The altimetry processing chain

Bathymetry for BASE-platform

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The present article describes some of the most relevant features of the designed calculation chain for bathymetric products from satellite altimetry method that has been integrated into the BASE-platform service. We estimate bathymetry based on up-to-date data from Cryosat2 where the new generation of altimetry radar (SAR mode) is processed in-house by using analytical solutions for the retracking model. A new method is used for the de-noising of residual altimetry profiles. The solutions are calibrated with in-situ soundings to consider seafloor density variations.

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BASE-platform | Altimetry | Bathymetry | Satellite altimeter | Gravity anomaly | Geoid

1 Introduction

The ocean on earth is enormous, deep and unknown. In the deep open ocean, in locations where there has not been investment in measuring the seafloor relief, the radar sensor in satellites (altimetry) can be used to model it. This is done by measuring the sea surface deflections generated by the gravity anomalies produced by volumes of seafloor irregularities (Smith et al. 2004). Satellite altimeters transmit signals to earth and receive the echo from the surface (the ›waveform‹). This is analysed to derive a precise measurement of the time taken to make the round trip between the satellite and the surface. This time measurement, scaled to the speed of light (the speed at which electromagnetic waves travel), yields a range measurement. However, as electromagnetic waves travel through the atmosphere, they can be decelerated by effects that require corrections. Also independent measurements of the satellite's orbital trajectory are needed for exact coordinates. Altimetry thus requires a lot of information to be taken into account before being able to use the data (Andersen and Knudsen 2009).

The sea surface height, from processed satellite radar data, can be used to estimate bathymetry based on gravitational laws. If the earth was a perfect sphere with a single and homogeneous density material then the normal gravity would be constant along its surface. In our planet the seafloor undulations are formed by large volumes of geological material that are perturbing the normal gravity field. These gravity anomalies are shaping the ocean surface having permanent or long-term effects (as long as a seamount exists, its gravitational attraction persists). Because of that sea surface height static (or long term) effects are the ones that have interest in bathymetric studies. However, not all the relief in the seafloor can influence the ocean surface. Large geological features are flexing the Mohorovičić discontinuity and replacing materials from the mantle by lower density material from crust (Smith and Sandwell 1994). Long wavelengths in the bathymetry are the isostatic compensation piece of the spectrum and can be estimated by filtering a solution from a different source. Afterwards, the deviations from the isostatic compensated solution are added to the smooth solution to obtain the final estimation.

Altimetry bathymetry is a product for deep and open ocean in extensive areas suitable for preliminary studies. Our products are based on up-to-date data from Cryosat2 where the new generation of altimetry radar (SAR mode) is processed in-house by using analytical solutions for the retracking model. The solutions are calibrated with in-situ soundings to consider seafloor density variations. Seafloor relief from altimetry shows some major geological features such as the mid-ocean ridges formed between plate tectonics, undersea volcanoes forming chains, submarine canyons or landslides, etc. It is used in offshore industry (pre-planning for deep-sea operations such as mining or oil exploration, modelling, geological studies) and it has several scientific applications from global estimations of water currents and flows to lithospheric structure studies (Kearns and Breman 2010).

BASE-platform is a service that provides satellite-derived bathymetry on a global scale using tidal modelling and crowdsourced data collection techniques to enhance accuracy by refining existing techniques, developing methods and tools for merging data from these sources, integrating with tidal modelling for reducing the depths to the local chart datum, etc. The project also aims to improve the service experience by making data available through data portals and working with end users of bathymetric data to carry out trials in a number of areas and assess the results with them. The present article describes some of the most relevant features of the designed calculation chain for bathymetric products from satellite altimetry method that has been integrated into the platform.

Up to now there have been mainly two approaches regarding the detection of outliers and spurious oscillations in the residual altimetry profiles for the bathymetric calculation. An option is to compare the profiles against prior models of geoid slope for a sanity check (Sandwell and Smith

2009). Another option could be to compare each altimetric observation with the interpolated value from the nearest 64 points (Andersen 2012). In our calculation chain we have innovated with a combination of iterative loops applied before interpolating into grids.

The support of the research and innovation program BASE-platform allowed several improvements to build a robust processing chain that works regardless the satellite mission and altimetry mode. Also a combination of methods and iterative loops has been implemented to detect the outliers in altimetry profiles on a robust way. Geolocation-dependent parameters were added to automatically ingest the appropriate data sets given a target area. The Cryosat-2 SAR mode altimetry L2 data is processed in-house from L0 passing by L1B processing (Makhoul et al. 2017) and with a new retracker (Ray et al. 2015) and has been integrated in the bathymetric algorithms.

2 Method

First step is to ingest all the data needed along the calculation chain. Data from Cryosat-2 in SAR mode is processed by isardSAT with an in-house L2 process based on the analytical solutions for the retracker. The satellite data processing workflow is summarised in the two following subsections. Afterwards the procedure for bathymetry is presented.

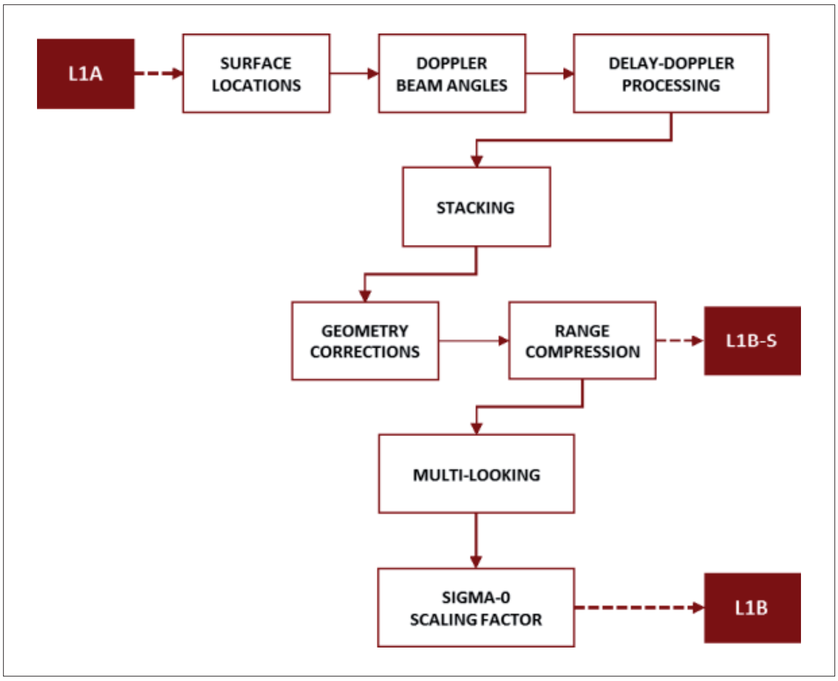
2.1 Delay-Doppler

The Delay-Doppler altimeter uses the power backscattered from the scene more efficiently than does the conventional altimeter, since the whole beam-limited along-track signal is exploited, instead of the pulse-limited area typically considered by conventional altimeters (Raney 1998). This is achieved thanks to the proper slant range (or delay) variation compensation. The extra delay observed from each Doppler bin in which the along-track beam is partitioned is removed, aligning all the Doppler beams to the same delay or range, known as range migration correction. The additional selectivity in the Doppler domain, which confers an additional degree of freedom, allows increasing the along-track resolution (i.e., reducing the along-track footprint), such that the impact of surface variability on the imaged footprint can be minimised (Makhoul et al. 2017). This selectivity in the Doppler dimension can be also exploited to perform a specific focusing to a given defined location. This requires performing additional processing in the along-track direction, which mainly consists on beam steering (to the desired surface position) and Fourier transformation. In this manner, several looks are made available for a specific surface position, i.e., different Doppler beams from different bursts are pointed towards it, forming the Doppler stack (ibid.). Therefore, the final signal-to-noise ratio (SNR) can be improved once the different range-compressed power waveforms are incoherently accumulated; such processing is known as multi-looking. Hence, the intrinsic 2-D (range/Doppler) nature of the Delay-Doppler altimetric signals requires, as theoretically described above, to perform accordingly a 2-D processing, properly exploiting the potential capabilities, conferred by this relatively new operational mode. The considered SAR (also known as Delay-Doppler) processor is based on the experience gained by isardSAT in the study and implementation of the Ground Prototype Processor (GPP) within the Sentinel-6 project (Roca et al. 2016).

A high-level block diagram of the L1B processor is shown in Fig. 1. The main processing stages of the Doppler-Delay processor are:

- Surface locations (and their corresponding data and orbit parameters). They are defined by the intersection of the Doppler beams and the estimated surface positions along the satellite track.
- Beam angles computation (for every burst). It calculates angles between the satellite velocity vector and the directions defined by the satellite location and the computed surface locations under the satellite's boresight.
- Azimuth processing, Delay-Doppler processing and stacking. There are two purposes: to steer the beams to the different surface locations and to generate the stacks.
- Geometry corrections for each stack. The Doppler, slant range and window delay misalignments corrections are applied.
- Range compression. This algorithm performs the range compression of the input stacks and then generates the power waveforms.
- Multi-looking. To average (incoherent integration) all the waveforms that form each stack.
- Scaling factor computation (sigma0 extraction). It computes the scaling factor that allows converting the power of the multi-looked waveform into normalised radar cross section (sigma0) values.

Fig. 1: Level L1A/L1B SAR processing chain



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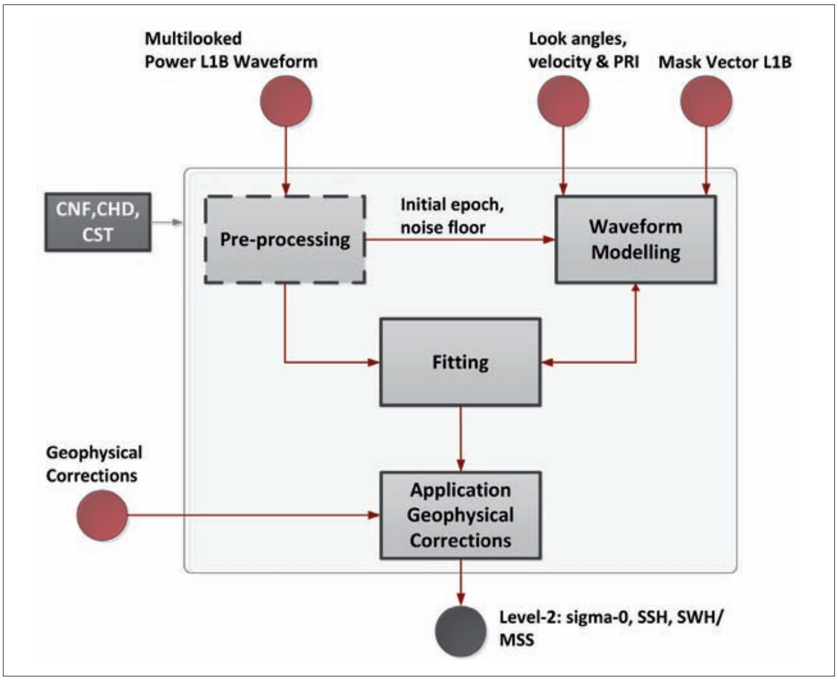
2.2 Retracking

Radar altimeters are equipped with on-board tracking algorithms which provides a first raw estimation of the range between the spacecraft platform and the scattering surface being illuminated beneath. Such information provides only a rough estimate of the range to the surface since it can be biased depending on the type of surface being illuminated and on the range bin sampling. In this sense, and in order to have a much accurate estimation of the range, an on-ground »retracking« is required. The basic idea behind this processing is to perform an accurate fitting of the received echo with a well-developed waveform model. In this manner, it is possible to infer geophysical parameters' estimates of the underlying scattering surface being illuminated, e.g., sea surface height (SSH), significant wave height (SWH) and radar backscattering coefficient (sigma0). A general differentiation can be done between the physical-based retrackers and empirical retrackers (Makhoul et al. 2017). The latter are statistically-oriented approaches, which basically search for the peak of the waveform to infer the sea surface height without considering any physical relation to the backscattering mechanisms being observed. On the other hand, the physical-like retrackers try to model the echo waveforms on the basis of the electromagnetic interaction between the transmitted pulse and the surface beneath the altimeter. The evolution towards a SAR altimetric operation, which improves resolution and potential performances, requires to migrate to a new characterisation and formulation of the analytical retracker. The analytical retracker implemented by isardSAT (in Makhoul et al. 2017) is based on the model proposed by Ray et al. (2015).

The block diagram of the Level-2 processing based on the analytical retracker is depicted in Fig. 2.

Fig. 2: Analytical retracker block diagram



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The main steps included in this processing chain are:

- Pre-processing,
- Stack modelling,
- Fitting procedure,
- Geophysical corrections.

The pre-processing stage is performed by extracting refined epoch estimation from leading edge detection and using an adaptive window for thermal noise estimation. Then, the fitting procedure adjusts the multi-looked model waveform (obtained from the corresponding stack modelling) in a least square error minimisation procedure. Afterwards, geophysical corrections can be applied.

2.3 Bathymetry calculation

Satellite altimeter data is processed to obtain sea surface height as explained in previous sections (Fig. 3).

At this step the processed sea surface height samples are localised by following a linear data pattern commonly named »track« where the direction reflects the projected satellite position on earth.

Useful satellite data would cover both space and time being the former determined by the track spacing and the diversity of track directions. Given the present study requirements, the spatial coverage (low tracking space) is a priority over temporal resolution (repeated tracks). Thus, geodetic missions are more useful. Specifically Cryosat-2 is the best for its track spacing; however, its orbit inclination leads to great uncertainties in the east-west direction, therefore the calculations are complemented with Jason-1 in its geodetic mission that has a lower orbit inclination (Garcia et al. 2014).

The best approach is to resolve the full spectrum of the gravity field in two separate pieces: the long wavelengths component and the high-resolution piece. On the one hand, the EGM08 is an earth gravity model in spherical harmonics that can be used as part of the final solution. On the other hand, the short-wavelength piece of the total spectrum is estimated by using a flat projection approach with the »remove-compute-restore« technique (Marotta et al. 2015), where:

- A geoid model from spherical harmonics is removed from the altimetry profiles;
- Residual slope grids are interpolated from the above data;
- Residual gravity anomalies are estimated by Laplace equation in a flat-projection approach;
- Gravity by spherical harmonics is recovered to obtain the total anomaly field.

One of the main difficulties is the detection of outliers and spurious oscillations in the processed L2 along-track data. At first some manual editing is always required since conventional methods are not working in all cases. A combination of methods and iterative loops helps to detect the outliers in a robust way. The following steps are applied in order to detect useless measurements:

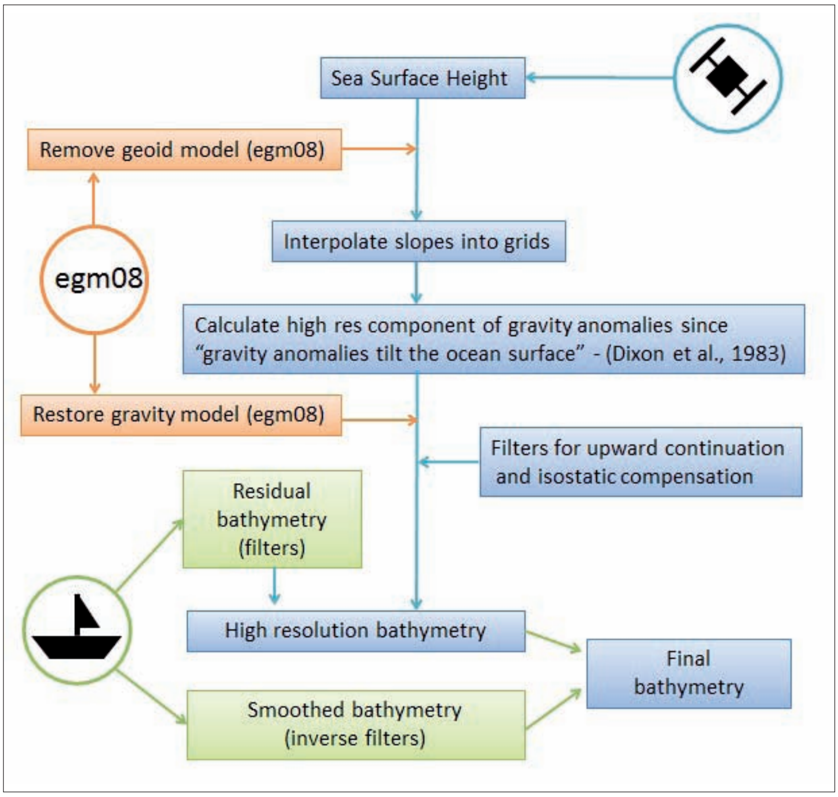

Fig. 3: Block diagram for bathymetry from processed satellite data

The first step is to compare the sea surface height profiles with an interpolated along-track geoid model. When the differences between them are greater than their median differences plus a cutoff the data point is marked as an outlier. This happens following an iterative loop where the spike condition is smoothly approaching the cut-off target.

Afterwards a second iterative loop is done between the profiles and the geoid model. This time the condition used is the correlation coefficient between the sea surface height and the geoid along track. The aim is to increase it up to a defined cutoff by getting rid of further outliers.

Later on a second phase for de-noising the data is applied to each track by using along-track slopes conditions. The first step is to remove standardised directional slopes that are greater than a cutoff. The standardisation is estimated by using medians and median absolute deviations as estimators for the expected value and the variance.

Then, several versions of the fitted profile are compared against the original data to detect more outliers. Some of them are the weighted moving median or the weighted moving mean. These de-spiking routines are identifying standardised data greater than a cutoff and the estimators were defined using the same median estimators as in previous step.

Finally all the tracks from different satellites are merged and compared with an algorithm to identify more outliers. The condition here is to make sure the standardised directional slopes are not greater than a cutoff.

It has always been important to smoothly approach the target cutoff criteria by iteration since the statistics are updated into the loop and they have a direct effect in the outlier condition. Another critical problem is with the missing values and deleted outliers in the residual along-track slopes. If they were not treated carefully, they would act like spikes towards zero. The estimation of residual gravity spectrum comes from residual deflections of the vertical that have been treated carefully with several algorithms to de-noise, filter as well as interpolating between tracks. Therefore some FFTs were applied on the profiles with missing data. The solution was to apply the FFTs to joined pieces of valid data. Otherwise any gaps-filling algorithm would perturb the spectrum response. The major gaps (land), on the other hand, where filled by interpolation from the neighbours with a smooth trend towards zero. The ›missing values‹ method has been designed robust and works for all regions on earth.

The next step is to interpolate the residual heights into grid gradients (at north-south and east-west directions). One can interpolate the absolute heights by removing first the dynamic effects with complementary products or studies and estimate the gradients later on. Alternatively, the along-track slopes can be used directly to interpolate the gradient grids by avoiding most of the dynamic effects component in the residual sea surface slopes. The second approach has been used and projected the eastings and northings in UTM tiles by following a local flat projection. Subsequently the residual gravity anomalies can be solved with the equation for gravity anomalies from DOV (Sandwell and Smith 1997). :

$$f(\Delta g) = -i\frac{\gamma}{|k|}(k_xF(\eta) + k_yF(\xi))$$

Where $|k| = \mathrm{sqrt}(k_x^2 + k_y^2)$, k_x and k_y are the wave-numbers equal to one over half the wavelength in the x and y direction, $F(\eta)$ and $F(\xi)$ are east-west and noth-south slopes, γ is the normal gravity and i is the complex number.

At this point one can build the full spectrum by recovering the spherical harmonics gravity solution (EGM08 for gravity). Afterwards gravity anomalies are downward continued on seafloor. The full resolution cannot be recovered due to the attenuation by distance (upward continuation effect). Hence, smoothing is applied to remove unreliable wavelengths. On the other hand, long wavelengths (>~135 km) are filtered due to isostatic compensation effects and a very smooth bathymetric solution will be added instead. The long-wavelengths solution will be equal to a surface interpolated from an alternative source (i.e. single-beam bathymetric surveys) and its filter will be the inverse of the isostatic compensation effect filter.

The gravity anomaly spectrum can be related with a piece of the bathymetric spectrum as well as a deviation from seafloor model. The second variable can be easily defined in the deep ocean by considering the density of the crust materials.

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However, in areas with thick sediment cover or regions with variable seafloor density, alternative methods must be applied (Kearns and Breman 2010). Basically, the ratio between filtered gravity anomalies and target bathymetry spectrum is estimated by correlations between them where seafloor depth measurements from alternative sources are available.

3 Results

Two combined digital models are used for comparison and validation of the results. Data sources building the combined bathymetric models are described below.

3.1 GEBCO2014

It is made from a combination of data sources and methodologies. The sources are mainly multibeam echo sounders and single-beam ship track soundings. The methodologies are various types of interpolations (kriging, splines with variable tension, etc.). Some interpolations are guided by satellite-derived gravity data. It also includes depth data from several alternative digital bathymetric models.

3.2 DTU10BAT

The Technical University of Denmark (DTU) has made a global bathymetric map that has variable influence of gravity data in the product depending on the area on earth. Gravity has been used around the range from 20 km to 120 km wavelength by optimising coherency (Andersen et al. 2008). GEBCO-1 is used outside these bands as well as for depths above 100 metres. GEBCO-1 is a global bathymetric version that has no altimetry-derived bathymetry.

There are two use cases that have been considered, one is from Mauritian islands where GEBCO2014 has 89.33 % of the area with gravity (altimetry) influence in the calculations. On the other hand the Balearic Islands case has 20.37 % of the area with gravity (altimetry) influence in the estimations. The DTU map has variable gravity influence depending on the analysis of optimal coherency. The usual band is from 20 to 120 km wavelengths. However, the exact piece of the spectrum filled by gravity-guided estimations in these particular areas of the study is unknown.

An estimation of the root mean square error (averaged rmse against the two above-mentioned combined bathymetric models) is presented for two separate cases: The Mauritian islands and the Balearic Islands (Fig. 4).

In the Mauritian islands the RMS is around 220 m for depths down to 5,500 m. In the Balearic Islands the RMS is around 100 m for depths down to 3,200 m. The first case has Cryosat-2 altimetry LRM mode coverage whereas the second has SAR mode for the same satellite. Both have Jason-1 data. GEBCO2014's Balearic map only has altimetry influence in the very bottom right corner. In both cases there are geological sediments with unknown dimensions and thickness leading to variable seafloor densities that will generate lower gravity anomalies. Essentially this means a no uniform relation between residual gravity and bathymetry that is difficult to model. The sources and methods used in the combined models are explained at the beginning of the present section.

4 Conclusions

The main objective of the present investigation has been the creation of a full robust calculation chain for bathymetric products from altimetry sensors with the integration of the in-house processed new generation of SAR mode from Cryosat-2 altimetry (Ray et al. 2015; Makhoul et al. 2017; Roca et al. 2016).

Bathymetry estimation from satellite altimeter is a long procedure that requires several inputs along the calculation chain. Required data sets must be properly ingested by making its format suitable for the workflow. The main input is the Cryosat-2 altimetry data because its mission is geodetic and has great spatial coverage as well as number of completed cycles. The new generation of altimeter sensor SAR is processed in-house by isardSAT with innovative methods (Ray et al. 2015; Makhoul et al. 2017; Roca et al. 2016).

One of the most difficult challenges when implementing the bathymetric procedure has been the detection of spikes and spurious oscillations. It has been observed that it is worth investing resources on that where one should be able to detect and treat problematic data before interpolating the profiles into grids. Since our very first attempts where done by manual editing the profiles, one could suggest supervised machine learning as an alternative technique for the de-noising problem.

Our altimetric bathymetry products are 0.01° × 0.01° cell size for areas deeper than 300 m. These calculations are also offered in the ›merged products‹ along with bathymetric solutions from other sources to complete the full depth range. The products are delivered in GeoTIFF format along with XML metadata following the standards of the project. ⚓

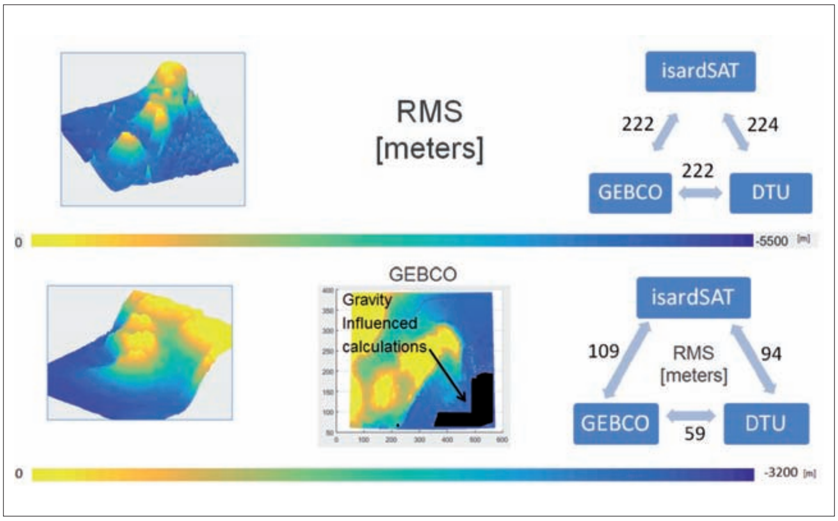

Fig. 4: Root mean square error between the three sources (isardSAT, GEBCO and DTU). Above: Mauritius, below: Balearic