Direct Geocoding for Generation of Precise Wide-Area Elevation Models with ERS SAR Data

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ABSTRACT: An improved technique for generation of Digital Elevation Models (DEM), capable of dealing with full scene images (100x100 km) coming from an interferogram obtained with ERS satellite data is presented. Starting from an interferometric processor aimed to the geocoding of smaller areas, now we show the new improvements based on the use of a direct geocoding algorithm and Ground Control Points (GCP), in order to calibrate some imprecisions which appear in the case of very wide swaths. The direct geocoding algorithm is based on the transformation of phases directly into heights over a UTM grid, without an intermediate transformation of phases into heights in slant range. This technique provides more accurate results. A generated DEM of the test zone of *Tarragona* (Spain) and its error assessment are presented.

Introduction

A critical step in the interferometric process [3] is the transformation of unwrapped phases into geocoded heights. Several imprecisions in orbit generation, timing knowledge and geocoding can lead to significant height errors when we are working with wide areas. It is easy to observe false height slopes along the image during the process due to this imprecisions [1]. On the other hand, if we work with small areas these errors are more difficult to observe because their propagation is not so critical. Our goal in this paper is to present some techniques developed by our research group to obtain high quality DEM's (Digital Elevation Map) of small or wide images.

The first step is to calculate in a precise way the satellite position for each range line in the image. The orbits files of D-PAF provide state vectors spaced 30 seconds. This is equal to 225 km of distance between each known orbital point. Therefore, it is necessary to interpolate the data from the two nearest ephemerides [2][4]. The problem is that with this interpolation we achieve a precision of about 15 cm in radial direction, and it is not enough to avoid systematic errors due to the lack of precision in baseline. Thus, we apply additional information coming from a GCP in order to calibrate the interpolated orbits.

The geocoding process can be carried out when precise orbit information and the unwrapped interferogram are available. But this step may generate systematic errors as well, and must be studied carefully. After completing phases into heights conversion, some phase errors can be observed when geocoding wide areas, which lead to height slopes in range and azimuth directions. They appear basically as a result of the atmospheric propagation and the wrong baseline calculation, even using calibrated orbits. In order to solve this problem, we propose the use of GCP's to measure these slopes, and thus, to remove them. We have developed a direct algorithm that improves the preceding one, which consisted of flat earth removing, phase to height conversion, and ground range projection [1]. This new procedure generates the geocoded map transforming directly phases into heights over a cartographic grid, without carrying out the approximation done in phase to height conversion.

Finally, we have checked this methodology by geocoding a full ERS tandem scene of *Tarragona* (Spain), and assessing its error with the help of a high accuracy DEM.

Orbit Generation

To obtain an accurate DEM we need the highest quality orbit product. This product is based on an intensive post processing of measured data using advanced orbit propagators. The achieved accuracy is 15 cm in the radial direction. We have to purchase it independently from the SLC images since its generation is independent of the raw data processing.

The orbit information used in this work has been the D-PAF orbit product. The state vectors are spaced 30 seconds, and considering an approximated 7500 m/s speed for the ERS satellites, this means that we know the satellite position every 225 km. The area covered by a SLC frame is about 100 km on ground in the azimuth direction, so if we want to know the satellite position for every range line, we will have to interpolate this information [2][4]. The use of a third degree polynomial was shown to be precise enough.

The next step is the orbit registration in the azimuth direction. To obtain the interferogram, the two images are registered carefully in order to be coincident. In a similar way, we have to compute precisely which pair of orbit positions corresponds to every range line. This registration is made with a Zero Doppler Algorithm. The process starts with the first orbit satellite position, using direct geocoding and a given point of the image, the algorithm calculates its ground position. For this purpose we have used an ellipsoid as an Earth model (the topography is not taken into account). Once we have the ground location, using indirect geocoding (obtaining satellite position from pixel coordinates) the algorithm calculates the azimuth position in the second orbit. Then, we assure that the two orbit positions are imaging the same ground point with zero Doppler geometry. Finally, the algorithm cuts out the orbits to obtain only the satellite positions that cover the imaged area. After these steps, we have obtained the baseline for each image line in azimuth.

The delays in range and azimuth included in SLC header are not precise enough to obtain accurate registered orbits. Thus, in order to know this delays accurately we need to use a GCP identified over a map and the amplitude master image. The following options are available:

- A reference DEM.

- A topographic map where unambiguous features can be located (large infrastructures, crossing roads, rivers, bridges, etc).

- Knowledge of some heights of natural targets.

The complete orbit generation process is described in figure 1. Doing an inverse geocoding of this GCP we can obtain the delay errors and therefore the new corrected delays. After that, the orbits are calculated in a much more precise way.

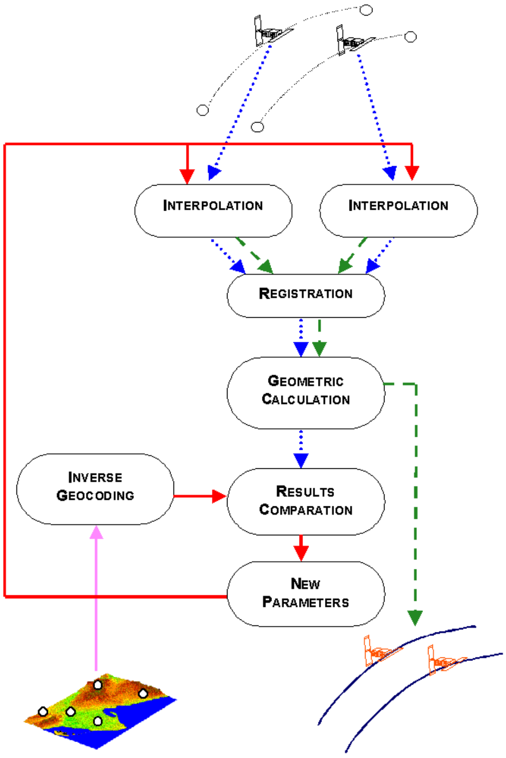

Figure 1. Orbit generation layout

Direct geocoding

Once we have obtained precise orbits, the transformation of unwrapped phases into geocoded heights must be done. The geocoding process can be carried out with three fundamental steps [5]:

- Flat Earth removing
- Phase to height conversion
- Ground range projection

The first step requires the generation of precise flat earth term. This is not easy and therefore additional errors are introduced in the final phase without flat earth term. It is critical to obtain only the topographic term because in the next step we have to transform phase into height in slant range, and non-topographic terms will introduce height errors. It is important to note that a high order approximation is done when converting phase to height. This approximation can be another source of errors. The expression of phase to height transformation is [4]:

$$\Delta h = k_1 + k_2 \cdot \Delta\varphi + k_3 \cdot (\Delta\varphi)^2 + \ldots + k_n \cdot (\Delta\varphi)^n$$

where Δh is the height increment, $\Delta\varphi$ is the phase increment in the interferogram, and k_n are the coefficients of the approximation.

Finally, the third step is oriented to the conversion of height information from slant range coordinates to a standard cartographic reference system. The standard equations to carry out the transformation from slant range to ground range coordinates are [4]:

$$|S - P|^2 = (S_x - P_x)^2 + (S_y - P_y)^2 + (S_z - P_z)^2 = R^2$$

$$f_D = \frac{2}{\lambda} \cdot \frac{(v_s - v_p) \cdot (P - S)}{|P - S|}$$

$$\frac{P_x^2}{(a+h)^2} + \frac{P_y^2}{(a+h)^2} + \frac{P_z^2}{(b+h)^2} = 1$$

where S is the position vector of the master orbit, P is the position vector of the unknown point, R is the range distance from master orbit to the point, f_D is Doppler frequency which is considered zero, λ is the wavelength, v_s and v_p are the velocities of the satellite and the unknown point (considered equal to zero), a and b are the ellipsoid semiaxis, and finally, h is the height of the point.

In this paper we propose a direct geocoding algorithm. The main difference with the previous one is that the algorithm is reduced to only one step, a direct transformation of phase into geocoded heights. This new algorithm achieves better results because it does not need flat earth removing and phase to height conversion. Therefore, we can avoid the imprecisions of this two separate steps. Note that the input of this algorithm is the complete phase (topography and flat earth). The direct geocoding is based on the next non-linear system:

$$|S_1 - P|^2 = (S_{x1} - P_x)^2 + (S_{y1} - P_y)^2 + (S_{z1} - P_z)^2 = R^2$$

$$|S_2 - P|^2 = (S_{x2} - P_x)^2 + (S_{y2} - P_y)^2 + (S_{z2} - P_z)^2 = \left(R + \frac{\lambda\phi}{4\pi}\right)^2$$

$$f_D = \frac{2}{\lambda} \cdot \frac{(v_s - v_p) \cdot (P - S)}{|P - S|}$$

where S_1 and S_2 are the positions vectors of orbits 1 (master) and 2 (slave), and ϕ is the complete interferometric phase. As we can see, beginning with the interferometric phase, the orbits, and the geometric parameters and solving the previous system, the geocoded position of the unknown point is obtained. To solve this system the Newton-Raphson method has been selected, because it implies a fast convergence in few iterations.

Before applying direct geocoding, a correction of the interferogram is done because of imprecisions in baseline and atmospheric propagation. This correction is done using several GCP's spread over the scene. Applying indirect geocoding, range and azimuth coordinates of this points are known. Finally, the interferometric phase of each GCP can be calculated with:

$$\phi_{GCP} = \frac{4\pi}{\lambda} \cdot (R_2 - R_1)$$

where R_1 and R_2 are the distances from GCP to orbits 1 (master) and 2 (slave). Once we have the theoretical phase of each GCP, the algorithm generates the best phase slope which minimizes the errors. Finally, direct geocoding method and transformation onto a standard cartographic reference system (like UTM) is applied to the corrected phase to obtain the final geocoded height map. Figure 2 shows a block diagram of this process.

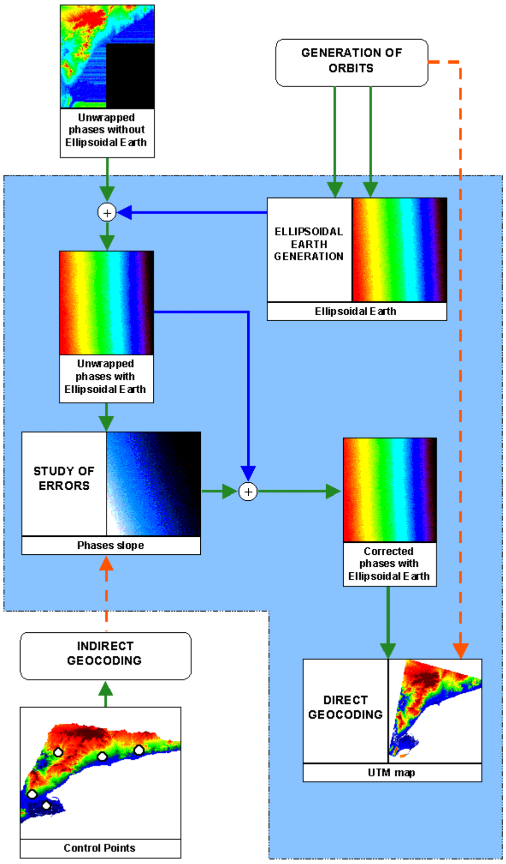

Figure 2. Direct geocoding layout

Results with ERS data

We have applied the previous direct geocoding process starting from an unwrapped interferogram of the area of *Tarragona* (Spain). This interferogram was generated with ERS-1 and ERS-2 data with a 100 m baseline. This is a very interesting zone of study, because it is quite heterogeneous, with coastline, the *Ebro* river, and a wide range of topographic features from the flat area in *Delta del Ebro* to the mountains in the inland up to 1200 m. Figure 3 shows a SAR image of the area.

The unwrapped interferogram expressed in phase cycles is shown in figure 4.

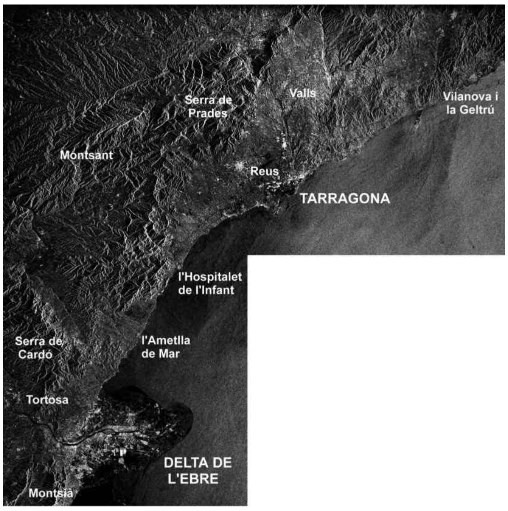

Figure 3. SAR image of the studied area

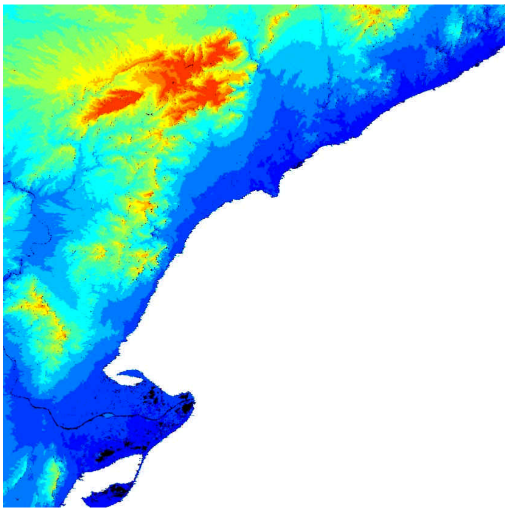
Figure 4. Unwrapped phase cycles

Phase to height conversion has been performed using 14 control points spread over the image. Finally, the map has been geocoded to a UTM grid with a 30 m spacing. Figure 5 shows the final geocoded map.

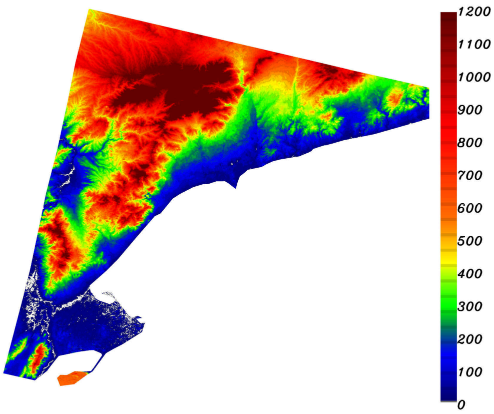

Figure 5. Final geocoded DEM

Error assessment

To validate the results obtained in the previous section, an error study must be done. For this study we have used a DEM with 2 m rms vertical accuracy and 30 m horizontal grid spacing provided by the *Institut Cartogràfic de Catalunya* (ICC). We have obtained a precise error map by Comparing this reference DEM with that obtained with the geocoding process.

To perform a detailed study, we have selected three different areas inside the whole image. These areas are *Ametlla de Mar*, *Serra de Montsià* and *Serra de Cardó*, and they are shown at figure 3. Furthermore, a complete error map of the whole zone has been generated and compared with that obtained with the previous geocoding algorithm based on flat earth removing, phase to height conversion, and ground range projection. Figure 6 shows this results. The map on the left corresponds to the previous algorithm and the one on the right is obtained with direct geocoding. As we can observe, the new error map has less red and green zones, and this means that errors have been reduced with respect to the previous geocoding algorithm. The new average error is 8 m and the standard deviation is 47 m.

Studying carefully the three small areas, we can obtain several differences between them:

- *Ametlla de Mar*: It is not a rough zone, and the results obtained are very good. At this site, the average error is 8 m and the standard deviation is 15 m. Figure 7 shows this absolute error map.

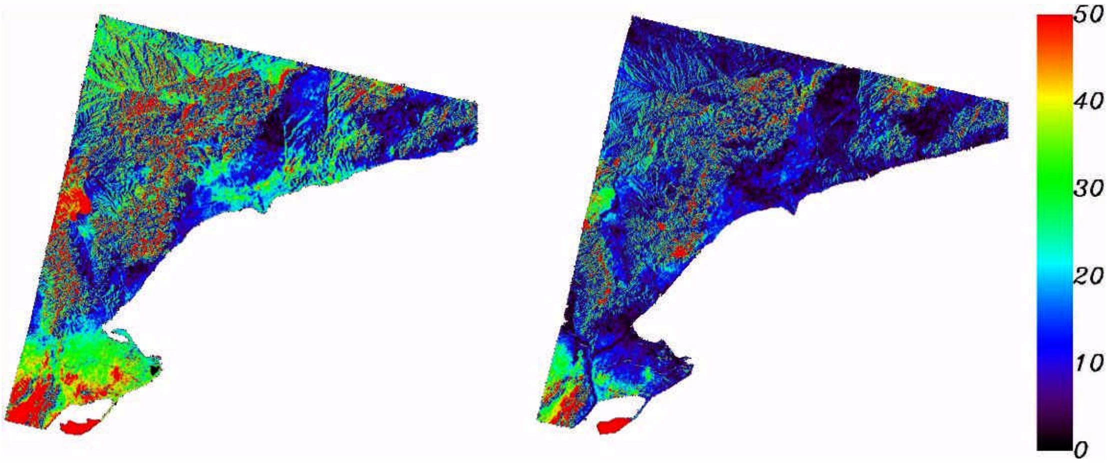

Figure 6. Comparison between error maps. Left-previous map, Right-new map

- *Serra de Montsià*: It is a rough area more complicated than *Ametlla de Mar*. The topography rises up to 700 m. The average error is 33 m and the standard deviation is 57 m. This bad results are mainly due to atmospheric artifacts and unwrapping errors. The error map is shown in figure 8.

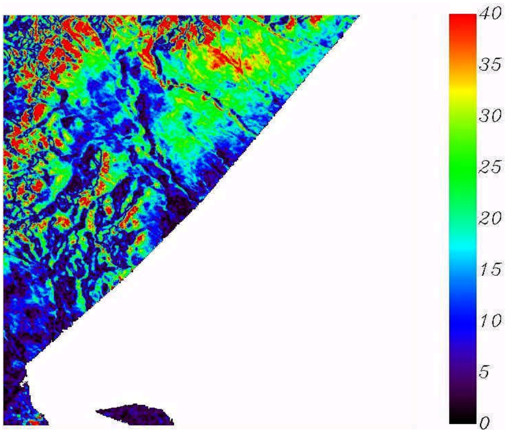

Figure 7. Error map at Ametlla de Mar

- *Serra de Cardó*: It is a very rough area with heights beyond 900 m. The average error is 2 m and the standard deviation is 46 m. In this case the errors are mainly associated to topography. Figure 9 shows this results.

Conclusions

Once a quality unwrapped interferogram is generated, the geocoding process is critical to obtain a good final geocoded DEM. Orbit precisions of centimetres and time accuracies of nanoseconds are required. The use of GCP's allows the generation of precise orbits and the refinement of range and azimuth delays. We have shown that the precision of the geocoding algorithm itself is very important.

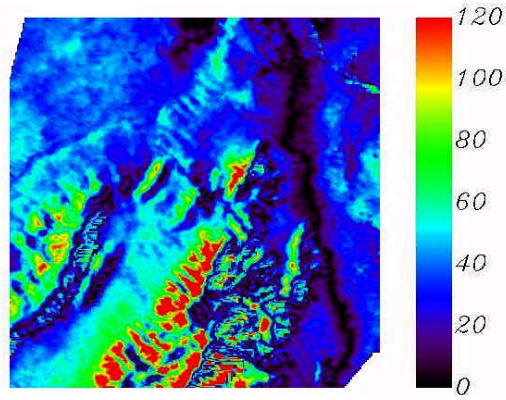

Figure 8. Error map at Serra de Montsià

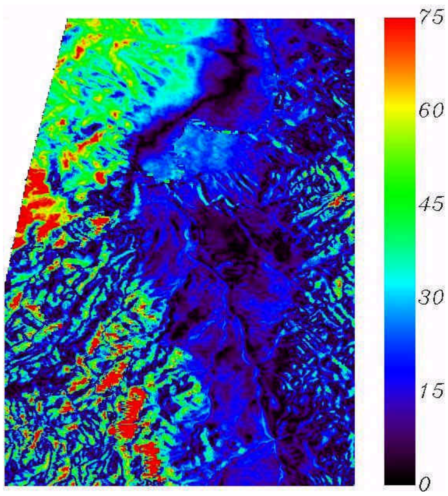

Figure 9. Error map at Serra de Cardó

In this paper we have presented a complete geocoding process including use of GCP's and direct geocoding. An improvement compared with the algorithm based on phase-slant range-ground range transformation has been observed according to the error assessment. An additional study of three different small zones has been done. This improvement is possible because direct geocoding does not need to perform a flat earth extraction neither an intermediate transformation of phases into heights in slant range. Therefore, we have less error sources along the process. Actually, it is possible to affirm that the geocoding step itself does not introduce any approximation, thus, the remaining height errors can be attributed to the level of quality of the unwrapped phase and baseline knowledge (input information).

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