Gamma SAR Processor and Interferometry Software

Urs Wegmüller
Gamma Remote Sensing, Thunstrasse 130
CH-3074 Muri b. Bern, Switzerland
Tel: +41(0)31-951.70.05, Fax: +41(0)31-951.70.08
email: gamma_rs@pingnet.ch

Charles Werner
Gamma Remote Sensing, Thunstrasse 130
CH-3074 Muri b. Bern, Switzerland
Tel: +41(0)31-951.70.05, Fax: +41(0)31-951.70.08
email: gamma@primenet.com

Abstract

Based on the previous work of C. Werner and U. Wegmüller in the frame of their research at the University of Zürich and Jet Propulsion Laboratory, as well as up to da published in the literature Gamma Remote Sensing developed its advanced SAR processing and interferometry software packages.
The SAR processor and the interferometry software are modular software packages written in the widely supported ANSI-C language. The well documented structure processing approach permit users to experiment with new algorithms and applications. Data of both airborne and spaceborne sensors including ERS, JERS-1, SIR-C, a StripMap mode, and the Dornier DOSAR have been successfully processed interferometrically. The processor is currently being certified by ESA for ERS processing and
The overall design of the software, algorithms used, special features implemented, typical sequences for processing with the Modular SAR Processor (MSP) and the In Processor (ISP), as well as a few examples for results will be presented.
Keywords: SAR processing, SAR interferometry, software, phase unwrapping, height mapping

Introduction

The Modular SAR Processor (MSP) is a system for deriving synthetic aperture radar images from raw SAR data from both airborne and space-borne sensors. Overall, the design philosophy has b processing of the data, while still permitting processing of the data on a workstation computer in a reasonable amount of time. The processor consists of a suite of ANSI-C programs. The ANSI- for its portability and efficiency in processing of large data sets. The MSP runs on SUN/HP/DEC/SGI workstations with the UNIX operating system and DEC computers running VMS. Processing r data characteristics are saved as text files with system parameters referenced using simple keywords. This is in contrast to the difficulty to decipher the variable CEOS format for SAR products. main steps in SAR processing, the functions of the MSP modules are described in more detail. Up to the present time, MSP processing has been performed using airborne data from the Dornier radar operated by DLR, and ERS-1/2, JERS-1, RADARSAT and SIR-C space-borne radar.

Characterization of the Modular SAR Processor (MSP)

The main modules of the Modular SAR Processor (MSP) are pre-processing, range compression with optional azimuth prefiltering, autofocus, azimuth compression, and multi-look post processir step processing parameters are determined from the CEOS leader files and extracted from the raw data. During range compression, data may be decimated in azimuth by prefiltering for quick-l The azimuth processor uses the range-Doppler algorithm with optional secondary range migration as required for RADARSAT data. The user can select the output geometry of the images to be deskewed in azimuth. The autofocus algorithm refines the along-track platform velocity estimate. The processed images are radiometrically normalized for the antenna pattern, along track gain length of the azimuth and range reference functions, and slant range. It has been demonstrated that the Gamma processor is phase preserving from interferometric processing. Multilook image domain averaging of the single look complex image samples. An advanced motion compensation module is also available for processing of airborne SAR data.

In the following a description of the main processing steps of the Modular SAR Processor (MSP) is given. The steps are discussed in the order in which they are usually used in a processing sequ be used to run sequences of programs, convenient to automate the use of the software.

Raw Data Transcription and Processing Parameter Generation

A series of c-shell scripts support the copying of raw data tapes from different facilities to disk. This step is a pre requisite before further processing occurs. Parameter generation programs inge extract the appropriate parameters, query the user on the section of the image section to be processed, and set up the processing parameter file.

Range Spectrum Estimation

The range spectra of the SAR data are useful for estimating the SNR of the final image. Typically, the chirp spectrum extends over about 80 percent of the digitized bandwidth. The SNR estimat comparing the average level chirp bandwidth to the level in the noise only region. This estimate is then used for radiometric compensation of the antenna pattern gain used for calibration of the antenna gain correction applies only to the signal and not the noise fraction of the SAR image.

Missing Line Detection and Correction

ERS data from the different PAFs sometimes contain missing data lines. For interferometric applications even one missing line results in an almost complete loss of coherence, a completely una Therefore, the spacecraft binary line counter and the cross correlation between adjacent lines are used to determine if the raw data contains missing lines. Missing lines are removed by duplica line, preserving the image intensity statistics as much as possible. The same program also permits the user to concatenate several image frames to create a single long image. The MSP has suc images consisting of 5 frames (500 km) long strips that have then be used for interferometric mapping of ice motion in Antarctica. ERS changes the range gate position (slant range to the first every 30 seconds along track. Such changes and shifts the raw data are corrected such that the entire data set has a common starting slant range.

Doppler Ambiguity Resolution

The ERS-1 and ERS-2 SAR platforms employ yaw steering of the radar in order to maintain the Doppler centroid of the data within ½ of the pulse repetition frequency of the SAR. In this case a Doppler centroid is unambiguous because the Nyquist criteria for sampling of bandlimited signals is satisfied. A more general form of the Nyquist criteria states that as long as the bandwidth of the sampling rate (the PRF), the original signal can be recovered if the correct multiple of the sampling frequency is known. Estimation of the fractional part of the Doppler centroid can be obtai summation of azimuth spectra (Li et. al., 1985) or cross correlation (S.N. Madsen, 1989). Both of these approaches provide reliable estimates of the centroid modulo the PRF.

As it turns out, the pointing algorithm for ERS makes errors in the southern hemisphere such that the actual Doppler centroid is 1 to 2 multiples of the PRF away from baseband. Both RADARSA employ yaw steering to control the PRF and so the centroid is a function of the sensor latitude. Large amounts of yaw in the SAR data not only complicates processing, but degrades image reso should definitely be yaw steered to obtain the best resolution. Lack of precise yaw steering will also lead to degraded interferometry results because optimal correlation of passes requires that a viewed from exactly the same angle for repeated passes.

Currently two different algorithms to estimate the Doppler ambiguity have been implemented. The first algorithm is known as multi-look cross correlation algorithm (MLCC) and is based upon B examines the shift in Doppler as a function of frequency by estimating the Doppler centroid for different bands of the radar range chirp bandwidth. The estimate of the centroid is performed by correlation between echoes. The phase of the correlation coefficient is directly proportional to the centroid. Examining the shift in centroid as a function of frequency yields an unambiguous esti

The second algorithm, called multi-look beat frequency (MLBF) algorithm, was developed by Wong et al. (1996). The MLFB algorithm uses the idea of processing different range looks, but rathe correlation coefficient, the spectrum of the product of the range looks is evaluated. This algorithm only works in regions with high contrast, such as urban regions, and is generally less accurate algorithm. While regions of high contrast can introduce errors in the MLCC algorithm, processing of a large data block reduces this sensitivity.

For both algorithms a confidence measure for the Doppler ambiguity estimation is provided.

Doppler Centroid Estimation

The fractional part of the Doppler centroid can be estimated using either the estimate of the line to line complex correlation, or by examining the centroid of the azimuth power spectrum. The c quite constant across the swath and the azimuth spectrum approach works well. But RADARSAT and JERS data often have a large squint and the centroid can change more than ½ a PRF across correlation approach is preferred.

The implemented azimuth power spectrum approach runs for IQ format SAR data from ERS, RADARSAT, and JERS. Short azimuth segments from a region in the center of the range swath are F the powers are added incoherently to form a periodogram. The program then determines the centroid by finding the frequency that balances the spectrum. This program finds the centroid only image and is used for ERS processing.

The implemented cross correlation algorithm obtains a centroid estimate for each range bin. These individual estimates are somewhat inaccurate and a least squares polynomial fit of the Doppl required to get a result that can be used for processing. If both the MLCC and MLBF algorithms fail to give a correct answer for the ambiguity, the program to estimate the Doppler centroid as a accept an integer value for the ambiguity from the command line, or estimate the ambiguity using the slope of the Doppler as a function of range. Estimation of the ambiguity from the function centroid with range is quite sensitive to the pitch of the platform and, while it does work for some RADARSAT and ERS data sets, it is not recommend relative to the algorithms used in the Dopp program.

JERS-1 Interference Estimation

Radio Frequency Interference (RFI) is a serious problem for JERS in many images because the radar band is shared with other users such as narrowband FM point to point communications. The is to cause streaking and additional noise in the image that obscures the scene. The MSP averages the range power spectra in blocks of 1024 echoes over the entire raw data set. These power s the range compression program to notch out interference cause by narrow-band RFI. The RFI signals appear as spikes in the power spectra. A median filter is used to detect spikes in the range regions that will be set to zero in the range matched filter. The filter is updated for each block of raw data that is processed.

Range Compression/Azimuth Prefilter

The raw SAR data are complex valued samples of the successive SAR echoes received by the radar as it moves along the flight track. The radar samples can be recorded in one of two formats. been heterodyned to baseband, then each sample is a complex pair designated the I and Q channels (In-phase, Quadrature). If the receiver output spectrum is on a carrier offset from DC, ther

Digital converter (ADC) is required and the data samples are real valued in Offset Video format. If the data are in the offset video format, processing of the data will subtract the carrier. The on video sampling is that the ADC must sample twice as fast as the 2 ADCs in the IQ system. The net number of data values is the same for the two systems. Offset video has certain advantages l to be concerned with channel amplitude or phase imbalance.

As the radar travels along the flight track, pulses are transmitted that are linear FM modulated chirp signals with a large time-bandwidth product. The range compression program applies a mat recorded data. A set of different sensor dependent range compression programs have been developed in the MSP.

All programs function approximately in the same way, but take into account the sensor dependent variations in compensation for backscatter variation along-track and across the swath. All prog data histogram, and data statistics, including the mean of each channel, standard deviation, and in the case of IQ data, the correlation between the I and Q channels. For JERS the range compr compensates for the along-track variation in the receiver gain and compensates for the along-track gain variation called the Sensitivity Time Control (STC). For RADARSAT the range compressic for along-track receiver gain variations for RADARSAT. RADARSAT updates the receiver gain every 8 echoes, while JERS performs this update every 64 echoes. In all cases the programs normal length of the transmitted chirp signal.

An important parameter for determining the sidelobe level and resolution of the range compressed data is the window applied to the range reference function. All programs in the MSP utilize th as the weighting function. The relationship between the resolution and sidelobe level can be changed by adjusting the window parameter beta. The default value of the parameter is 2.12 that le -30 dB range with only moderate loss in resolution. This window is discussed in most standard texts on digital signal processing.

The range compression programs for ERS, RADARSAT, and JERS have the option of decimating the data in azimuth by prefiltering around the Doppler centroid prior to range compression. This r quick-look survey product is desired. This step can also be performed after range compression using the prefilter program. The user specifies the desired decimation factor and the relative leng response (FIR) filter.

Autofocus

An improved estimate of the along-track velocity of the radar platform is estimated from the data based on the cross correlation of images formed from different parts of the azimuth Doppler sp algorithm requires some image contrast in the test region or the correlation matching between sub-images will fail.

The algorithm is based on the idea that given the Doppler centroid of a sub-image, the azimuth shift as a function of time is directly related to the velocity. Sub-images with different squint ang directions. If these images are overlaid using the estimated velocity, misalignment is primarily caused by the inaccurate velocity. The image offset is then used to correct the velocity estimate. I refines the estimate. A minimum of two iterations is suggested to achieve the best possible focus. A quality measure for the along-track velocity estimation is provided. One cause of poor focus wrong Doppler ambiguity.

Azimuth Compression

The azimuth compression of the range compressed data is done with the standard range-Doppler (RD) algorithm. The range compressed data are divided into along-track patches of user select migration of the range compressed data is required since each point in the image follows a parabolic range trajectory. The RD algorithm is based on the idea that all points at a particular Dopple be migrated by the same amount at a particular range. This is why in the RD algorithm, the migration is done after an azimuth FFT of the data is carried out. A 9-point sinc interpolation kernel interpolation. After migration, an azimuth matched filter derived from the range history of a point target is applied. The range history is calculated without approximation and updated for every

Relative calibration during azimuth processing takes into account the antenna pattern in range, the variation in slant range, and the variation in length of the azimuth reference function. The ra normalized to take into account the estimated signal to noise ratio of the scene. The relative calibration of the SAR image assures that the noise power is uniform as a function of range. The de antenna pattern file is given in the SAR sensor parameter file, but the user has the option to select another file on the command line.

Multi-look Summation

A multi-look intensity image is produced by detecting and averaging the single look complex image. This program also generates a new processing parameter file that contains the image size a multi-look intensity image. A rectangular window is used to average the data. The user can specify the number of number of range and azimuth samples that are averaged. Each sample value i number of looks.

Results

Examples for SAR processing of ERS and JERS data are shown in Figures 1 and 2. Single look complex data processed with the MSP numerously used for interferometric analysis confirming the the processor.

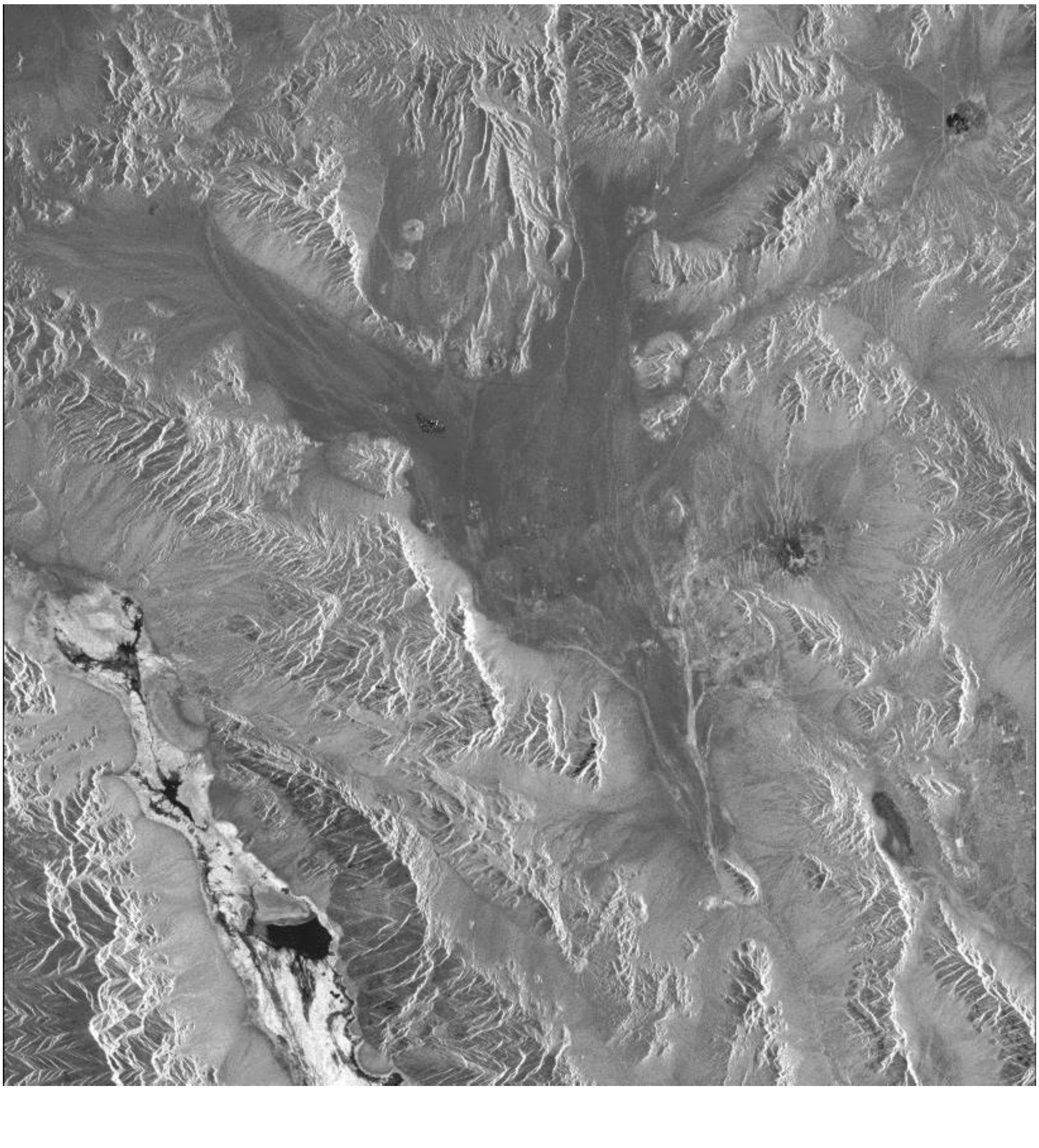

Figure 1: ERS-1, Frame 2871, descending orbit 8059 (29. Jan. 1993) multi-look intensity image over Death Valley test-site, USA. SAR RAW data with courtesy of ESA, SAR Processing of full

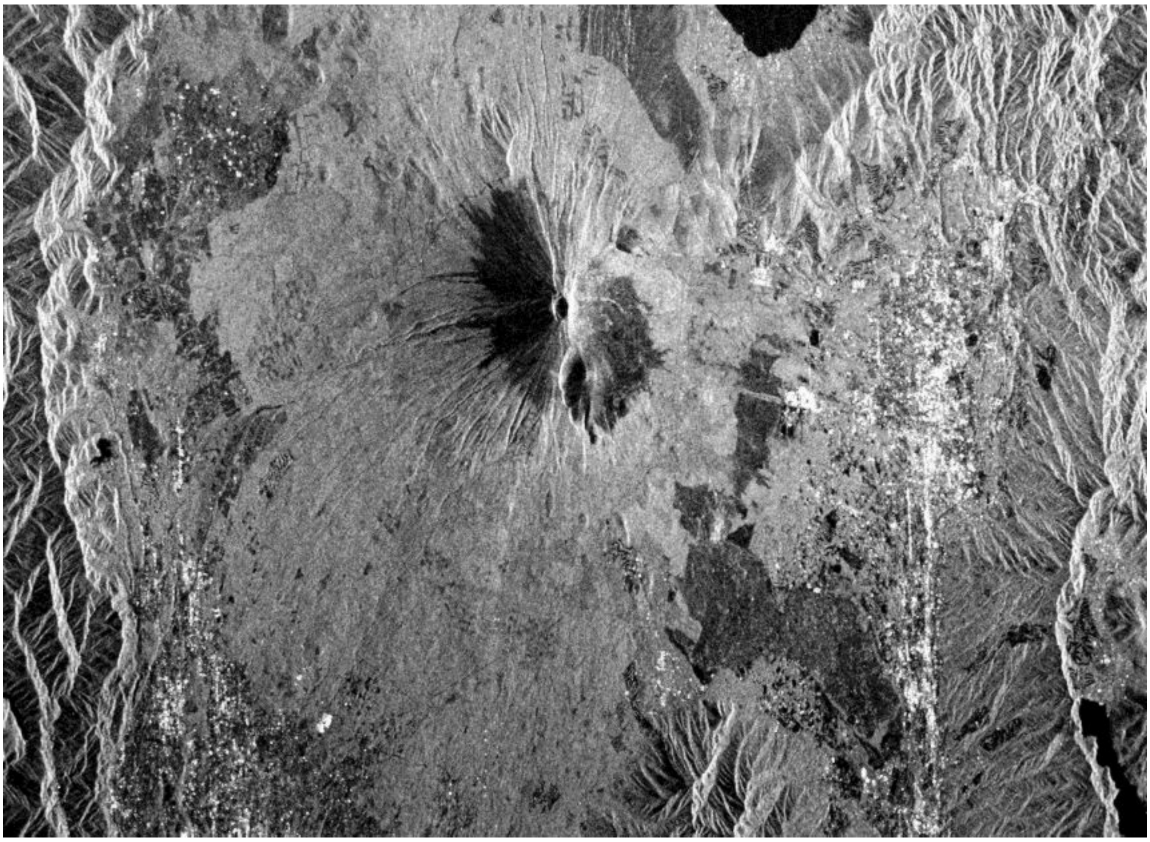

Figure 2: JERS-1 SAR image over Mount Fuji. SAR RAW data with courtesy of NASDA. SAR Processing with MSP.

Characterization of Interferometric SAR Processor (ISP)

The Gamma Interferometric SAR Processor (ISP) encompasses a full range of algorithms required for generation of interferograms, height maps, coherence maps, and differential interferometri include baseline estimation from orbit data, precision registration of interferometric image pairs, interferogram generation (including common spectral band filtering), estimation of interferomet of flat Earth phase trend, adaptive filtering of interferograms, phase unwrapping using a branch cut algorithm, precision estimation of interferometric baselines from ground control points, gene height, and image rectification and interpolation of interferometric height and slope maps. The display of the final and intermediate products is supported with display programs and programs t portable images in SUN rasterfile format. Processing related parameters and data characteristics are saved as text files that can be displayed using commercial plotting packages.

In the following the ISP is described. A flow chart of the ISP is given in Figure 3. The main processing sequence is complemented by quality control and display programs.

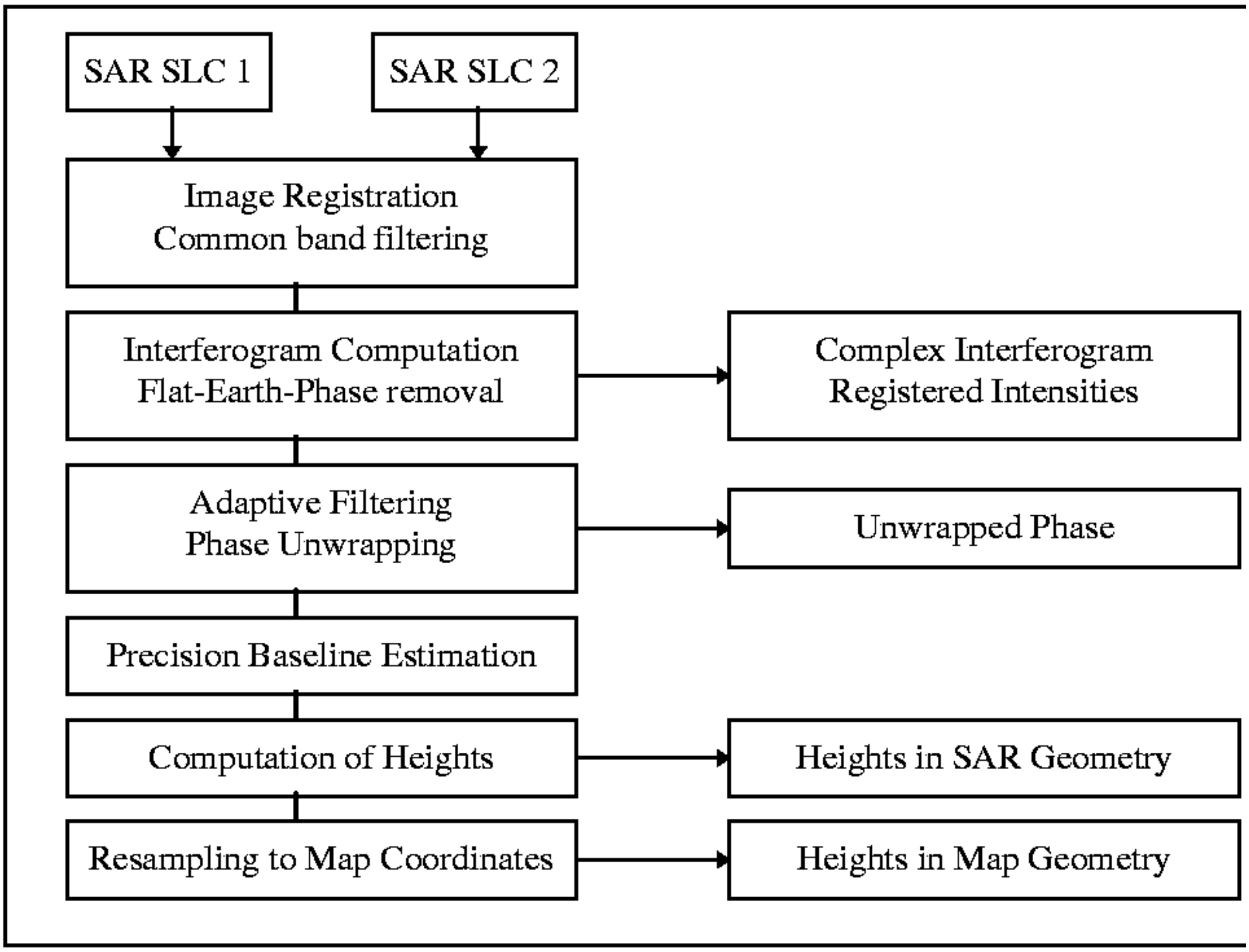

Figure 3: ISP flow chart.

Image Registration and Common Band Filtering

nterferometric processing of complex SAR data combines two single look complex (SLC) images s_1 and s_2 into an interferogram. This requires co-registration of the two images at sub-pixel accu accuracy of better than 0.2 pixel is required in order not to reduce the interferometric correlation by more than 5%. The image offsets are modeled as functions bilinear in range and azimuth. D offset polynomial coefficients is the first step in interferometric processing (Zebker et al., 1994). The co-registration of the images is performed by calculation of the local spatial correlation func 1'000 small areas throughout the image. The image offsets which maximize the local correlation are determined. These values are used to estimate polynomial coefficients for offsets in both ra the whole image. Once the offset functions are known the two SLC images can be co-registered. As this is done to the sub-pixel resolution resampling of one of the images is necessary. Approp methods are used to minimize interpolation errors.

The next step is to determine an estimate for the baseline component perpendicular to the line of sight based either on track data or on the range offset slope. Knowing the perpendicular baseli the common band filtering of the range spectrum can be determined. A discussion of this type of filtering was given by Prati et al. (1992) and Gatelli et al. (1994). Similarly, the azimuth spectra non-identical Doppler centroids, are filtered, in order to include only those parts of the spectra which are common to the two spectra.

Interferogram Computation and Flat-Earth-Phase Removal

Then the two images are cross correlated, i.e. the normalized complex interferogram is computed. In order to improve the estimates of the interferometric phase and correlation multi-looking is and range phase trends expected for a flat Earth are then removed from the interferogram. This is done in order to facilitate consecutive filtering, averaging, and phase unwrapping. The magnit normalized complex interferogram correspond to the interferometric correlation.

Adaptive Filtering and Phase Unwrapping

From the complex interferogram the interferometric phase is only known Modulo 2π . In order to be able to relate the interferometric phase to the interferometric imaging geometry and finally t topographic height and true ground range the correct multiple of 2π has to be added. This is done in the phase unwrapping step. Phase unwrapping is a problematic step due to discontinuities (layover) and inconsistencies (residues as a result of high phase noise). Filtering and multi-looking may be performed to reduce the phase noise. Relatively flat areas of intermediate to high coh problematic. More care has to be taken in more rugged terrain and for areas of low coherence. In order to account for the local terrain slope an adaptive filter is provided. As an alternative the techniques presented by Werner and Goldstein (1997) were encoded.

Phase unwrapping is then done applying a region growing algorithm such as described by Rosen et al. (1994) to the filtered interferogram. Critical areas such as areas of very low coherence or and avoided in the phase unwrapping. The encoded phase unwrapping algorithm is reasonably reliable and runs time efficient.

Precision Baseline Estimation and Computation of Heights

A first estimate of the interferometric baseline was determined from the orbit (track) data or the average interferogram fringe frequency. This estimate was sufficient for the subtraction of the f carried out to facilitate the filtering of the interferogram and the coherence estimation. This estimate is not accurate enough, though, to convert the unwrapped interferometric phase to topogra a refined baseline estimation is done using a least squares fit for a number of control points of known height.

The unwrapped interferometric phase together with the precision baseline are the used to derive the topographic heights and true ground ranges based on the geometric relationships as descril Madsen et al. 1993, Zebker et al., 1994, Small et al. 1994.

Resampling to Ortho-Normal Coordinates

Knowing the topographic heights in SAR image geometry allows then to transform the images from SAR coordinates (slant range, azimuth) to orthonormal map coordinates. An example for an map in map coordinates is given for the Death Valley test site in Figure 4. In addition to the height other products such as the backscatter intensity or the coherence map may be resampled to coordinates.

m.

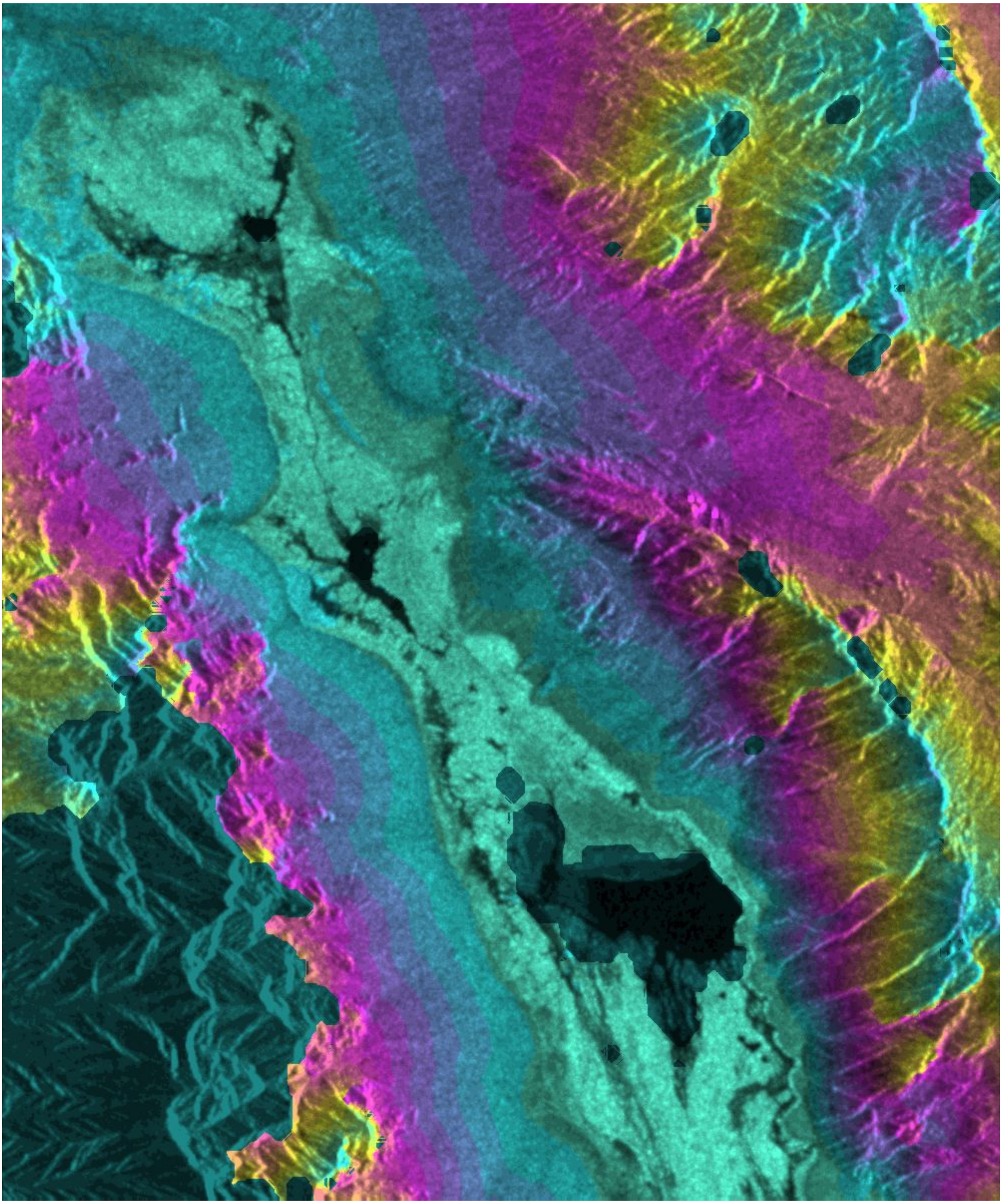

Figure 4: Death Valley, terrain height estimated with ERS-1 SAR interferometry with the colors corresponding to terrain height (see color key), and the image brightness to the backsca

Summary and Conclusions

SAR processing and interferometric processing software were presented. The range-Doppler SAR processor allows the generation of complex and real valued SAR images from raw data of the c as well as of airborne sensors. The processing includes radiometric calibration and is phase preserving. Special features to optimize the processing of data of the current spaceborne sensors we features are autofocus (all SAR), radio interference filtering (for JERS), Doppler ambiguity estimation (JERS, RADARSAT), missing line detection (ERS-1/2), and secondary range migration (JERS

The interferometric processor gives end to end support in the generation of interferometric products starting with complex SAR data as the SLC products provided by the PAFs or as processed b modules include baseline estimation from orbit data, precision registration of interferometric image pairs, interferogram generation (including common spectral band filtering), coherence estima Earth phase trend, adaptive filtering of interferograms, phase unwrapping using a branch cut algorithm, precision estimation of interferometric baselines from ground control points, derivation c and image rectification and interpolation of interferometric height and slope maps. The display of the final and intermediate products is supported with display programs and programs to genera images in SUN rasterfile format.

Advanced, up to date, algorithms were implemented in order to achieve accurate processing of the data (phase preserving, radiometrically calibrated, use of advanced filtering, etc.) while perm of large data sets on a workstation computer. The modular software was written in ANSI-C language guaranteeing a high portability. User-friendly display tools and full documentation in HTML l the software. Both binary and source code licenses are provided by Gamma Remote Sensing.

References

Li F.-K, D. N. Held, J. Curlander, and C. Wu, 1985:
Doppler parameter estimation for spaceborne synthetic-aperture radars, *Geosc. Remote Sensing*, vol. GRS-23, no. 1, *IEEE Trans.* pp 47-56, Jan. 1985.

Madsen S. N., 1989:
Estimating the doppler centroid of SAR data, *IEEE Trans. Aerosp. Electron. Syst.*, vol. 25, no. 2 pp. 134-140, Mar. 1989.

Bamler R. and H. Runge, 1991:
PRF ambiguity resolving by wavelength diversity, *IEEE Trans. Geosc. Remote Sensing*, vol. GRS-29, no. 6, pp 997-1003, Nov. 1991.

Wong F. and I. G. Cumming, 1996:
A combined SAR Doppler centroid estimation scheme based upon signal phase, *IEEE Trans. Geosc. Remote Sensing*, vol. GRS-34, no. 3, pp. 696-707, May 1996.

Gatelli F., A. Monti Guarnieri, F. Parizzi, P. Pasquali, C Prati, and F. Rocca, 1994:
Use of the spectral shift in SAR interferometry: applications to ERS-1, *IEEE Trans. Geosci. Remote Sensing*, Vol. 32, No 4, pp. 855-865, 1994.

Madsen S.N. H.A. Zebker, and J. Martin, 1993:
Topographic mapping using radar interferometry: Processing techniques, *IEEE Trans. Geosci. Remote Sensing*, Vol. 31, No. 1, pp. 246-256, 1993.

Prati C., F. Rocca, A. Monti Guarnieri, and E. Damonti, 1990:
Seismic migration for SAR focusing: interferometrical applications, *IEEE Trans. Geosci. Remote Sensing*, vol. 28, no. 4, 1990.

Rosen P.A., C. L. Werner, and A. Hiramatsu, 1994:
Two-dimensional Phase Unwrapping of SAR Interferograms by Charge Connection Through Neutral Trees, *Proceedings of IGARSS'94*, JPL, Pasadena 1994.

Small D., C. Werner, and D. Nüesch, 1994:
Geocoding of ERS-1 INSAR-derived digital elevation models, *Proc. EARSel Workshop "Topography from Space"*, Göteborg, Sweden, June 8-10, 1994.