RADAR INTERFEROMETRY WITH PUBLIC DOMAIN TOOLS

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ABSTRACT

The development of public-domain software in the scientific community has stimulated a fast and free dissemination of ideas. Here we present latest contributions to public-domain radar interferometry software to create interferometric products and to analyze and visualize these products. We present the feasibility of the Doris radar interferometric software of Delft University of Technology to create ENVISAT interferometric products such as DEMs and deformation maps. A stepwise description of the creation of an ENVISAT DEM of the Las Vegas area is presented, using besides Doris the ESA BEAM toolbox, the statistical cost phase unwrapper SNAPHU (Stanford University), the Generic Mapping Tools (University of Hawaii), and the PROJ.4 package (USGS). Finally, the GRASS GIS software is used to drape a LandSAT image on top of the computed DEM in order to show the analysis and visualization capabilities of this free GIS package. These packages are also described briefly in this paper. Both advantages as well as drawbacks of these tools are discussed. It is the intention of this paper to demonstrate how a larger scientific community can benefit from freely available tools, and which contributions need to be solicited for.

1 INTRODUCTION

The Delft object-oriented Radar Interferometric Software package "Doris" is been developed in the C++ since September 1998 [5] [6]. In 1999, it was made available in the public domain to stimulate joint development and to take advantage of feedback by a larger user community. The availability of technical public domain software is important for a fast acceptance and integration of a technique in other disciplines, enabling scientists to gain experience with new techniques at low cost. Currently, many scientists from various research groups are using Doris and querying the Doris website [12]. These people are members of a user group that automatically receives notice of new releases and who can ask and answer questions from other users. These questions and answers are archived using a free yahoo group email account [13], which serves as a searchable FAQ (list of frequently asked questions).

Public domain software is generally distributed "as is", and "any express or implied warranties, including, but not limited to, the implied warranties of merchantability and fitness for a particular purpose are disclaimed". Installation of public domain software is not always straightforward, mainly due to differences in configurations of users (different platform architectures and conventions, compilers, etc.). A disadvantage of public domain software versus commercial software may thus be the lack of reliable support, concerning installation, running, and documentation. However, commercial software also does not always run smoothly and it is for a user almost impossible to repair, or even to gain insight in the problems. Since public domain software is often free of charge, it is often quickly updated after a report of a problem. But the main advantage of the software discussed here is the availability of the source code, and thus complete openness of implementation details and the possibility of adapting it to ones needs.

Doris is free for research purposes and has been installed on virtually all existing platforms. The GNU compiler suite [20] is used as default compiler, which is available on most platforms. Before installation a configure script is run that figures out compiler and platform specifics (mainly big or small endian). Also, dedicated libraries are used when available (the public domain FFTW library for Fourier transformations [15], LAPACK for Cholesky decomposition, and on HP systems, the commercial VECLIB library for fast matrix multiplications). If these libraries are not available, an internal implementation is used. The memory (RAM) usage of Doris can be set with the input file. The user manual and technical documentation is extensive (over 100 pages), and approximately 20% of the source code are comments. A test data set can be downloaded to get familiar with the software.

The basic interferometric tasks computed with Doris are described in section 2. During this processing, the basic information (height or displacement) is extracted from the phase data in the input Single Look Complex (SLC) images. Doris integrates other dedicated (public domain) programs where possible, particularly for the phase unwrapping, see section 2.7. Further analysis and visualization of the results is then performed using PROJ.4, GMT, and GRASS, which is described in sections 3 and 4. Finally, section 5 concludes with a review of the main advantages and disadvantages of the public domain software described in this paper.

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2 INSAR PROCESSING

Doris is capable of performing most common radar interferometric processing steps in a modular setup. The following sub-sections describe these modules. In order to demonstrate the capabilities of the software suite, we compute a full-scene interferogram and corresponding DEM from ENVISAT ASAR data on a laptop. The total processing time was about 1 hour, with a 900 MHz processor and approximately 100 MB of RAM available. The operating system was Windows XP, while Cygwin was used as a shell. Cygwin is a Linux-like environment for Windows. Most Cygwin tools are released under the GPL (GNU General Public License, i.e., free software, [20]), or are in the public domain. Installation of Cygwin is extremely straightforward using a setup script directly under Windows, see [11].

2.1 Doris' philosophy

Doris' philosophy is to use simple format definitions, and a single main program that keeps track of the processing. There are 3 small ASCII files that are used to store relevant parameters on the master image, the slave, and on the products. Each processing step can read and write to these files, updating them with the latest available results. Typical parameters are for example the name of a binary data file and the number of lines it contains, the Doppler centroid frequency, orbital data points, etc. The data products themselves are stored in simple binary data streams (i.e., files), without a header.

Doris uses other public domain software to perform dedicated tasks that can be handled well by these programs. This includes *getorb* to obtain precise orbital data records for the ERS satellites [8] [17], SNAPHU for phase unwrapping [27], GMT for general plotting and gridding [19], PROJ.4 for coordinate transformations [26], and GRASS GIS for powerful analysis and data fusion with other layers of information [21]. Furthermore, it can handle the publicly available GTOPO30 global height model of the USGS to remove the topographic phase [22], or the GLOBE DEMs [18]. Although the resolution of this DEM is rather limited, in the near future the SRTM DEMs should become available for (almost) the whole earth [28].

A shell script has been written that generates template configuration files and can be used to run Doris. For each step, the output can be automatically visualized by generating SUNraster quicklook files of the intermediate products. There also is a quicklook processing option build in the shell script that performs an automated processing to quickly obtain a lower quality interferogram and coherence image. The speed-up comes from skipping filtering steps, using large multilooking factors, and using simple interpolation kernels. People not used to the UNIX environment can have a disadvantage running the Doris software at start (and the other described public domain software). But the concept of using ASCII input files and a pipeline of programs instead of a graphical user interface (GUI) is quite powerful, and with the provided documentation and examples it is easy to apply.

2.2 Reading the ASAR parameters

Doris was originally written to handle ERS SLC data. Adding an option to Doris to be able to process data from a new satellite mainly means adding the ability to read a new data format, since the other modules are not affected. For example, for ENVISAT, the data is no longer distributed in the CEOS format, as was used for the ERS and JERS satellites. Nevertheless, the main processing steps to create the interferogram are hardly affected, as long as the data and the parameters can be read from the CD-ROM in the distributed format. The number of parameters required for interferometry is small, but they still need to be read from the distributed data formats. For this purpose, ESA has made the Basic ERS & Envisat (A)ATSR and Meris Toolbox (BEAM) freely available, see [14], making the task of adapting the software a lot simpler. With the library functions in this toolbox, a simple stand-alone program reads all available information from the ASAR SLC distributed file, and dumps it to a temporary ASCII file. Simple UNIX commands are then used to extract the parameters that are required, and to write them to the Doris parameter file in the correct format and units. The reading, extracting and converting the parameters only takes a few seconds of CPU time.

Details on the processed scenes can be found in tables 1 and 2. The temporal baseline is only 35 days, resulting in minimal temporal decorrelation for this dry area. The interferometric amplitude of the scene is shown in Fig. 2 (top left). The city of Las Vegas is located at the bottom of this image, whereas the top part consists of mountains. The maximum topographic difference in the scene is about 3000 meter, see also Fig. 4.

2.3 Cropping (ASAR) data to hard disk

Using the ESA BEAM toolbox, we implemented a program that is able to read the data in the distributed format, and writes an area of interest to hard disk. This program is included in the Doris distribution. We read and write the data per line to keep the implementation simple and memory requirements low. In Doris a system call is made to this stand-alone

Table 1: Image parameters for the processed master and slave ASAR SLC. These parameters are read from the ENVISAT data file using a small program written with the freely available ESA BEAM library.

Image parameter	**Master**	**Slave**
Frame number	12	11
Orbit number	4418	3917
Acquisition date	03-JAN-2003	29-NOV-2002
Acquisition time [UTC]	17:52	17:52
Number of lines	26894	26894
Number of range pixels	5195	5195
Doppler centroid frequency [Hz]	230	185

Table 2: Product parameters for the interferogram. Most of these parameters have been computed by Doris.

Product parameter	**value**
Scene identification	Las Vegas
Scene size [km^2]	100×100
Scene center longitude [deg]	-115.007
Scene center latitude [deg]	36.4614
Perpendicular baseline [m]	100.9
Parallel baseline [m]	-14.7
Height ambiguity [m]	81.4
Temporal baseline [d]	-35

program. The only requirement for this to work is that the executable program is in the search path. The (wall clock) time required by this program was about 7 minutes for a full scene (650 MB of complex short integer data, including byte swapping), performed for the master and slave image.

2.4 Coregistration

Maybe the most important step in interferometry is the alignment of the slave on the master image . The determination of the coregistration polynomial that describes the transformation of the slave to the master is performed in 4 steps in Doris.

First the orbital data of master and slave are used to compute a single coarse offset on pixel level between master and slave image. The estimate for this offset is then improved using a cross correlation performed on the intensity data of master and slave on a small number of relatively large patches. The initial offset is taken from the previous computed coarse offset based on the orbits. In the third step, the fine coregistration, the offset vectors between master and slave are computed at a large number of small patches (64 by 64 pixels), also using a cross correlation of the intensity data. Fig. 1 shows the computed offset vectors at these patches, which project the slave image on top of the master. Only vectors are plotted that have a correlation larger than 0.4. Above the image, an overview of the estimated offsets is given in a table. GMT is used to plot these data. This plot is generated by Doris, while optionally the magnitude of the master image can be used as background.

Finally, when we have obtained these offsets at a number of positions in the image, a threshold is chosen to select patches that contain useful information, and a 2D-polynomial of degree 2 (by default) is fitted through these offset vectors. A least squares fit weighted by the coherence is used. In general, not all selected offset vectors fit well within the model. We use a manual or automated iterative process to improve the estimation of the transformation polynomial. Each time after a polynomial is fitted, we can detect outliers and exclude them from a next polynomial fit. This gives a large control to the user, who can check the coregistration in a detailed manner. Plots of the least squares residuals (2D vector plot, histograms and an xy-plot) are also generated automatically by Doris. The maximum least squares residual was about 0.2 pixels for this dataset and selected offset vectors (computed offset versus model). Using the estimated polynomial, the slave image is resampled to the master grid. We account for the Doppler centroid frequency of the slave image, and can use several interpolation kernels, ranging from nearest neighbor to cubic convolution, to a 16 point truncated sinc. Default we use a 6 point cubic convolution kernel, see [4]. The actual resampling is by far the most time-consuming procedure, about 24 minutes of CPU time in this case. The output format was chosen to be 4 byte float values, making the size of the data file about 1.3 GB.

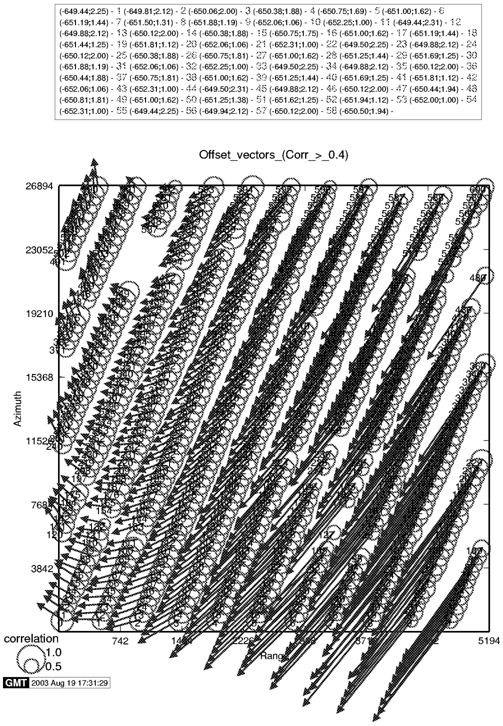

Figure 1: Offset vectors between master and slave image computed with Doris and plotted with the GMT. This is standard output during the coregistration with Doris.

2.5 Spectral filtering

Spectral filtering in range and azimuth can optionally be applied to increase the signal to noise ratio. For the azimuth filter the non-overlapping spectrum is removed based on the given Doppler centroid frequencies (read from the annotation of the SLC data, see section 2.2). The range filtering can either be performed based on the orbital data (thus disregarding local terrain slopes due to topography), or the non-overlapping spectrum can be locally estimated after resampling of the slave image. For this demonstration we did not apply any spectral filtering, mainly because we expected only a very small amount of decorellation due to the small perpendicular (and temporal) baseline, and the small difference in Doppler centroid frequencies (table 1).

2.6 Interferogram generation

The interferogram is computed using a multilook factor of 5 in azimuth and 1 in range. It is simply the dot product of the master and complex conjugated slave, i.e., it contains the product of the amplitudes and the difference of the phases of master and (aligned) slave. The phase difference contains information on topography, possible deformation, and possibly atmosphere.The interferogram generation took less than 2 minutes.

The interferometric phase is corrected for the phase of a reference body. In this case the WGS84 ellipsoid was used to compute the reference phase, but an external DEM can also be used as input in Doris. This DEM could be in a variety of input formats, but it must be on a regular grid in the WGS84 datum. The reference phase corrected interferogram is multilooked again, now by a factor of 4 in both directions. The pixel size of the product is thus about 80 by 80 meters. The multilooking reduces the size of the data files considerably, and also reduces memory requirements for the unwrapping. Fig. 2 shows the quicklook output of Doris for the corrected phase.

Doris can also compute the coherence image, that can be used as input for the cost function computations in the unwrapping program. Phase filtering can be applied using different methods. We normally use a simple pre-defined spatial averaging kernel, but optionally 2D convolution kernels can be read from ASCII input files, or the Goldstein filter can be used [3], [1]. In this case we did not perform phase filtering because of the already high coherence of these data.

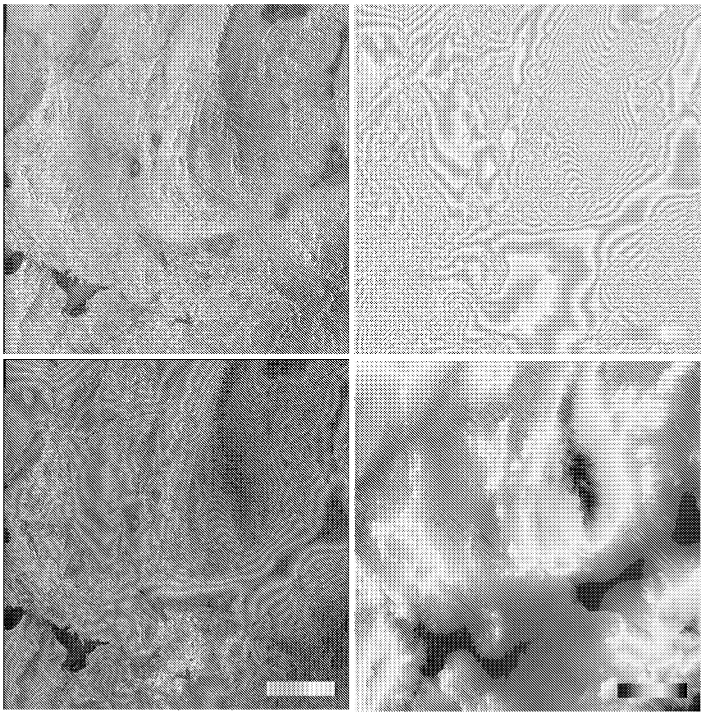

Figure 2: Overview of interferometric processing with Doris. The interferometric amplitude and phase are shown (top panels), as well as their overlay (bottom left). The phase is corrected for the reference phase of the WGS84 ellipsoid. The unwrapped phase is shown in the bottom right panel. These images are automatically generated by Doris. Original data are copyright of ESA.

2.7 Phase unwrapping with SNAPHU

The SNAPHU phase unwrapping software is described in [2]. It stands for Statistical-Cost, Network-Flow Algorithm for Phase Unwrapping. It is a modern, sophisticated phase unwrapping program that uses information on the expected smoothness of the unwrapped phase, and can use the interferometric amplitude and/or coherence image to compute the cost functions. It is called fully automatically from within Doris when it is installed on the system. The RAM useage of SNAPHU cannot be controlled by Doris, except by using larger multilooking factors, thus reducing the dimensions of the interferogram. SNAPHU can be found at the internet pages of the Stanford university, [27]. Fig. 2 shows the unwrapped phase in the bottom right. SNAPHU took 7 minutes of wall clock time to unwrap the interferogram of size 1297×1310 pixels.

2.8 Phase to height conversion and geo-referencing

The unwrapped phase is converted to a height, and the (azimuth, range) coordinates are geo-referenced. The algorithm described in [9] was used for the phase to height conversion, and took about 5 seconds. Two other implementations can also be used to perform this step. The geo-referencing took about 1 minute, and was done by constraining each pixel to the previously computed height, to be perpendicular to the master orbit, and to be at the range given by its range coordinate.

The output of this step is the height for a large number of pixels at an irregular grid of (longitude, latitude) pairs, which in itself is not that useful. These output matrices however are gridded using the GMT tools, while with PROJ.4 we can perform coordinate transformations to obtain the DEM in the desired gridding and coordinate system. Alternatively, GRASS can perform the gridding. Note that also other images, such as the coherence image, are thus automatically geo-referenced in this way.

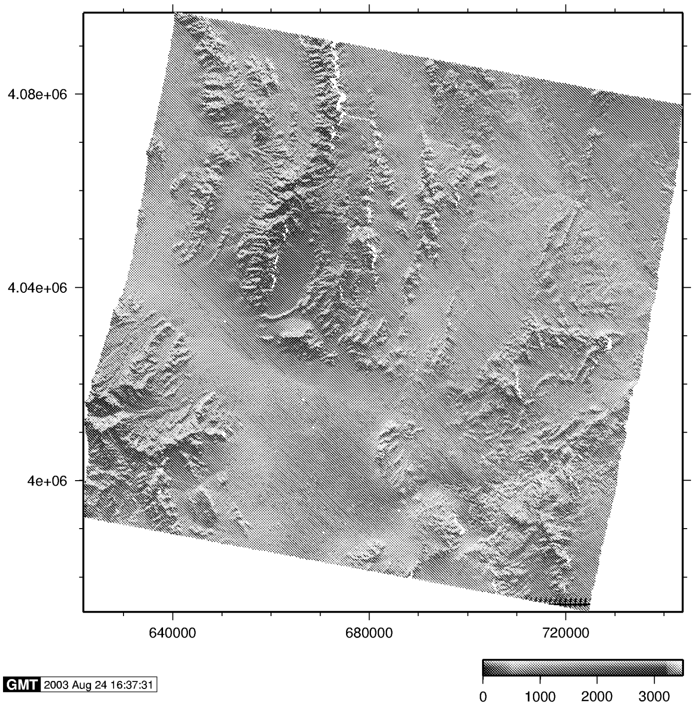

Figure 3: DEM (shaded relief) of the Las Vegas area computed with Doris and other public domain tools. The data gaps in high-relief areas are caused by shadow.

3 COORDINATE TRANSFORMATIONS AND GRIDDING

The PROJ.4 package [26] is a "Cartographic Projections library" that can perform respective forward and inverse transformation of cartographic data to or from Cartesian data with a wide range of selectable projection functions, including datum translations. It has been originally written by Gerald Evenden then of the USGS. It is well documented and can be used to transform the geo-referenced output of Doris to any desired projection, such as UTM. An example script for these transformations is included in the Doris distribution.

The GMT software is a set of tools to handle {x,y,z} data, implemented as UNIX filters. Each program performs a specific task, such as creating a vector plot, or to perform gridding. The output of each program is either a processed data file or a postscript plot. The concept of applying programs on output of previous programs makes the GMT extremely flexible, particularly in combination with standard UNIX commands. GMT is extremely well documented, with a "Technical Reference and Cookbook", the "GMT Tutorial", and the "GMT UNIX man pages", which are all available online. GMT is free software, released under the GNU General Public License. See also [19] and [10]. The GMT software can be used to create postscript plots of the output of Doris, but also for data interpolation and gridding. Scripts for gridding are included with Doris, but the GMT can be used for an endless variety of analysis purposes.

An example of the final output of Doris is given in Fig. 3, where the DEM is gridded in UTM coordinates. For comparison we plot the computed DEM next to a high precision reference DEM obtained with SRTM, see Fig. 4. The difference between both DEMs appears to be small on visual inspection, showing at least that no significant errors occurred during the processing with Doris.

4 GRASS GIS DATA ANALYSIS

The Geographic Resources Analysis Support System (GRASS) [21]) can be used after geo-referencing of the end product. In this way, the computed DEM or deformation map is a layer in a geographic information system, and can be combined with other layers, such as ground-truth data. GRASS is an open source, Free Software Geographical Information System

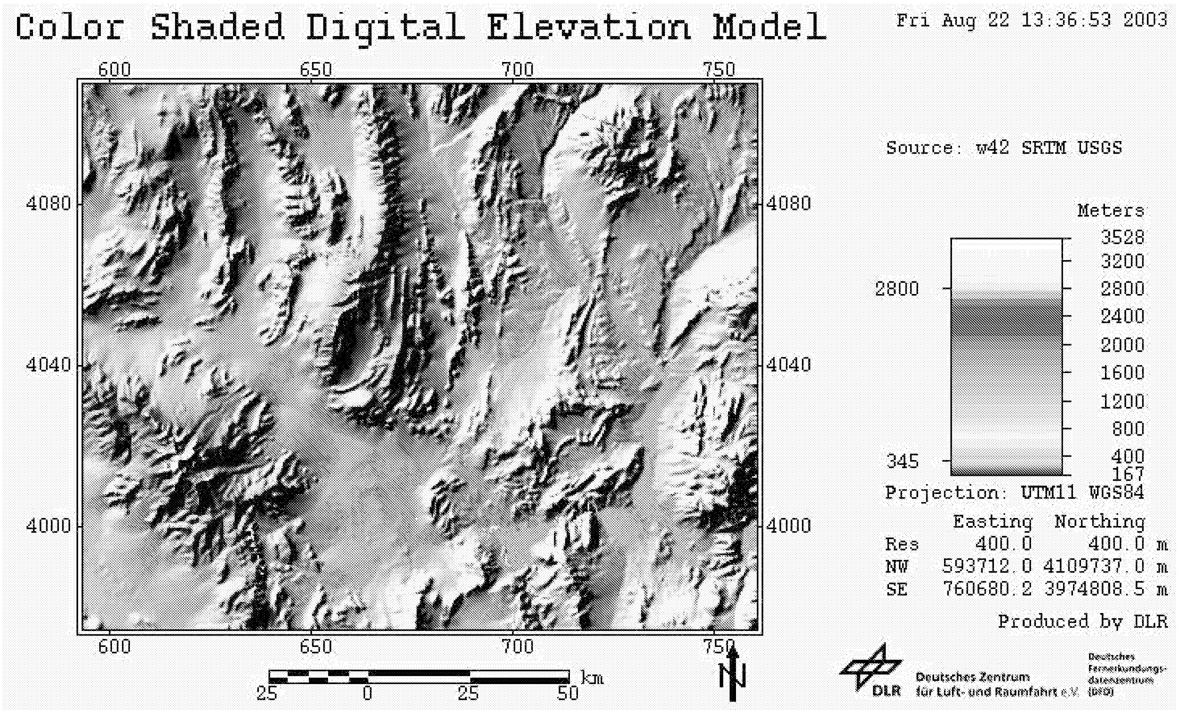

Figure 4: High quality USGS DEM. Original horizontal resolution is 25 meter. This figure was created using the shade_dem program of the German Space Agency (not in the public domain).

(GIS) with raster, topological vector, image processing, and graphics production functionality that operates on various platforms through a graphical user interface and shell in X-Windows. GRASS is released under the GNU General Public License (GPL).

GRASS offers a set of tools for DEM or deformation map analysis like calculations of surface parameters (e.g., slope, aspect, and curvature), and allows to perform more detailed analysis like flowliles and their densities, watershed calculation, and flow tracing. The latest version of GRASS includes *nviz*, a module for viewing data surfaces in three dimensions with the ability to visualize multiple raster, vector, and site files at one time, with the addition of volume data. GRASS, like other GIS systems, has the ability to perform spatial analysis of data from different sources and stored in different formats. GRASS can read a wide variety of data formats since the import function is supported by the gdal library [16].

For this work, a GRASS installation on a Linux-PC was used (2GHz processor, 512MB RAM). The {x,y,z} topographic data from Doris was first converted to ASCII vectors using *cpxfiddle*, a generic utility distributed with Doris. This data was imported in GRASS, and then interpolated to a regular grid using spline with tension function [7]. After interpolation, selected functionals of the surface parameters were calculated, specifically slope, aspect, flowlines and their density. Additionaly, for data analysis and visualization purposes, the Landsat data were imported. We used the Landsat geocoded composition archive from 1990 which is freely available for the largest part of the world, see [25]. The data are stored in compressed MrSid format. The freely available decoder from Lizard Tech [24] has been used for extraction of the data for our area of interest, and saved in GeoTiff format. Landsat data were applied for 3D visualization of the interferometric DEM. Fig. 5 and Fig. 6 show examples of the GRASS capabilities.

5 CONCLUSIONS

Radar interferometry using freely available software has matured to a stage in which data from different sensors can be routinely processed to interferometric products. It is demonstrated that Doris is capable of handling the data format of ERS and ENVISAT ASAR. Together with other public domain tools—for phase unwrapping, coordinate transformation and data gridding—a DEM in UTM coordinates has been computed for the Las Vegas area. The flexibility of the software was shown by performing the computations on a 900 MHz laptop with approximately 100 MB of available RAM, running on a MS Windows operating system. The total processing time was approximately 1 hour.

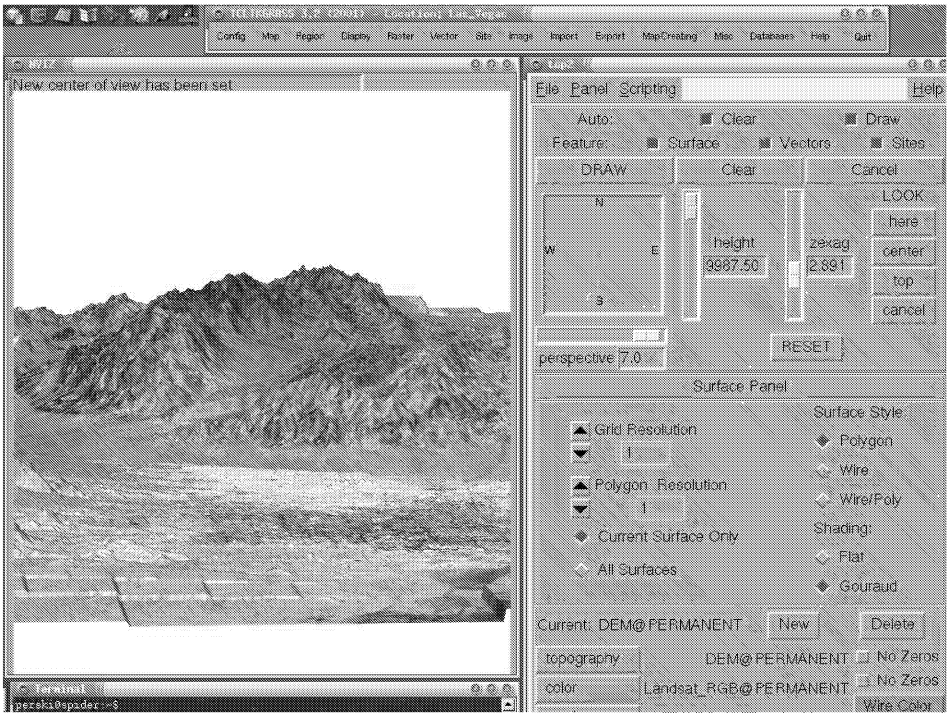

Figure 5: Screenshot of GRASS. A watershed analysis is made from the output of Doris. For visualization, a LandSAT image has been draped over the computed DEM.

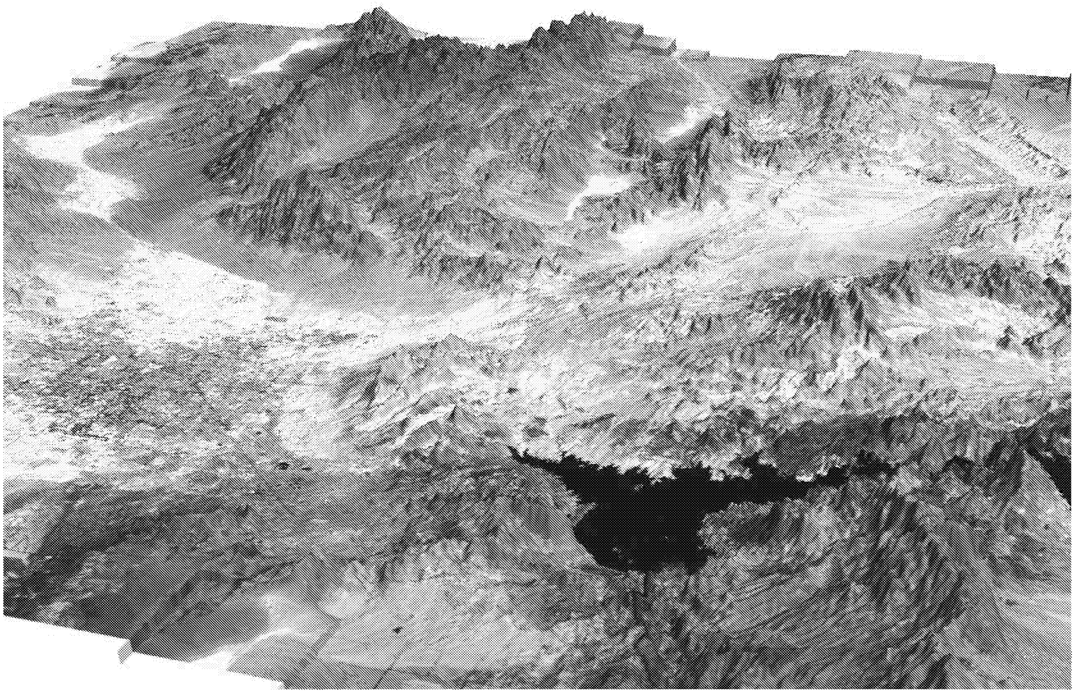

Figure 6: Perspective view of the Las Vegas area created with GRASS (nviz program) based on interferometrically derived heights and a LandSAT image.

A large scientific user community can take advantage of the developed software, and from the other described tools, which allows them to perform their research with ENVISAT data in a convenient manner.

Not included in the described software is the SAR processing, i.e., the focussing of the raw radar data to SLC images (which is the input to the Doris software). This may be overcome by the recent release of the JPL ROI_PAC software in the public domain [23] (at least for ERS). Also lacking is a generic multi-platform tool for interactive visualization of interferometric products. Here we may also benefit of the released DGX software [23].

Furthermore, it has not yet been investigated what the distribution format is for the SRTM DEMs, nor how to interface conveniently with this huge data set for topographic phase correction (or to use it to aid unwrapping, compute terrain corrected coherence, geo-reference deformation maps, etc.). For this step (reference phase computation using a DEM), the current algorithm is not very efficiently programmed, and the computations take a long time. It is also limited to the usage of DEMs in the WGS84 datum, in a regular grid, while most people may have a high accuracy DEM of their area of interest in some local datum. The PROJ.4 software in combination with the GMT can be used to circumvent this problem, but a standard solution is not provided by the Doris software.

A possible drawback of including several public domain package to perform different tasks may be different philosophies of different authors. For example, it is not possible to control memory usage of the SNAPHU software from within Doris. In general however, most users nowadays will have a powerful computer available.

Further improvements to the described software that are considered are an interface to RadarSAT data format, and module to enable the subtraction of an available reference deformation model.

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