# Along track repeat altimetry for land studies : application to ice sheets.

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**Abstract :** Satellite altimetry is the unique possibility for continuous and extensive survey of the large polar ice sheets volume change. With ERS1 it became possible to measure the surface topography of 80% of the Antarctic and quite all of the Greenland ice sheets with an unprecedented accuracy. The accuracy of the classical radar altimeter measurements over continental surfaces is however limited by a number of factors of which the first is the topographic induced error (commonly called slope induced error). In addition volume echo induce penetration effect on the altimeter waveforms. The temporal survey of the surface height is classically made using crossover points differences in order to limit the topographic induced errors. However the measurements show difference as to volume echo induced errors between ascending and descending tracks. A method has been developed at LEGOS to survey along track by taking into account the fluctuations across track of both the height measurement and the waveform shape parameters. This method has the advantage to avoid the ascending/descending difference in echoing and also to lead to around 100 times more measurements available to survey the evolution. It also helps to look at the time evolution of the ice sheet surface at small scales of the order of few km in regional or local studies. In this presentation, we'll show the principle and aspects of the methods and the impact in terms of accuracy and local signal. We show applications on Antarctica and Greenland, using ERS and Topex. The development of a systematic correction to be included in ENVISAT products at GDR level is discussed.

**Principle:** Along track repeat altimetry consist in considering every single point of measurement along the satellite track and computing the time series of each of these individual points.

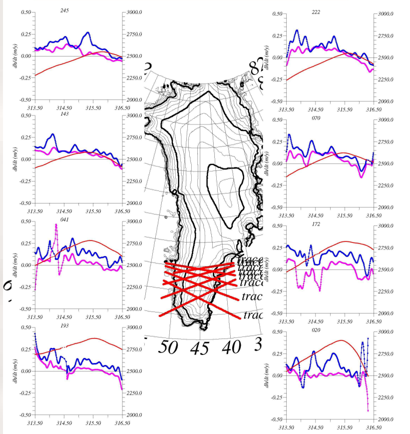
The orbit of satellite altimeters in repeat mode is constrained to fit in a limited range of across track repeat position. For example ERS in 35d repeat mode is constrained to be in a +-1km around the nominal track. This mean that if we plot the repeat tracks nadir position we obtain a distribution of measurements in a 2km wide band. This size is similar in size to the first impact of the radar altimeter echo. Thus over ocean most studies consider it exact repeat and are not affected by across track variations in topography which are negligible. Over land surfaces, it is not the case. First if the across track slope is 1m/km (that is a small value over lands and very average over ice sheets) a displacement across track induces a 1m difference in the measurement. If the topography is not a simple slope but includes curvature and undulations at small scale, the effect becomes rapidly annoying for the interpretation of time series. What we developed is an analysis of the data that try best estimate the signal from across track and along track displacement to remove it and be able to work with the time series with the less possible contaminations of these effects.

Another annoying point when using radar altimetry over ice caps and radar penetrating surfaces is that the surface to volume change with time depending on the surface state. The measured height is then variable according to the surface state (or microroughness) variations or other volume echo intensity variations (linked to temperature changes impacting the medium's absorption). The retracking that we use (ENVISAT ICE-2 or equivalent for ERS) describes the altimeter return through 4 main parameters : The height (H), the intensity of the Backscatter (Bs), the Leading edge width of the echo (LeW) and the Trailing edge Slope of the echo (TeS). The last 3 parameters describe the shape of the radar echo and help detect physical measurement induced variations of the height measurement. We use the time series of the 3 parameters to estimate this impact and correct for it in order to recover height variations the most possible representative of the actual surface height variations.

**Method:**

The first step of the processing is to stack the repeat segment so as to have all the repeat of one point in one rectangle of 2km by 350m (which is the along track distance between successive measurements).
Then we evaluate the geographical function of the parameter variations (H(lon,lat), Bs(lon,lat),LeW(lon,lat), TeS(lon,lat)).
Then we take the time series and remove the geographical component.
The next step is to estimate the dependency of the height in the other parameters.
Then we remove the effect of radar echo shape variations.

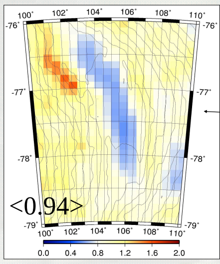
Topex measurement of the surface height trend over South Greenland.




The 8 tracks studied are displayed over the Greenland topography on the top plate. The corresponding surface height trends as measured by Topex are displayed on the eight other plates from top to bottom as from north to south. The trends are drawn in pink for Ku Band and in blue for C Band. The geodetic surface height is also diplayed in red.

**Advantage of this method:** Classically, mainly crossover point analysis have been used over ice caps to circumvent the difficulty of this geographical height variations. But taking only the crossover points dramatically limit the number of measurements used in the analysis. In addition, it has been found that the combination of the volume echo, the altimeter antenna polarization and of the surface preferential orientation induce differences between ascending and descending track height at the crossovers which limits the precision of these analysis. The along track repeat method allows to use as many as 100 times more individual measurements over Antarctica. It increases the Signal/Noise ratio of the analysis and allows to increase the spatial resolution of the studies. It also authorize to work locally along track to seek for local scale phenomena much better than the sparse crossover points. Over Greenland with Topex 10d repeat as many as 350 repeats occur on each point which allowed previous studies using this method to accurately follow the southern ice divide migration (Figure below and Legresy et al. 2001).

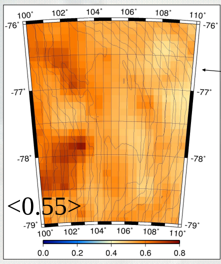
**Limitations :** This method needs that the satellite be in a repeat phase. This means for example that the ERS1 geodetic phase period cannot be used in this kind of analysis. The time series are then limited. However, the ERS2 time series are followed by ENVISAT. The ERS2 time series show 8 year long valid data which are followed by ENVISAT until now.




The Vostok lake area is 900 km inland on the Antarctic plateau. It's extremely cold area with extremely small precipitations and not much wind. It is very flat after the ice floats on a subglacial lake. The expected variations of height are very small, of the order of few cm variations at the yearly scale, less variations is expected in trend or longer term. Therefore the temporal variability in the area can pretty much be considered as the measurement noise level.

This map represents the variance of the height variations as measured by ERS2 over 82 cycles or 8 years.
At this stage, the processing consist of retracking the waveforms and applying essential corrections for orbit, atmosphere, doppler…
For mapping we computed the square root of the variance which is expressed in meters here. One understands that the obtained signal is very large while the actual surface height signal is expected to be nearly nil.
Still the lake area appears in blue where the surface slope limits the across track effects.

Computing and removing the geographical function

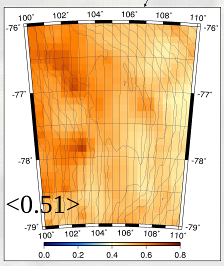



This map represents the same quantity as above, except that the height has been corrected for the non exact repeat
The color scale has been changed to show the signal better. The improvement is dramatic showing that the main signal present in the measurement relates to the topography at small scale. But still the noise level is important. It is noticeable that there is no more appearance of the lake Vostok or other topographic feature, which means the correction made the topographic induced error very weak.

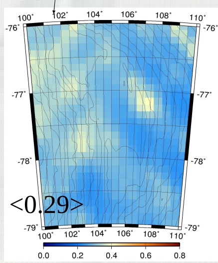
When we fit and remove an annual cycle and a trend, the map change slightly, but it's clear that these expected signals are very small and that time variations related to surface height change do not impact the variance and that we still have an important noise level.

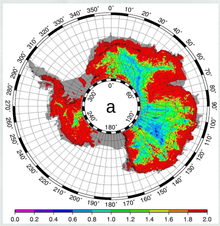
After removing the effect of echo shape variations, the variability drops to another lower level.

Removing a trend and an annual cycle

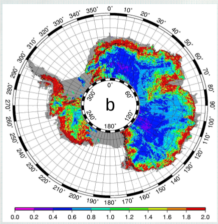


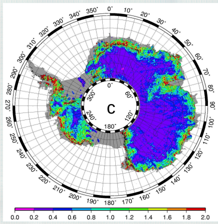

Removing radar echo shape variations




R.M.S. Variability (in m) of the altimetric measurements
a) Raw, b) after the geo correction is applied, c) after both geo and echo corrections are applied




Finally the processing has been applied to the whole Antarctica and Greenland ice sheets allowing us to build the maps bellow with a resolution of 10km. Essential features are visible, like the vast recession of the ice in the west Antarctic marine glaciers, but also in some place of east Antarctica, like the cook ice shelf drainage, the Totten glacier and glaciers in East Dronnig Maud Land. There are also some area of significant thickening in west Antarctica accumulation zone next to the Transantarctic Mountain and in large areas of East Antarctica. The Greenland ice sheet shows a almost null trend over most of the high altitude interior, a positive, but not strong trend on the southern half plateau. It shows a lot of glaciers basins with negative trends in agreement with observed dynamical trends of these glaciers.

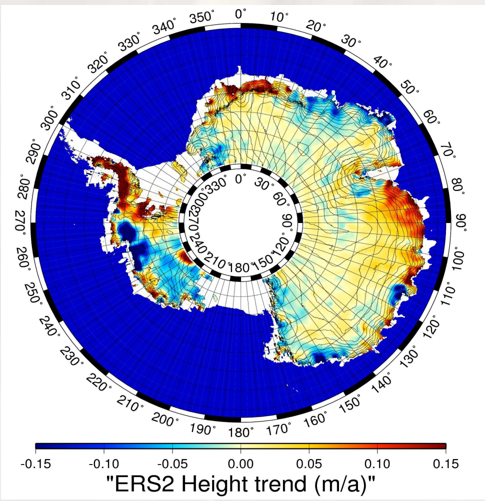
**LILA (Land Ice Level Anomaly)**
(or LLA, Land Level Anomaly?)

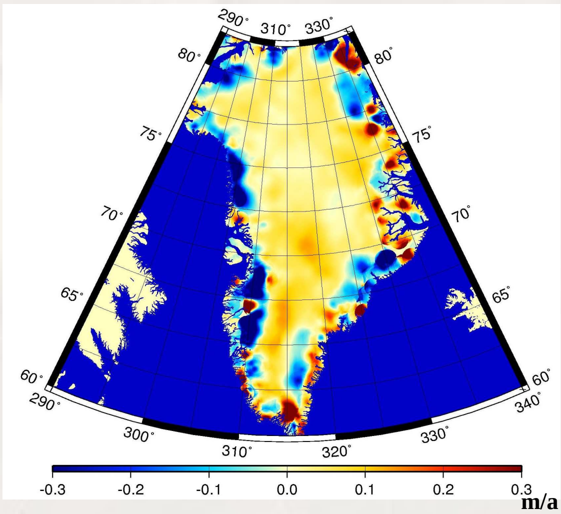
With this method, it is possible to compute the geo correction (correction for the across track shift induced geographic variations) for the range measurement and also for the echo shape parameters. It is also possible to compute the echo correction (correction for echo shape variation with time) for the range measurement. The corrected range would have to be **range_corrected = range(from GDR) + geo_H + echo_H**, the corrected backscatter **Bs_corrected = Bs - geo_Bs**, the corrected leading edge width **LeW_corrected = LeW – geo_LeW** and the trailing edge slope **TeS_corrected = TeS – geo_TeS**.
We observed that these difficulties to cope with the height measurement over land ice and land in general prevented the use of altimetry over these surfaces (or say outside liquid water surfaces) by a large scientific community.
The kind of product that could be distributed to scientists outside the very small community of land altimetrists can be called LILA as

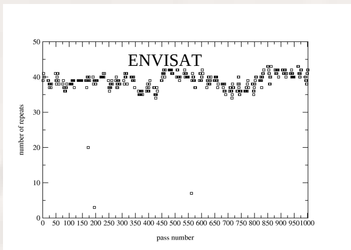
**LILA = H – Href – geo_H – echo_H.**

Where H would correspond to the classical Height over the ocean (including all classical corrections) **Href** is an equivalent to the MSS, and **geo_H** and **echo_H** are the corrections discussed in this poster.
It is then possible to distribute an along track product. It is also much easier to make anomaly maps from this along track product. It is also possible to distribute along track corrected echo shape parameters in order to study the surface characteristics evolution.

It is possible (as we did here) to compute these corrections (geo and echo) along track after a minimum of 35 repeat measurements have been achieved (in order to avoid aliasing in the distribution of ground tracks, seasonal and intra seasonal signals, mathematical adjustment…). The graph below shows the number of repeat measurements available over Greenland from ENVISAT track by track. It means it's now possible to start this computation for ENVISAT.

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