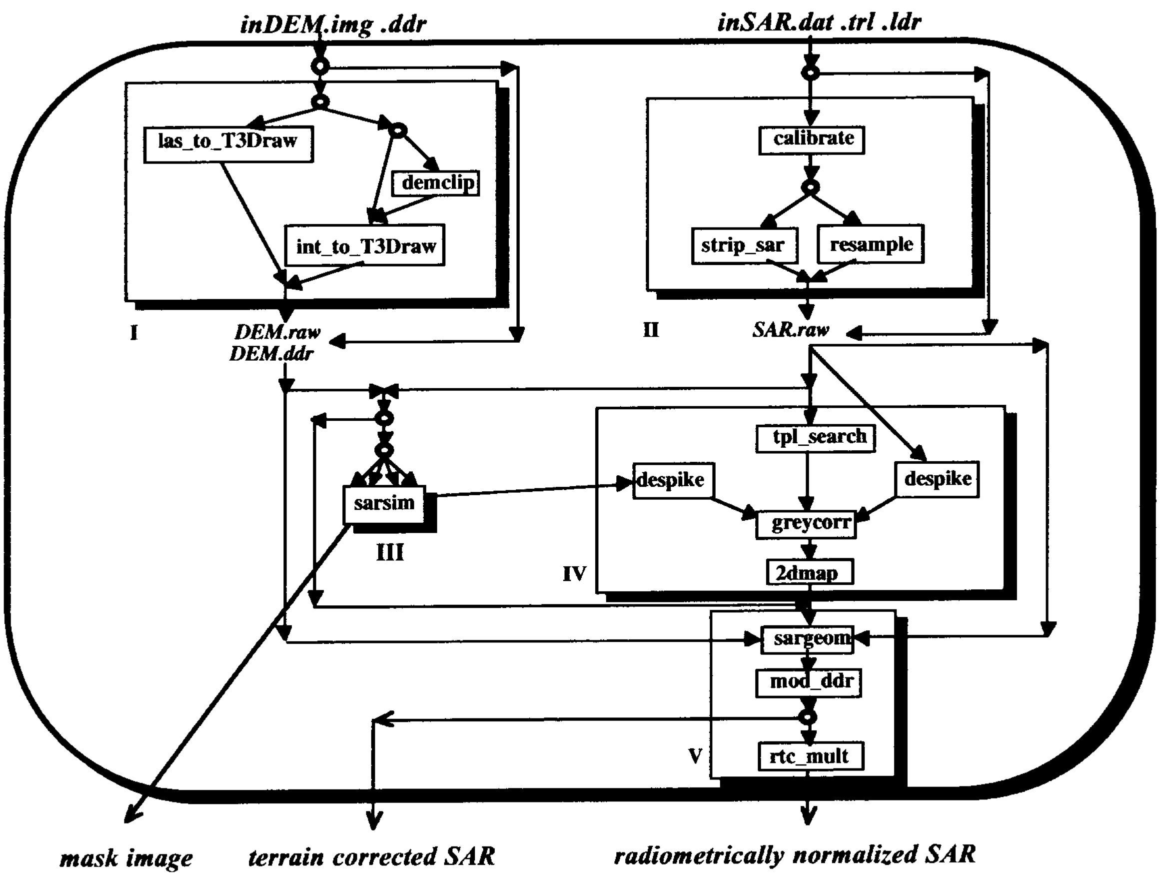

Figure 1: Terrain Correction Flow Graph. A flow diagram for the ASF parallel terrain correction software running at ARSC. Each shaded box is one phase of the processing: (I) DEM Preprocessing, (II) SAR Preprocessing, (III) Creation of Simulated SAR, (IV) Image to Image Correlation, and (V) Final Rectification Phase. Each inner box represents one executable program. Different options are represented by decision circles. The procedure requires two input products, an ASF SAR image triplet and a DEM file, and produces three output images: a radar shadow/layover mask, a terrain corrected SAR, and a radiometrically normalized SAR.

first two phases preprocess a SAR image and a corresponding Digital Elevation Model (DEM) into raw files with identical pixel resolutions. In phase III, these are used to create a simulated SAR image based on an imaging radar model. Phase IV spatially correlates the simulated SAR with the actual SAR to tighten the mapping from the DEM to the SAR image space. Once the best correlation is achieved, the radiometric values of the actual SAR are placed in the terrain corrected output image by inverting the mapping found from the DEM to the SAR image space. Thus, the SAR image is geocoded and geometrically rectified in one final step. Optional products include shadow/layover mask images, which show where radar shadowing or terrain layover have occurred, and radiometrically normalized SAR images (see discussion below).

Recent Code Modifications

Over the last year, many new features have been added to the code. The ability to clip a large area DEM file to the coverage of a SAR image was added with the program *demclip*. By using a YMP based metaprogram, the optimal number of T3D processors is selected before each T3D program run, thus improving algorithm efficiency. A new program, *tpl_search,* was added that increases the probability of proper correlation while drastically decreasing the time required for correlation by intelligently finding 250 tie-point search locations instead of using over a 1,000 locations on a regular grid.

All products now come with metadata files describing the size, type, and geolocation of the images. Processing can be accomplished at many different resolutions from 12.5 to 100 meters and beyond by use of a command line switch. To increase bullet proofing, more of the resilient legacy bugs were exterminated and memory usage for several programs was altered to allow very high resolution processing without memory allocation failures. Additional points of interest include the batch queue and satellite strip processing metaprograms used to create the Alaska mosaic and the creation of a comprehensive users guide and tutorial session. As a final note, a serial version of the current ASF terrain correction software was created for the Solaris operating system. It offers significant improvement over the LAS dependent EDC version previously available for this workstation environment.

Incidence Angle Normalization

Beyond the geometric distortions previously mentioned, brightness distortions also occur in SAR images. Similar to the geometric distortions, these result from the variance of real world terrain orientation.

The primary cause of brightness distortion is the dependence of the effective area illuminated by the radar beam on the local terrain slope. Figure 2 displays this dependence graphically for the two dimensional case. Several area correction formulas have been developed to remove this backscatter intensity distortion in SAR imagery [7]. The simplest of these applies a factor proportional to the ratio tangents of the global and local incidence angles. More sophisticated three dimensional versions include the global, local slope, and local aspect incidence angles in their calculations.

A secondary cause is the variation in scattering intensity with the local incidence angle. Figure 3 displays how the terrain slope effects signal echo strength. The material composition of the surface being imaged determines the type and amount of scattering that occurs. Many scattering intensity correction models have been developed that combine both specular, or directional, and diffuse, or non-directional, reflection types.

Thus, brightness distortion acts as a function of the local and global incidence angles and the reflective properties of the surface imaged. Area corrections and scattering models combine to remove these brightness distortions, leaving a product that minimizes dependence on local terrain elevation. Currently five radiometric normalization formulas are offered by the ASF software package.

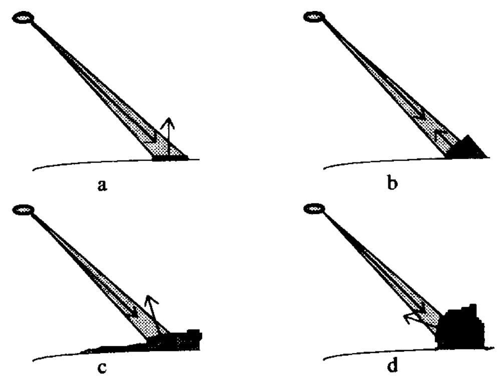

Figure 2: Dependence of illumination area on local slope.

These diagrams show a radar beam cross-section with a constant (global) incidence vector. In each, the terrain slope is varied and the resulting (local) surface normal is shown. Notice that the resulting effective area of illumination for the beam (the short heavy lines) varies with the terrain slope. (a) Shows the default geoid surface, while (b) shows a minimum area illumination. (c) and (d) show how two different terrain slopes can have the same area of illumination, thus revealing the dependence on the global incidence of the beam.

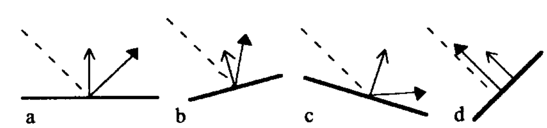

Figure 3: Dependence of specular reflection on local slope.

Constant global incidence (dashed lines) onto surfaces with varying normals (^ arrows) result in different reflectance directions (solid arrows) for perfect specular reflectors. The material composition of a surface determines the amount of specular (directional) and diffuse (non-directional) reflectance. (a) shows the reference plane, (b) a normal facing towards the incident beam, (c) a normal facing away from the incident, and (d) a normal exactly facing the incident.

Creation of the Alaska Mosaic

Steps in the creation of the Alaska mosaic included: collection of 90 meter DEM data for the entire state, ordering ASF ERS-1 lo-res SAR images for the entire state, checking the quality of DEM and SAR data prior to terrain correction, searching the ASF SAR image database and reordering SAR data wherever the boundary between image swaths was noticeable, terrain correcting individual SAR images, and mosaicking the resulting images.

All available 90-meter DEM data for Alaska was gathered from the US Geological Survey. However, a few 100 km by 100 km gaps still exist in the USGS DEM coverage. For these areas, no terrain correction of the SAR images can be performed. However, to avoid the distasteful appearance of blank windows in the final mosaic, radiometrically calibrated and geocoded SAR images of these areas were included.

SAR images were collected during two phases. During the initial effort, the criteria of selection included reasonable lateral overlapping, continuity along an image swath, and summer season coverage. These criteria led to the summer images acquired in 1992 and 1993 when the 35-day repeat cycles of the ERS-1 satellite provided complete coverage of Alaska. Since the lateral overlapping of a single 35-day repeat cycle offers 60-75% redundancy, only every other swath was selected for use in the mosaic. During this initial phase, 800 images were ordered.

Quality controls for the DEM and SAR data were performed by mosaicking. Mosaicking of DEM data met no evident problems. However, mosaicking SAR images which had been radiometrically calibrated and geocoded revealed that a few noticeable and sometimes even distinct seams existed between swaths. These seams resulted from significant changes in soil moisture which were caused by rain events occurring between imaging passes. This complicated the efforts of making a seamless mosaic.

Extensive searching of the suitable images from an extremely large database of the available 1992 and 1993 summer ERS-1 sattelite imaging passes comprised the second phase of image collection. During selection, images which were considerably darker or brighter than their surrounding images were discarded and replaced by middle signature images of the same areas. Consequently, the images included are representative of the average conditions of their areas. More than 500 additional images were collected and considered. This process lead to the generation of a nearly seamless geocoded digital mosaic of Alaska at a pixel resolution of 100 meters without terrain correction.

Terrain correction of the SAR images was accomplished using the ASF parallel terrain correction software at ARSC. Using specially designed metaprograms and batch jobs, an entire swath of SAR images was terrain corrected and concatenated into a corrected image strip with a single command. Each of the terrain corrected strips were then mosaicked together. As previously mentioned, a modified Universal Transverse map projection with the 150º W meridian as the central meridian, which is typical for mapping Alaska, was used. This process yielded a 100 meter resolution terrain corrected image of the entire state of Alaska. The file contains over $700*10^6$ byte valued pixels. The geographic extent is 130º to 180º West and 55º to 85º North, representing in excess of 7 million square kilometers of earth surface.

During the terrain correction, some trouble arose in flat areas where the image to image correlation was failing due to a lack of recognizable terrain features. In the northern tundra plain, the results were taken as valid since the lack of terrain relief gives a lack of substantial image distortion. In other areas, interactive methods had to be employed to ensure data validity. One such technique substituted warping coefficients from images that properly correlated for images within the same swath that had failed correlation. In some areas, hand correlation of the SAR and simulated SAR images to within subpixel accuracy was the only answer. Through these efforts, the correlation problem was satisfactorily overcome. However, efforts to increase the accuracy, reliability, and scalability of the correlation process are continuing.

Applications of the Alaska Mosaic

Although no DEM quality problems were detected during initial mosaicking, the final terrain corrected SAR mosaic and the DEM data in the southern part of the Kuskokwim mountains showed discrepancies. These discrepancies are readily apparent by the existence of V-shaped features in the terrain corrected SAR images. This simple diagnosis is based on the fact that V-shaped features, caused by foreshortening of the foreslope and elongating of the backslope on the non-terrain corrected SAR images, should be removed during terrain correction. A close comparison of DEM data with 1:250,000 scale topographic maps confirms that the DEM data of the Goodnews Bay USGS quadrangle are actually inaccurate.

The Goodnews Bay quadrangle problem shows how the mosaic was used to check the quality of DEM data. This mosaic is an ideal information source for regional mapping. The potential applications of this mosaic include statewide or regional soil moisture mapping, classification of forest and other vegetation types, classification and zoning of arctic glaciers, geological mapping, and volcanic investigations [8].

Further effort is being made to create a radiometrically normalized version of the mosaic. This should further improve the mapping capabilities of the mosaic. Work is also underway to upgrade the mosaic to publication standards. Future plans include making a CD-ROM of the final products.

Conclusions and Future Work

The tasks essential to bringing the ASF terrain correction package to an operational environment with minimal man involvement have been completed. Capabilities have been extended to allow complete reliable SAR image processing at various resolutions. Incidence angle normalization formulas offer specialized brightness distortion corrections. The mosaicking tools allow automated creation of large scale SAR mappings. To close the loop, all of the software has been extensively tested, debugged, validated, and documented using the 1,000+ SAR images from the Alaska mosaic as an ample test bed.

Work on the ASF parallel terrain correction package continues in 1996. Three major issues are to be addressed. First is the indubitable operation of the image-to-image correlation phase. Next, capabilities will be extended to allow processing of data from other SAR platforms, specifically JERS1, ERS-2, and RADARSAT. Finally, efforts will persist in providing a complete and reliable SAR image correction and large scale mosaicking software package.

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