# POTENTIAL OF ERS-1 DERIVED ORTHOMETRIC HEIGHTS TO GENERATE GROUND CONTROL POINTS FOR ABSOLUTE ORIENTATION OF IMAGERY AND DEM QUALITY EVALUATION

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**ABSTRACT:**

Though the ERS satellites are today out of service, the huge quantity of altimetric data collected during the so-called "geodetic missions" covers the globe with sufficient density for many mapping projects. This paper first describes the general principle of ERS altimetric measurement . Then, the paper shows the method adopted to take advantage of ERS high-energy measurements (specular), which come usually from water bodies (rivers, lakes,…). ERS heights are processed along with a middle-scale vector data base, through a software which attempts to associate specular measurements with a cartographic item. As a result, we get a list of exact altitudes, applying to water bodies easily visible on SPOT imagery. In the next section, the research and production works to extract very accurate altitude values over flat areas (10 km wide) are detailed. The method to select the relevant ERS measurements is explained. The validation stage, using test sites distributed all over the world, showed a 2 to 5m height accuracy, adequate enough to control a global height database, and as a valuable input into image block-adjustment process . Finally, this paper will focus on the quantitative evaluation of ERS altimeter accuracy relatively to terrain height and slope variations within the whole impact area of the altimeter radio pulse contributing to the return signal ; we show that, after correcting several systematic errors through an original simulation method, developed by GRGS, absolute vertical accuracy better than 10 meters is kept available with ERS altimeter data in moderately rough terrain areas without any ground geodetic infrastructure.

**RESUME :**

Bien que les satellites ERS ne soient plus aujourd'hui en service, l'énorme quantité de données altimétriques collectées durant la mission géodésique couvre le globe avec une densité suffisante pour de nombreuses applications cartographiques. Cet article décrit d'abord le principe général de la mesure altimétrique radar avec les données ERS disponibles. Dans le paragraphe suivant, l'article décrit la méthode adoptée pour tirer parti des mesures ERS d'énergie élevée (spéculaires), provenant généralement des zones d'eau libre (fleuves, lacs …). Les hauteurs ERS sont combinées à une base de données d'échelle moyenne, à l'aide d'un algorithme qui a pour but d'associer les mesures spéculaires avec des éléments cartographiés. On en déduit une liste d'altitudes exactes, pour des zones d'eau facilement détectables sur des images SPOT. Sont ensuite détaillés les travaux de recherche et de production qui ont conduit à l'extraction d'altitudes très précises sur des zones plates (s'étendant sur 10 km). On explique la méthode mise en œuvre pour sélectionner les mesures ERS adéquates. La phase de validation, utilisant des sites de test répartis dans le monde entier, a démontré une précision altimétrique de 2 à 5 m, satisfaisante pour contrôler une base mondiale de données altimétriques, et pour être utilisée dans la compensation de blocs d'images. Enfin, cet article se concentre sur l'évaluation quantitative de la précison de l'altimètre ERS en fonction des variations d'altitude et de pente à l'intérieur de l'ensemble de la zone impactée par l'impulsion radar contribuant au signal renvoyé : on montre que, après correction de différentes erreurs systématiques à l'aide d'une méthode originale de simulation, développée par le GRGS, une précision verticale absolue meilleure que 10 mètres est obtenue avec les données altimétriques ERS dans des zones de relief modéré sans aucune infrastructure géodésique.

## 1. INTRODUCTION

The huge quantity of altimetric data collected by ERS satellite during its geodetic missions in 1994 and 1995 can provide under certain conditions ground altitudes with enough accuracy to be used in quality control of global height database and as elevation control points in the block-adjustment of space imagery. This is particularly interesting when to avoid costly ground operations in some areas difficult to access and when the mapping project covers very large areas like whole continents.

After presenting the general principles of ERS altimeter measurement and the available ERS altimetric data we will describe the specific operational methods developed and validated to extract elevation data in flat areas and on water bodies which both give ideal conditions for accurate measurement. But, these ideal conditions are met only for a small minority of the total data, that is why we have concentrated our work on the feasibility of extending the exploitation of ERS altimeter data on moderately rough terrain.

So, we will report the results of a quantitative evaluation of ERS altimeter accuracy relatively to terrain height and slope variations within the whole impact area of the altimeter pulse contributing to the return signal used for the height measurement; the purpose of this evaluation is to empirically predict the accuracy of ERS altimetric data from terrain and ERS signal fluctuations, not only in completely flat areas but also in moderately rough terrain after correcting some systematic errors ; such predicted accuracy will determine whether ERS altimeter data can contribute to the ground control strategy according to the required accuracy specifications of the mapping project (orthoimage, densified DTM …).

## 2. PRINCIPLES OF RADAR ALTIMETRY

### 2.1 General principles

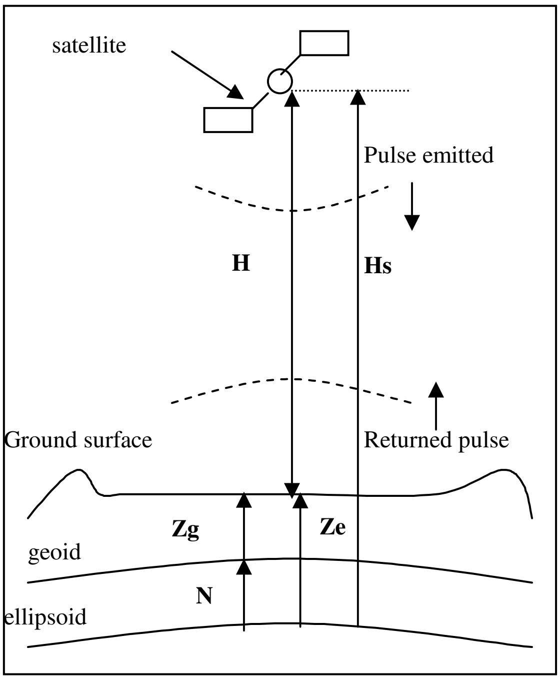


Figure 1. General principle of radar altimetry

The ERS radar altimeter measurement consists in measuring the distance **H** between the satellite and the near nadir reflecting ground surface (see figure 1.). This distance is derived from the travel time of a radar pulse emitted by the satellite and returned back after reflection on the ground surface. If **T** is the time between emission and reception of the pulse and **C** the propagation speed of the pulse, we get **H** by :

$$H = (C * T) / 2$$

The satellite height **Hs** above WGS84 ellipsoid is known with sub-decimeter accuracy through DORIS and GPS positioning systems. The ground altitude **Ze** referred to WGS84 ellipsoid is then computed from :

$$Ze = Hs - H$$

The ground altitude **Zg** refered to local geoid (equivalent to mean sea level) is finally computed, taking in account the height shift **N** between WGS84 ellipsoid and local geoid (the value of **N** is known from the latest global geoid model with an accuracy better than one meter) :

$$Zg = Ze - N$$

### 2.2 Waveform

The satellite altimeter emits spherical radar pulses towards nadir within a narrow cone at the rate of 1000 pulses per second. The varying power of the return signal, called the “waveform” is sampled and memorised during the reception gate adjusted by the tracking system on board before switching again to emission mode.
To explain the waveform shape we have to detail step by step the reflection sequencing of the wave on ground surface. For an ideally flat and equally reflecting surface, the reflection is going through the main steps presented on figure 2.

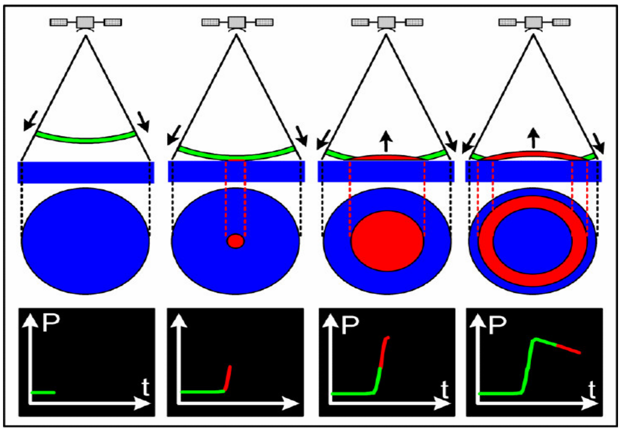


Figure 2. Waveform with reflection on flat surface

First, when the reception mode is activated by the on-board tracking system, a low power noise signal is received corresponding to parasite reflection of the pulse in the ionosphere and atmosphere.

When the leading edge of the radar pulse hits the ground, the returned signal rises up, the reflection surface being a disc linearly spreading with time, which makes the corresponding return signal increase up to a maximum corresponding to the passage of the rear edge of the pulse “through” the ground surface.

After the rear edge of the pulse passed “through” the ground level, the reflecting surface turns to a ring with increasing radius and area but like in a spherical radio wave the signal intensity decreases with the travelled distance, the returned signal to the altimeter decreases accordingly till vanishing down to the noise level or being cut by reception gate.
Significant return signal is available from reflecting surfaces situated up to 18 km off nadir, which makes the exploitation of altimetric data particularly delicate in case of strong variations of the surface reflectivity .

We face two main types of waveform depending of the ground surface reflectivity : specular and non specular waveforms described in following subsections .

**2.2.1 Specular waveforms :** Specular waveforms result of the return signal from very reflective surfaces like water bodies. In this case, the reflected energy is concentrated in a narrow cone of reflection, which gives a very strong return signal received by the altimeter in a very short period of time; this gives a very sharp waveform as presented on figure 3 (left).

**2.2.2 Non specular waveforms :** Non specular waveforms result from the interaction of the altimeter's transmitted pulse with scattering surface found in rough terrain. In this case, the return signal power is much lower than for specular waveform and reception of return scattered signal is spread over a larger time than for specular echo (the cone of reflection extends much wider from the vertical axis)

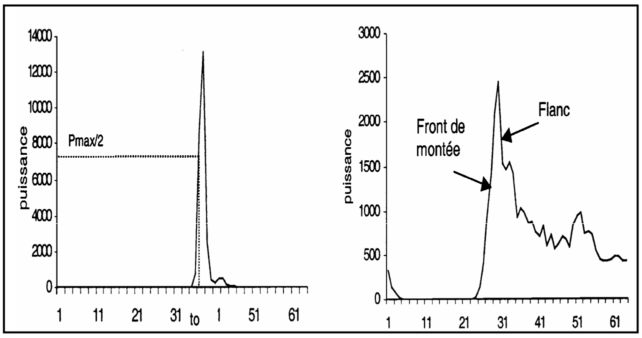


Figure 3 : Specular (left) and non specular (right) waveforms (note that Y power scale is not the same for both cases)

### 2.3 Retracking

Because of highly complex waveforms, particularly in non specular case, altimeter data over land must be post-processed to produce accurate surface elevation. This post-processing, called "retracking", is required because the leading edge (also called the "ramp") of the terrain return waveform deviates from the on-board altimeter tracking gate (predicted location of waveform ramp mid-point), causing a significant error in the telemetered range measurement. Retracking altimetry data is done by computing the starting point of waveform's leading edge from the altimeter tracking gate and correcting the satellite range measurement (and surface elevation) accordingly. Figure 4. illustrates this concept .

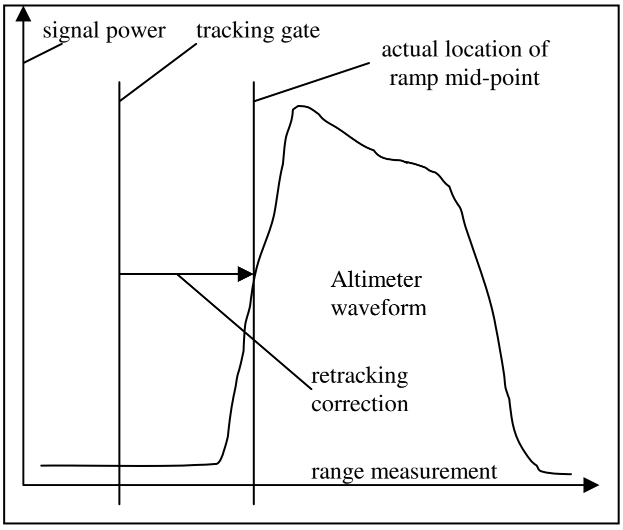


Figure 4. Retracking correction

## 3. EXPLOITATION OF SPECULAR DATA ON WATER BODIES

### 3.1 Threshold values for selection of specular echoes

Water bodies situated up to 18 km off-nadir can return strong specular signal . From our experience, a water body echo should be within the following threshold values :

**0,5 gate < ramp duration < 1 gate**
(1 gate = 12,12 ns equivalent to about 2m range for ERS)

**rear edge slope < -0,11 Neper/gate**
(Neper is the logarithmic value of the return signal)

**coefficient of reflection > 22dB**
(coefficient of reflection = total return energy / emitted energy)

### 3.2 Matching of specular data with water bodies

Though the range measured between the satellite and a water body is very accurate (thanks to the sharp return signal), the main problem is that the altimeter tracking system keeps locked to the water body even when it is well off-nadir (more than 10 km is commonly observed) causing a slope error which has to be corrected to get the water body elevation with enough accuracy.

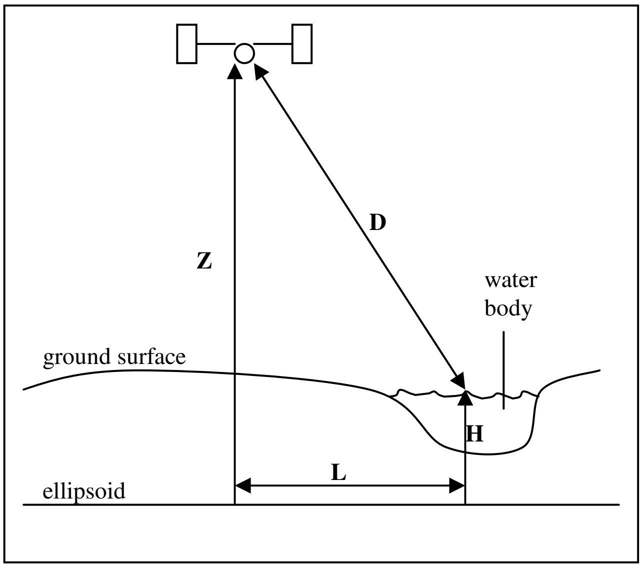


Figure 5. Off-nadir signal geometry

Simple geometric consideration as shown on figure 5 brings the corrected value :

$$H = Z - SQRT ( D^2 - L^2)$$

with
**H :** ellipsoid altitude of water body
**D :** Altimeter range measurement
**Z :** ellipsoid altitude of satellite
**L :** horizontal distance between satellite nadir and water body

The major cause of inaccuracy in the determination of altitude **H** comes from the inaccurate horizontal position of the water body itself (small scale available topographical maps give that position with about 250 m absolute accuracy, which makes a vertical error of about 4 meters for a water body situated 10 km

off-nadir). The best available geographical sources (raster maps, world or regional vector databases like VMAP0 or VMAP1, orthorectified space imagery) are used to get the most accurate position of the water body to derive the most accurate height from the altimeter data.
When many different water bodies are situated nearby the satellite nadir and are potential candidates to match with specular signal, an optimisation process is applied taking in account all available altimetric data from different orbits and keeping the most coherent solution among all the candidates (the different orbits should give the same altitude for a single water body)

### 3.3 Expected accuracy

When the satellite crosses vertically through the water body (lake or river), the altitude of this water body can be derived from altimeter data with about 2 meters accuracy. This result was established after comparison with elevation reference points extracted from best topographical sources along some French rivers (Maheu, 2000).

When the water body is off-nadir, its altitude (derived from altimetric data) will depend of the accuracy of its horizontal position . The impact of this horizontal error determination on the altitude determination can be approximated by the following formula derived from the general formula given in 3.2. :

$$\textbf{H}.\text{error} = \mathbf{(L/Z)^{*}}\ \textbf{L}.\text{error}$$

when

$$(L \ll Z\ ,\ L \ll D\ ,\ L.\text{error} \gg D.\text{error}\ ,\ L.\text{error} \gg Z.\text{error})$$

Numerical example : for L = 15 km , Z = 700 km and L.error = 250 m we get H.error = 5 m.

## 4. SELECTION OF ALTIMETRIC DATA IN FLAT AREAS

The exploitation of radar altimetric data on water bodies was very encouraging and made us extend its exploitation to land areas.
The “threshold retracking” method developed by GRGS for altimetric observation of continental ice sheets (Rémy, 1990 , Legresy 1995, 1997, 1998) and adopted by SPOT IMAGE to support image rectification and DEM control, rejects altimetric measurements in very rough terrain; then only flat to moderately rough terrain measurements are kept after retracking (about 80% of the on board memorised data).
We have to keep in mind that satellite radar altimeter was first designed for oceanographic purposes dealing mainly with specular data, that is why a severe selection process has to be applied to keep adequate data matching with required accuracy of the mapping project. To minimise unwanted or uncontrolled errors due to “slope effects” or “smoothing effect” (which will be studied in the next section of this paper), priority has been given to very flat areas to collect very reliable height measurements. The selection process designed to extract the elevation of very flat terrain areas is described in following subsection.

### 4.1 Criterions for selection of flat areas

Signal continuity is the first filter applied to available data after retracking. It consists in keeping only the “ideal” sequences of 20 measurements per second, that means without any discontinuity. A statistical analysis showed that about 50% of data are rejected by this first filter due to terrain roughness, on board tracking discontinuity or rejection by retracking .

Height variation within one sequence is the next filter applied to remaining data. To minimise uncontrolled reflections due to changing heights and slopes inside the impact zone of the radar pulse, only data associated with very flat surface are selected. A 0,75 m threshold for standard deviation within a one-second sequence (corresponding to a 8,3 km travelling of the satellite on his orbit), equivalent to a maximum slope of 2 meters for 10 km was finally adopted .
Statistically about 80% of the remaining data is rejected by this test .

Inter-cycle height variation is the last filter applied; it consists in computing for each height measurement the maximum height difference with all other height measurements derived from other passes of the satellite within a 2 km radius. This checks the coherency and stability of ERS measurements along time. The maximum height difference observed should be 5 m for a minimum of 3 cycles available 2 km around the data point to test.

### 4.2 Selectivity and accuracy

After passing through the different selection steps (retracking, signal continuity, height coherency between several cycles) about 5% of the total input data are kept for exploitation in DEM control or ground control in photogrammetric block-adjustment.

Comparison of this type of selected data with reference height points extracted from reliable topographical maps showed agreement better than 5 m in most cases (more than 95%) .

## 5. ACCURACY EVALUATION OF ALTIMETER DATA RELATIVE TO TERRAIN CARACTERISTICS

We have also tried to refine the modelisation of radar pulse reflection on moderately rough and heterogeneous terrain . The aim was to extend the domain of validity of ERS altimeter data providing it keeps satisfying the required accuracy for mapping projects .

For that purpose, we have used a special algorithm based on radar simulation, developed by GRGS (Pace, 2003).

### 5.1 Principles of GRGS waveform simulation algorithm

For each radar pulse, the simulation algorithm builds a simulated waveform taking into account the satellite position and a refined physical model of propagation and reflection of the radar pulse on the ground surface. The ground surface itself is simulated by the best available DEM or the DEM to control.
The variation of reflectivity inside the total zone hit by the radar pulse is modelised with the help of an existing vector database like VMAP (only the water bodies have been considered in the current version and were given a much bigger reflectivity compared to land surfaces). The simulated height is then computed from ramp mid-point of the simulated waveform. Then the simulated height is compared to the height derived from on-board data which is much more convenient than comparing directly ERS observed height with DEM height, as both the ERS observed height and simulated height carry the same systematic errors like “slope effect”, “smoothing effect” and “lock on off-nadir water body”.

A local discrepancy between simulated and observed ERS heights is the sign of a potential anomaly in the DEM.
A systematic shift between both height is the sign of a systematic shift error on DEM.

## 6. ERS ERROR ANALYSIS ON NON-FLAT TERRAIN.

We investigated the ERS elevation data error on rougher terrain, using a 30-meter digital elevation model considered as a reference. Two different study areas with different relief characteristics were selected. We derived parameters from this DEM. Errors between ERS data and DEM and also between the simulated responses obtained with the DEM were calculated. Finally, their correlation with the terrain parameters were analysed.

### 6.1 Study areas description

The first geographical area, located at the south-west of France, includes landforms ranging from extensive floodplains to low relief foothills, and high relief, long mountains slopes to the east. The other area, located in the North, is less rough but contained larger urban area, which can distort the altimeter response. The field areas are approximately 150 km².

### 6.2 Elevation data

*ERS elevation data* : we collected all data obtained after the retracking step in both areas. There were 5679 and 8634 elevation points over each area.

*30-m DEM :* the DEM is a level 1 data (DTED1) acquired by photogrammetric method from remote sensing images such as Spot, or by contour digitising from existing 25,000 scale maps. A root mean square errors (RMSE) is provided to express its quality . The RMSE is reported as 30 m for horizontal coordinates, and 5 m for height, relative to the WGS 84 datum. We extracted elevation at each ERS elevation positions using a bilinear interpolation method.
*ERS simulated elevation data* : at each ERS elevation position, we use the DEM to obtain a simulated ERS height based on the method described in previous section .

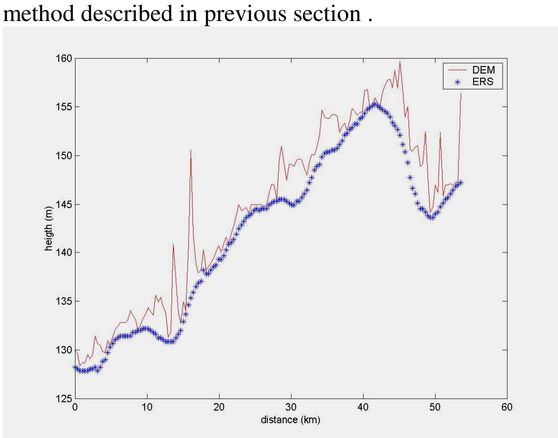


Figure 6. Height profiles from DEM and ERS altimeter

### 6.3 Exploratory data analysis

#### 6.3.1 Errors statistical distribution

Fig 7 shows the different data sets with their histograms. They seem similar for the three data sets. On the north area, they show a roughly normal distribution of the elevations. On the second sites they are broader, showing the various relief. The errors were calculated by subtracting the interpolated DEM elevation and the simulated elevation from the ERS measured elevation. The spatial distribution of these absolute error values and their histograms are plotted in fig.8.

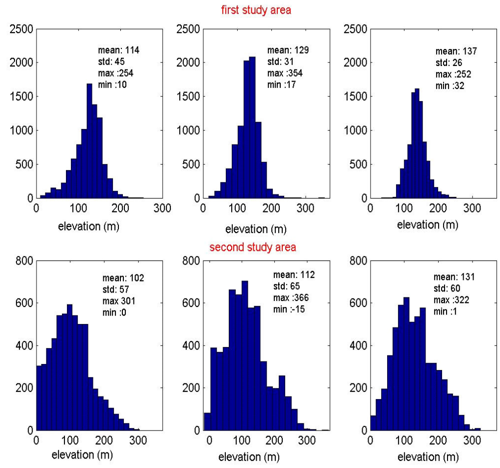


Figure.7. Elevation histograms in both study areas.

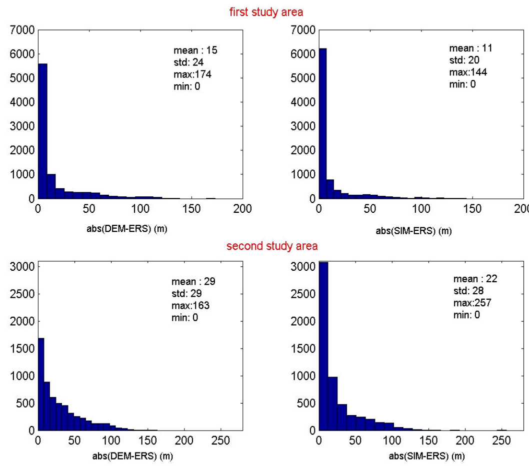


Figure.8. Absolute errors, DEM and simulated ERS elevations versus ERS measured elevation.

The histograms indicate that on average the altimeter gives a coherent elevation value over the study areas. However, the maximum absolute errors values show there are significant differences in some areas. The distribution error is narrower, particularly in the place with low roughness.

#### 6.3.2 Terrain parameters influence.

To understand the altimeter behaviour, we derived some parameters from the DEM reflecting the local topographic roughness around each elevation position within a moving window (a 20-cell or 10 km circle). The parameters are the following :

- P1 and P2: the slope mean and standard deviation.
- P3 and P4: the mean and standard deviation of elevations.

The next table shows the coefficient for correlation between the errors and the different parameters over both study area.

| | P1 | P2 | P3 | P4 |
|---|---|---|---|---|
| DEM-ERS | 0.50 | 0.56 | -0.16 | 0.66 |
| SIM-ERS | 0.33 | 0.38 | -0.20 | 0.43 |

Table 1.

All parameters are correlated with the errors. The coefficient for correlation is often greater with parameter P4 and lower with P3. Logically, the correlation is lower with the simulated-ERS error. The dependence is also confirmed by a $\chi^2$ statistics test. For each parameter, Figure 9 shows scatter plots of the maximum, mean, median and third quartile values of the errors in equal bins.

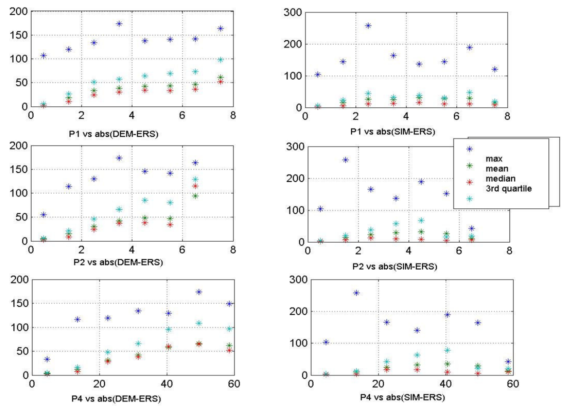


Figure 9. Maximum, median ,mean and 3rd quartile of the errors versus equal parameters bins.

The larger the parameters are, the wider the errors distribution is with a linear increase of the mean, the median and the 3rd quartile. So, the errors may be short whereas the parameters are larger. Moreover, it is possible to evaluate the risk of being under a given threshold versus the parameters.

### 6.3.3 ERS elevations continuity criteria.

We would like to define some rules from the ERS altimeter responses to make a decision about the validity of an elevation measure. Firstly, we noticed that a large number of isolated points (no measures before and after) have error values upper than 15 m. To avoid these points, we only considered continuous elevation profiles with more than 15 points in both side (about 5 kms). We found this threshold is a balance between a sufficient amount of data and a good precision on average. About the half of points was kept on the north site and 20 percent on the other one. Next figure shows, the absolute errors versus the logarithm of parameter P4.

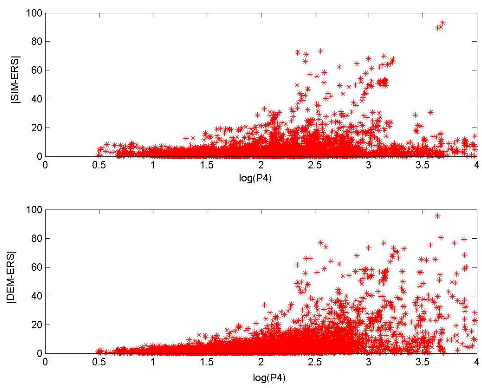


Figure 10. Errors versus the logarithm of P4.

A great part of the simulated and ERS error values are less than 10 meters, showing that globally on continuous profile the ERS altimeter measures can be used to evaluate errors in DEM, even for important relief area (the local roughness P4 ranges from 1 to 54 meters) .

## 7. CONCLUSION AND RECOMMENDATIONS

We have validated different methods of exploitation of ERS altimeter data which give respectively 2m, 5m and 10 m accuracy on water bodies, flat areas and moderately rough terrain.

Future work should concentrate on the refinement of reflectivity on land surfaces taking in account all available sources (VMAP1, GEOBASE …) and on the exploitation of data derived from other satellite altimeters like ENVISAT.

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