P. Exertier, P. Bonnefond, O. Laurain and F. Barlier
Observatoire de la Côte d'Azur - CERGA, Grasse, France
Pascal.Bonnefond@obs-azur.fr
Y. Ménard (CNES), E. Jeansou (NOVELTIS) and A. Orsoni (IGN)
Centre National d'Etudes Spatiales, Toulouse, France
B. Haines (JPL)
Pasadena, California, USA

Leveling the Sea Surface using a GPS Catamaran

Abstract

In 1998 a probatory experiment had been conducted at Corsica absolute calibration site (Senetosa) in order to determine the local marine geoid slope using GPS buoys. The very good results obtained during this campaign have encouraged us to extend the geographic coverage of the survey (May 1999). This was necessary to insure the calibration process by using more 10 Hz altimeter data and, above all, data far from the shore which are of better quality. The time required to cover the expanded area with GPS-buoy campaign was thought to be prohibitive, thus we decided to build a Catamaran with two GPS antennas (TurboRogue/Sercel) on board. Tracked with a boat at a constant speed (between 3 to 3.7 m/s) this have permitted to cover an area of about 20 km long and 7 km wide centered on the TOPEX/Poseidon ground track No 85.
Results shows a very good consistency between GPS receivers: filtered sea height differences give a mean of -0.2 cm with 1.2 cm standard deviation. Moreover, crossover differences between GPS filtered sea heights have been performed in order to control the quality of the process. No systematism or distortion have been evidenced and statistic results of crossover differences give a mean of 0.2 cm with standard deviation of 2.7 cm. However, comparisons with tide gauges data show a bias of 1.9 cm with a standard deviation of less than 0.5 cm. Even if this bias does not affect the geoid slope determination which is used in the altimeter calibration process, it needs further investigation in the framework of vertical reference studies. Results in term of altimeter calibration show an improvement of more than 1.5 cm rms by using the new geoid slopes.

Introduction

This experiment has been realized in the framework of the absolute calibration site in Corsica. The technical configuration of this site (point of closest approach on the coast, notably) implies that marine geoid needs to be well defined from the coast to offshore area where altimetric measurements are not corrupted. To this goal, we have used kinematic GPS technique to map the local sea surface.
During the 99 GPS campaign an area of 20x7 km has been covered. This represents about 250 km of 1 per second GPS data (~24 hours). For this campaign a Catamaran has been built using 2 wind-surf boards and a metallic structure on which antennas were fixed. Two GPS receivers have been used (Sercel and TurboRogue). GPS data have been processed using Geogenius software and the deduced raw sea heights have been filtered to reduce sea state and GPS processing effects. The Vondrak low-pass filter has been used with a 120 s cut-off (~400 m) to homogenize along-track and across-track wavelengths. Finally, filtered sea heights have been corrected from tidal effects using a reference epoch date (may 1998).

The data analysis consists of five main steps: Comparisons between receivers, Comparisons with tide gauge data, Crossover differences, Comparisons with 98 Buoys campaign and Impact on calibration

1- Comparisons between receivers

Comparisons between receivers show very good consistency and results are comparable to 98 buoys campaign (Table 1). No systematism has been evidenced (below 0.15 cm) between solutions and the standard deviation of ~1.3 cm is in agreement with Catamaran " attitude " variations. The very small mean difference between TurboRogue and Sercel also shows that the impact of radome (only used for TurboRogue antenna) is negligible.

The relatively large minimum and maximum values (-26.8 and +20.3 cm) for filtered height differences correspond to the transition between static initialization and kinematic mode (see Figure 7). Static initializations have been used to stabilize the GPS processing. Using velocity criteria (3<V<3.7) these values are reduced to -4.5 and 5.6 cm (for minimum and maximum). The mean and standard deviation of the selected set are -0.15 cm and 1.16 cm respectively
However, some systematic excursions of up to 5 cm appear to build up over periods approaching 1 hour or more. These differences are mainly due to bad weather conditions. For example on 05/08/99, between EC4b and EL4 (see Figure 1 and Figure 6), we have noticed a strong south-east wind (15 knots), with SWH of about 80 cm. During this period, the Catamaran attitude could have been gradually biased until the maximum wind speed was reached.

Table 1. GPS height differences Turbo-rogue - Sercel (Geogenius), units are in centimeter

Data	Number	Min	Max	Mean	Stddev	Comment
Raw	11963	-14.16	10.48	-0.99	3.04	05/06/99
Filtered	11963	-4.12	1.64	-0.99	0.85	05/06/99
Raw	30671	-18.31	20.97	-0.23	3.36	05/07/99
Filtered	30671	-3.86	20.26	-0.22	1.12	05/07/99
Raw	31038	-21.82	24.38	0.25	4.50	05/08/99
Filtered	31038	-0.27	0.056	0.24	1.35	05/08/99
Raw	73672	-21.82	24.38	-0.15	3.86	all
Filtered	73672	-26.79	20.26	-0.15	1.26	all

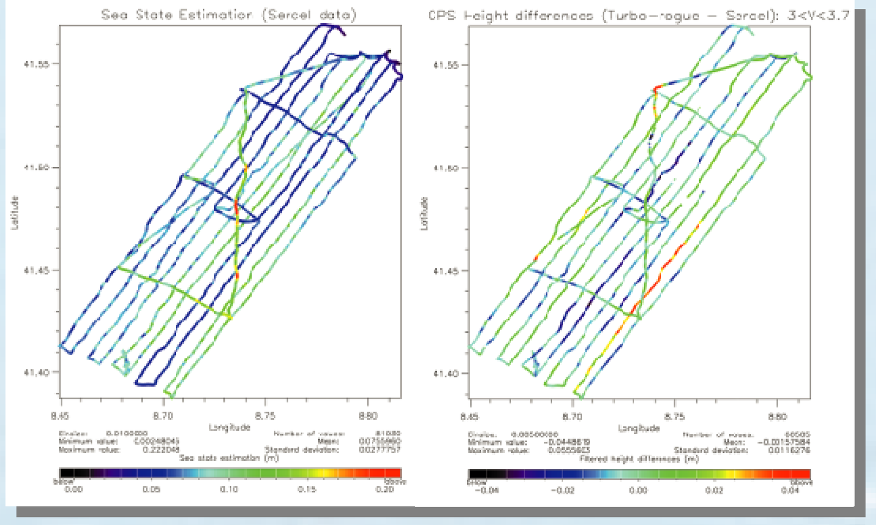

Figure 1. Sea State estimation using Sercel data from 06 to 08 May 1999 (left).
Spatial distribution of GPS sea height differences, TurboRogue - Sercel (right).

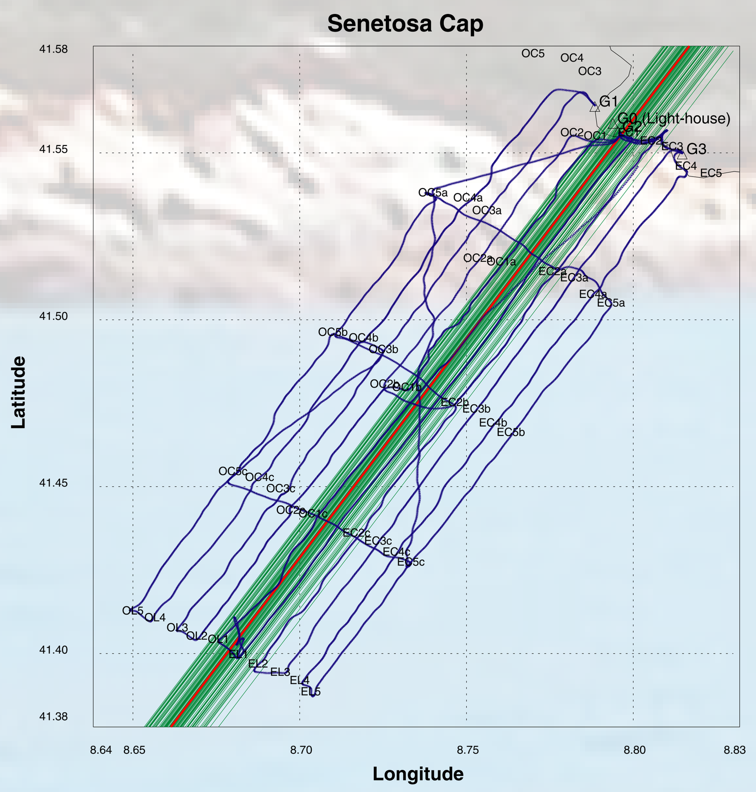

Figure 6. GPS data collected during 99 campaign in blue.
T/P ground tracks in green and mean T/P ground track in red.

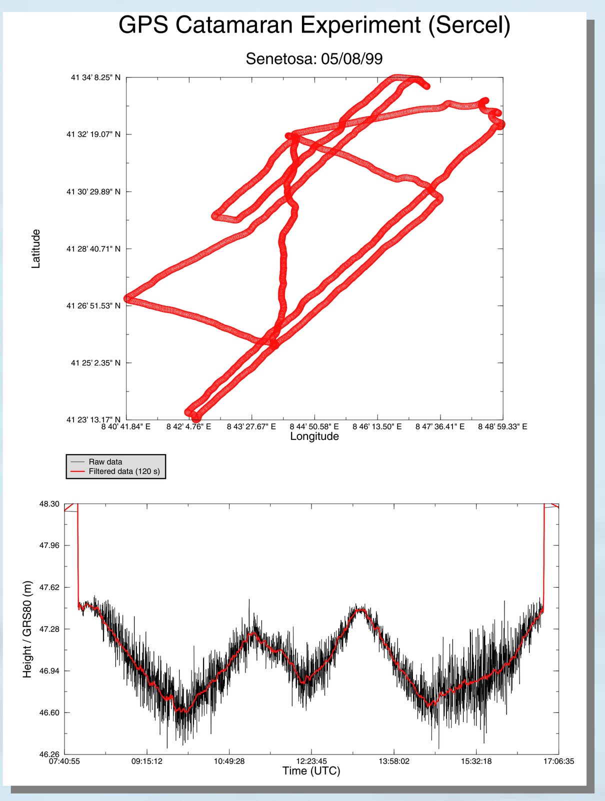

Figure 7. Example of GPS heights from SERCEL data showing the static initializations at the beginning and the end of the 05/08/99 session.
Red lines correspond to filtered heights using Vondrak filter.

2- Comparisons with tide gauge data

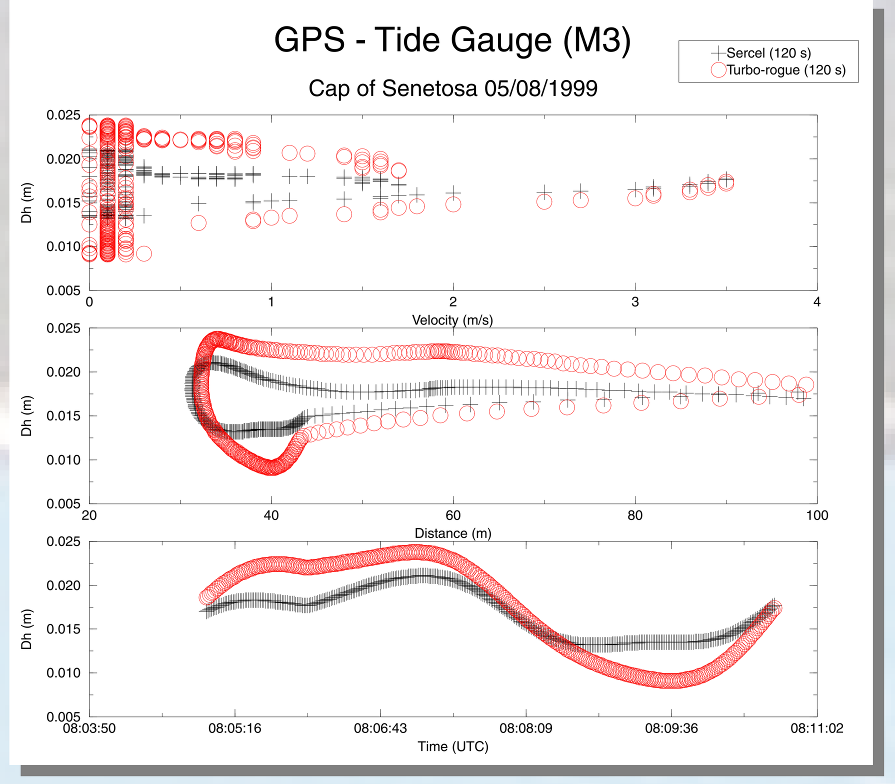

Figure 2. GPS minus tide gauge sea heights as a function of time, distance and velocity.

Table 2. GPS - Tide gauge: (M_3) Heights, units are in centimeter

Number	Min	Max	Mean	Stddev	Comment
258	0.30	2.49	2.05	0.58	05/07/99: 120s (Sercel)
338	1.32	2.11	1.68	0.27	05/08/99: 120s (Sercel)
338	0.91	2.38	1.74	0.54	05/08/99:120s (Turbo-rogue)

Table 2 shows statistics on GPS/Tide gauge comparisons. The very small standard deviation (~0.5 cm) is not really an estimator of the quality. Indeed, due to the sampling difference between GPS (1 s) and tide gauge (5 min), comparisons have been made using only 2 tide gauge data. However, this relatively small standard deviation shows that filtered GPS kinematic data give very coherent results over a period of 5 min. Moreover, the effects of velocity and distance (below 100 m) of the Catamaran relative to tide gauge location is below 1-2 cm (Figure 2).
On the other hand, differences show an average systematism at the level of 1.9 cm (M3). Such a bias had been already evidenced during 1998 between GPS-buoys and M3 but with a smaller value (0.6 cm). This is coherent with the height differences between buoys and Catamaran (see Table 4).
Unfortunately, no data were available for M1 and M2 during 99 campaign.

3- Crossover differences

As in altimetry, crossovers residuals have been used to control the filtered sea heights. GPS crossovers (Xovers) have been determined using the following criteria:
- distance between data of Xing tracks is below 10 m
- velocities of Catamaran for Xing tracks are between 3 and 3.7 m/s
These criteria lead to a high number of comparison because Xovers are not defined as geometric points but as multiple differences in a given area. This leads sometimes to more than 1000 Xovers, notably close to tide gauges where we were turning around. In order to be sure to not bias statistics due to different numbers of Xovers in each area of crossing, mean Xovers have been computed in areas of 10 m (Figure 3a). This gives a synthetic view of height differences at Xover points (Table 3). The mean standard deviation of each average is below 0.1 cm.

No systematism or spatial distortion have been evidenced (Figure 3b) and statistical results of crossover differences are listed in Table 3. The histograms (Figure 3c) for the TurboRogue are sharper than those for the Sercel; however, 70% of Xovers are within ±3 cm for TurboRogue compared to 80% for Sercel. From visual correlation between Figure 3b and Figure 1, the outliers seem to be linked to differences in thesea state. No correlation with distance or time lag has been evidenced (Figure 3c).

Table 3. Mean Xover of GPS filtered height differences (120s), units are in centimeter

Number	Min	Max	Mean	Stddev	Receiver
238	-8.33	7.72	-0.42	2.82	Turbo-rogue
380	-7.83	7.92	0.17	2.66	Sercel

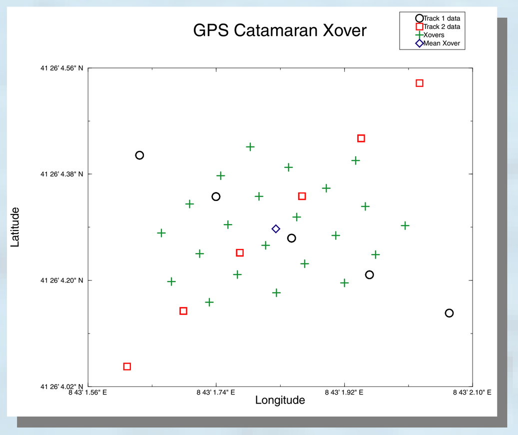

Figure 3a. Graph of Xover process, based on real data.
Circles and squares correspond to data from tracks 1 and 2 respectively.
Crosses are the Xovers between all data while diamond is the mean Xover for this area.

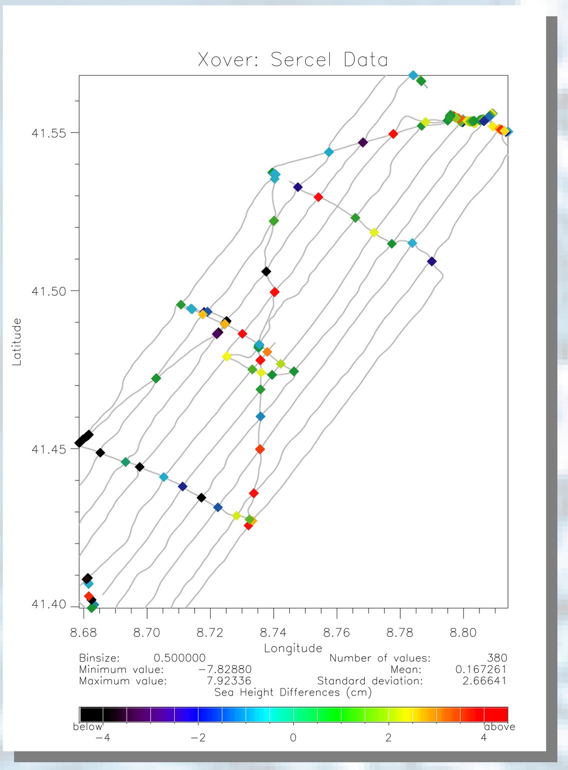

Figure 3b. Crossover differences for Sercel data using filtered sea heights.
Gray lines represent boat tracks.

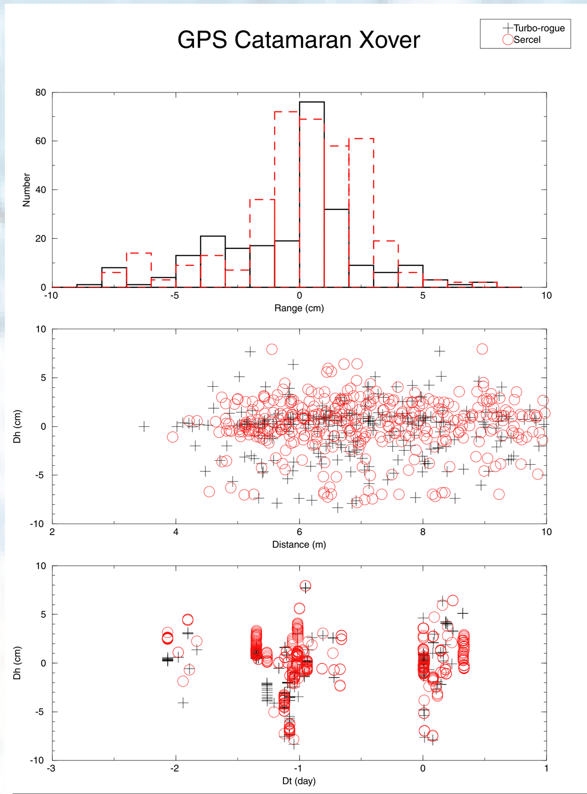

Figure 3c. Crossover differences for TurboRogue and Sercel data as a function of time lag (Dt) and distance. Upper panel show histograms of crossover differences.

4- Comparisons with Buoys campaign

Table 4. Gridded filtered height differences Cata - Buoys, units are in centimeter

Number	Min	Max	Mean	Stddev	Receiver
7401	-3.99	10.03	1.10	1.99	Turbo-rogue
4137	-3.67	7.78	1.47	1.51	Sercel
7950	-10.22	10.73	1.55	1.90	All

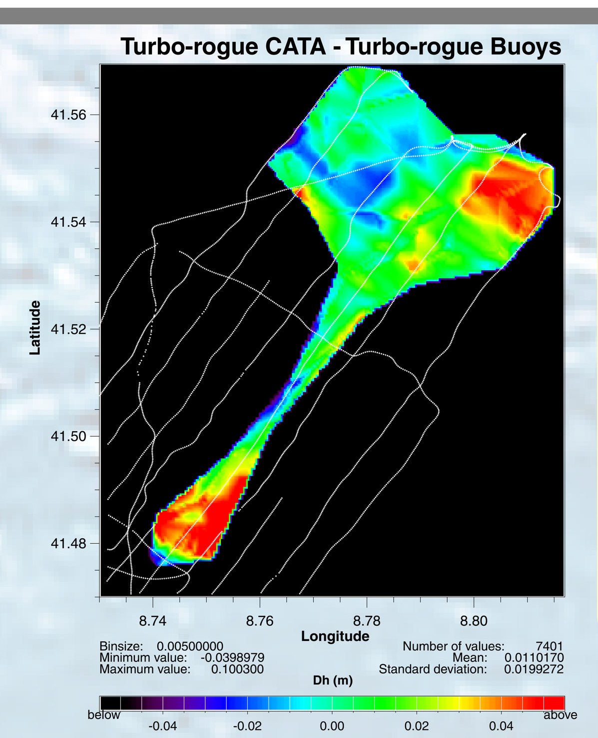

Figure 4. Map of sea heights differences between 98 and 99 campaigns (for TurboRogue data).

The 98 and 99 grids obtained from TurboRogue, Sercel and all data have been compared at each common mesh point. Results summarized in Table 4 show a systematism at the level of 1.6 cm (Catamaran grid higher than Buoy grid).

This bias could be interpreted as a difference between antenna height references for example due to the waterline definition. However, for the buoys the Sercel, TurboRogue and Ashtech results were coherent within a few millimeters. Moreover, the waterline and antenna heights for the Catamaran have been measured at the beginning and the end of the campaign using several techniques and people. Results were coherent also within the millimeter level.

This bias is thus likely related to the main difference between the two campaigns: the boat velocity. Indeed, waterline measurements have been realized without velocity. However, except in the case illustrated in Figure 2, it was really difficult to identify and quantify such velocity effect. Differences at the centimeter level can be due to a several effects which are difficult to separate (GPS process, filtering, boat behaviour, ...).

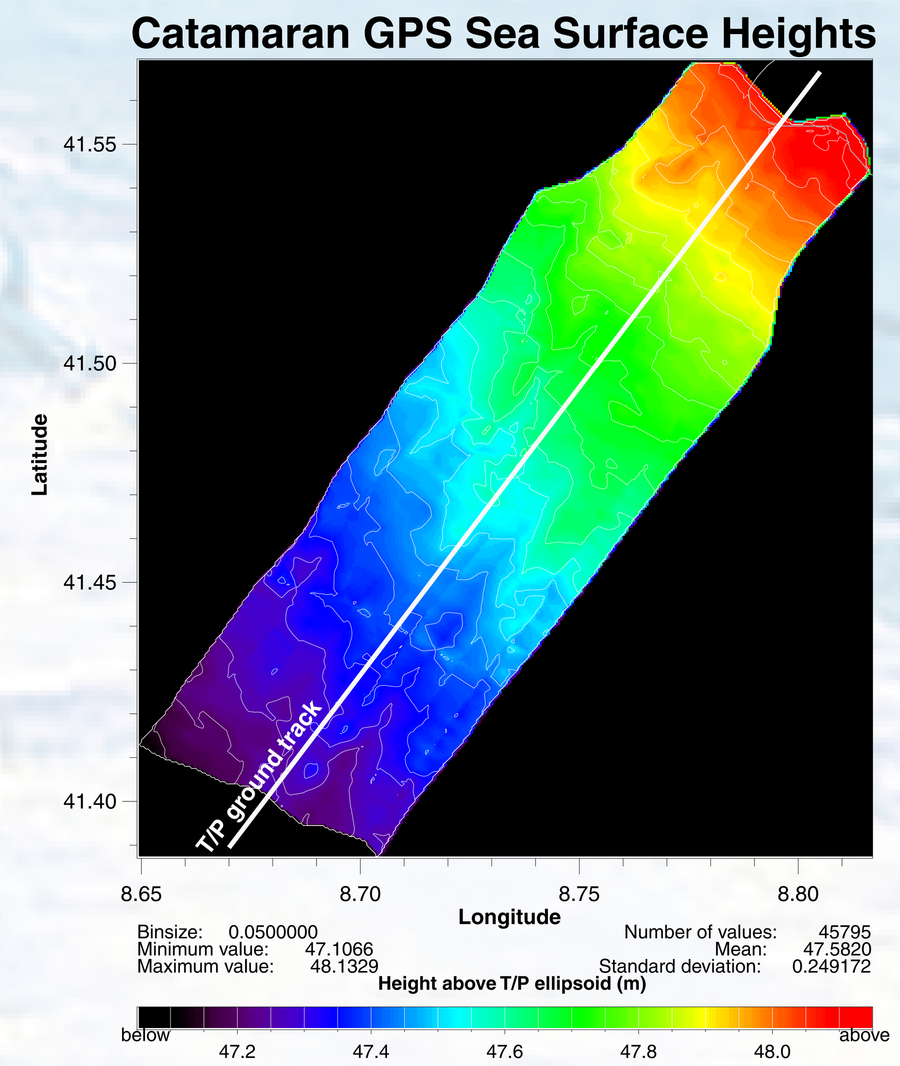

Figure 8. Map of GPS sea heights using both Sercel and TurboRogue data (99 campaign).

5- Impact on Calibration

In terms of calibration, standard deviation of the altimeter bias has been inproved by 1.6 cm rms (from 49 to 33 mm), thanks to the 99 campaign. The reduction can be attributed to both the improved quality of the grid estimates and to the better coverage (most notably off shore, Figure 8).

Moreover, apart from the vicinity of coast (<5 km) the GPS sea heights are in very good agreement with the corresponding T/P "mean sea profile". Differences are at level of 1.1 cm rms (Figure 5).

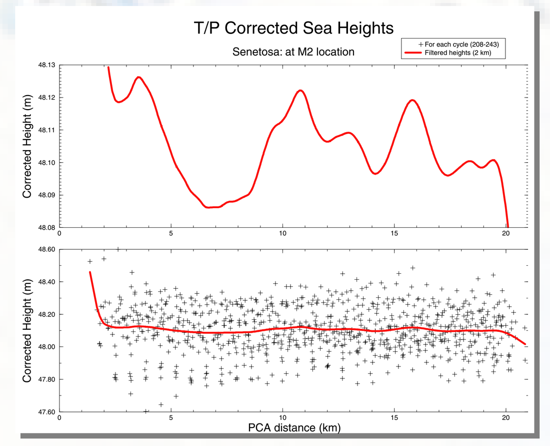

Figure 5. T/P Sea heights (1/10s) corrected from geoid slopes at tide gauge (M2) location.
Red lines correspond to filtered heights using Vondrak low-pass filter with 2 km cutoff.
Upper panel is a zoom for filtered heights.