CASE-STUDY OF THE NORTHERN ADRIATIC SEA

HYDROCOASTAL PROJECT

SUB-CONTRACT [SATOC-CNR] TO RACZIW CONTRACT N. [4000129872/20/I-DT]

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1. Introduction

The Northern Adriatic Sea, with Veneto and Friuli-Venezia Giulia regions has about 2.400 km^2 of low-lying areas along 300 km of coast (Bondesan et al., 1995). Some important inland water basins are found in this coastal zone: the lagoons of Marano-Grado and Venice, and the Po River with its delta (Figure 1). These areas are exposed to sea level rise and storm surge related risks. Coastal lagoons are similar to lakes but connected to the ocean (Tagliapietra et al., 2009). Coastal lagoons are a geographically well-defined typology, possibly protected from wave action and exposed to weaker and less persistent winds. A study in Arcachon Bay, a typical semi-sheltered lagoon located on the Atlantic coast of France, showed ERS, ENVISAT, SARAL and CryoSat-2 altimetry accurate at >40 cm against ground-truth (Salameh et al., 2018). There is no study (with validation) using Sentinel-3. The Po River has been flowing at extremely low levels since 2022, with the sea water going inland along the delta, making the water more saline and putting at risk the agriculture sector that uses water for irrigation. The surface level variability is an important driver of the salinity variability from the coast to upriver (Nienhuis et al., 2023). HydroCoastal project provides for the first time a joint coastal zone and river data set that will permit to relate coastal sea level and river water surface levels and discharge.

The results of the analysis presented in this study are separated for the lagoon areas and for the coastal zone. In the following sections the words “LAGOON” and “SEA” are used to distinguish results pertaining to the lagoon areas from those valid in the offshore coastal zone.

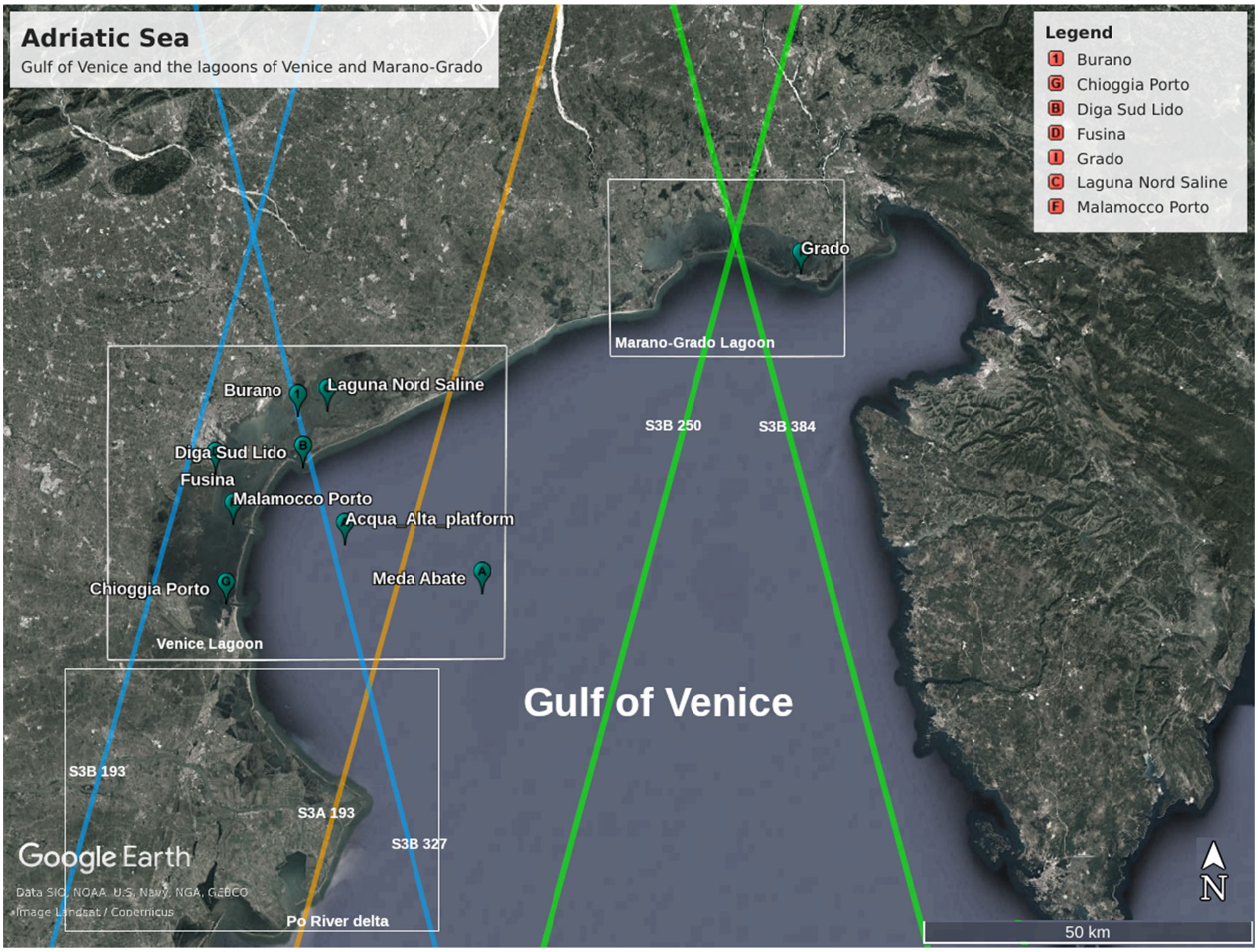


Figure 1.1: Study area: the Gulf of Venice in the northern side of the Adriatic Sea. The Venice Lagoon and the Marano-Grado Lagoon, in the white rectangles. The Venice Lagoon is cut by S3B tracks 193 and 327 (blue lines). S3B tracks 250 and 384 cross over the Marano-Grado Lagoon (green tracks). The orange track is S3A 193, crossing the coastal area in front of the Venice littoral. Several tide gauges record relative sea level inside and outside the lagoons.

2. Marano-Grado coastal lagoon

The Marano-Grado Lagoon covers an area of 160 km^2, with a length of nearly 32 km, an average width of 5 km, and shallow depth that is less than 1 m on average on the eastern part. Marine waters enter the lagoon, moving northward, via the main tidal inlets of Grado, Porto Buso, and Lignano. Sea level changes impact ecosystems (e.g., salt marshes), human activity (e.g., fishery) and land (e.g., salt water intrusion into aquifers) (Fontolan et al., 2012). The Marano-Grado lagoon is crossed by Sentinel-3B (S3B) along two tracks (250, 384) and CryoSat-2, also covering the offshore coastal zone.

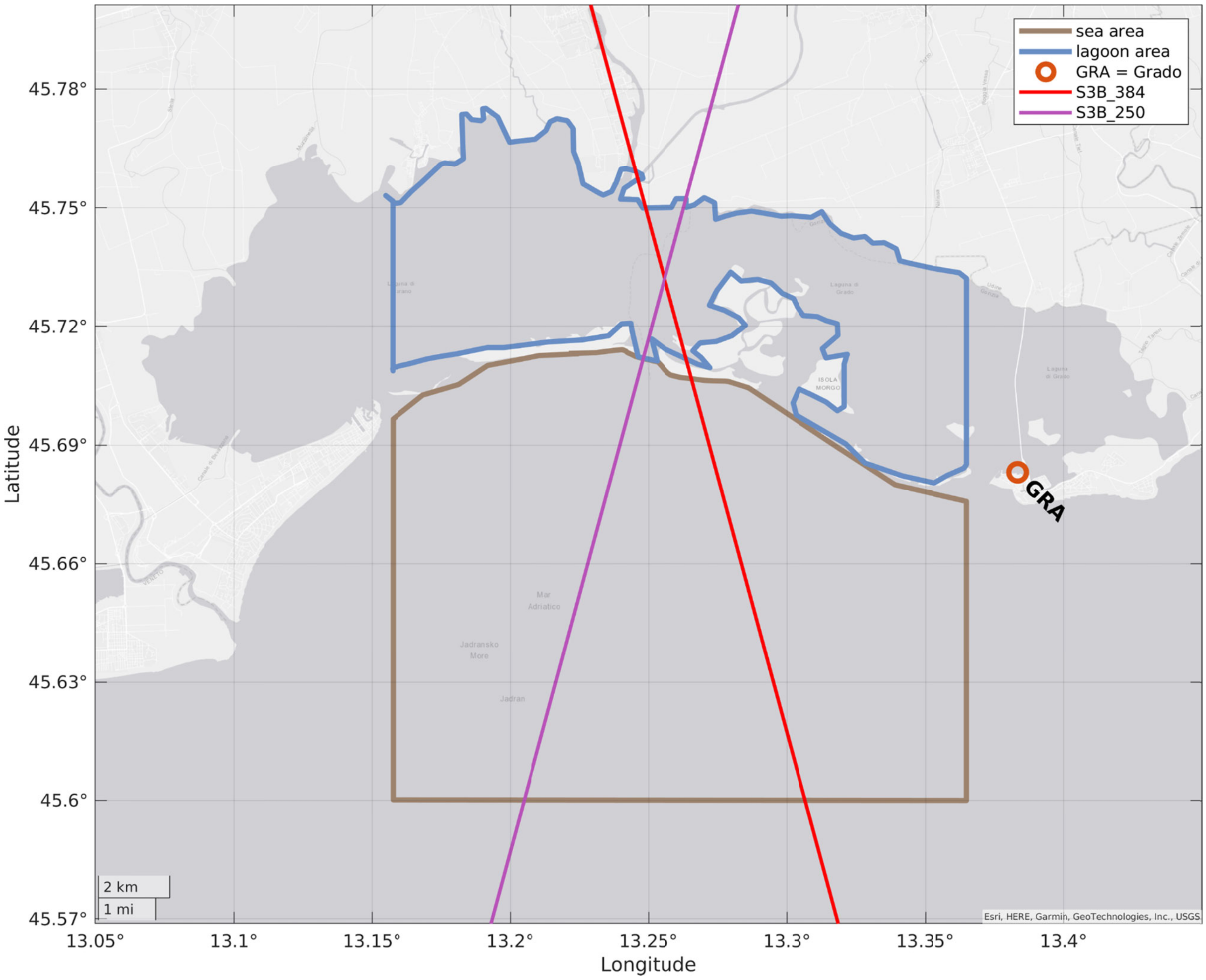


Figure 2.1: The position of the Grado tide gauge and of the S3B tracks 250 and 384 in the Marano-Grado Lagoon. The SEA and LAGOON areas are also highlighted.

The automatic meteo-marine stations of Grado in the Marano_Grado Lagoon AOI is owned by the Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA), Centro Nazionale per la caratterizzazione ambientale e la protezione della fascia costiera, la climatologia marina e l'oceanografia operativa, which kindly provided us with all available station data since 2010. The Grado tide gauge is located at 45.68313°N, 13.38344°E.

2.1 Objectives

The main objectives of the impact assessment with reference to the Marano-Grado lagoon are:

- to assess the HydroCoastal product in this lagoon;
- to show that coastal lagoon altimetry can be more accurate than coastal offshore altimetry;
- to demonstrate the benefits and the scientific value of an improved lagoon altimetry product.

2.2 Methodology / Data Processing

A land-sea processor for Sentinel-3 was coded in Matlab to assess the performance of the HydroCoastal product. The main functionalities of the processor were: a) to read the HydroCoastal product; b) to compute the surface level anomaly for comparison with tide gauges (TG) or for scientific exploitation; c) to inter-compare the HydroCoastal product with the official ESA product and other existing products. One is the SAR Versatile Altimetric TOolkit for Research and Exploitation (SARvatore) for Sentinel-3, starting from L1A altimeter data, that uses the GPOD (now EarthConsole, hereinafter GPOD) platform (Dinardo et al., 2016). The second is the range from the Precise Inland Surface Altimetry (PISA) processor (Abileah et al., 2021).

2.2.1 FES tide

We have assessed the performance of FES2014b tidal model (Lyard et al., 2016) in the lagoon through sensitivity tests, calculating the astronomical tide for ten years for the Grado tide gauge, with the Utide package (32 and 8 components), synthesising it with the FES2014b model (34 components), and comparing the results with the official astronomical tide analysis computed by the local authority in charge of tide forecasts (8 components). FES2014b gave results of similar or better quality with respect to the official analysis. The metrics used was the RMSD between the reproduced astronomical tide and the sea level time series.

2.2.2 Mean sea surface

The Mean Sea Surface (MSS), which is the average of Sea Surface Height (SSH) over a period of time, has been traditionally computed as an along track profile. Merging data from multiple missions permitted to create a MSS over a global grid. A gridded MSS is necessary for drifting missions as CryoSat-2. As large discrepancies are still noted after zooming in some coastal sites, two native MSS data sets were recovered and tested in the lagoon: CLS-CNES 2015 and DTU 2018. The CNES-CLS 2015 MSS model is referenced to the 20-year period 1993-2012 (Pujol et al., 2023). The DTU 2018 is referenced to the 25-years period 1993-2017 (Andersen et al., 2018). The two MSSs were compared with global and local geoids in order to ascertain their suitability. Comparison with TG measurements was considered essential to enable the full scientific exploitation in lagoons. The recipe used to transform range to a quantity comparable to tide gauge observations is reported in the following section.

2.2.3 Quality flags

The valid values retained for the HydroCoastal data are those for which the corresponding flag is set as good. They are:

● flags_ubo_swh	quality flag SWH	[**0** success, 1 failed]	for UBONN SWH
● flags_ubo_sig0	quality flag sigma0	[**0** success, 1 failed]	for UBONN σ_0
● flags_ubo_range	quality flag range	[**0** success, 1 failed]	for UBONN range
● flags_dtu	Use data with flags	[**0** and 1]	for DTU range

rain_flag and rad_surf_type were not used.

No flags were considered for the ESA range, σ_0 and SWH.

Moreover, only altimetry measurements collocated on water were considered:

● surf_type	Surface Type Flag	[**0** ocean, **1** enc.seas/lakes, 2 ice, 3 land]

In both the Marano-Grado Lagoon and Venice Lagoon, some additional land and water masks have been defined, and the surf_type flag set accordingly.

2.2.4 Methodology used to compare ALT and TG

In order to compare satellite radar altimetry observations with time series of relative sea level height registered at the Grado harbour, we calculated the total water level envelope (TWLE) anomalies for both the altimeter and the tide gauge. TWLE is the geocentric sea level height measured by the altimeters, i.e. the sea level inclusive of ocean, polar, load and solid earth tides, atmospheric forcing, wave setup, etc. As the relative sea level height measured by tide gauges does not include the solid earth tide, the load tide and a fraction of the geocentric polar tide, such terms are subtracted from the altimetric TWLE (Fenoglio-Marc et al., 2015). Finally, also the chosen MSS is subtracted from altimetric TWLE. Tide gauge observations are transformed to TWLE anomalies by subtracting the local MSS. Such TG MSS is obtained by averaging the TG sea level signal over the same time period used to obtain the altimetry MSS. This procedure permits us to compare the two anomalies in a consistent way, despite the fact that only relative measurements are used, instead of absolute ones. In terms of HydroCoastal L2 product parameters, the formulas for obtaining the altimetric and the tide gauge TWLE anomalies are given below.

TWLE anomaly for altimetry:

$$L_{alt} = altitude\ -\ range_{uncorr} - atmospheric_{corr} - tide_{land} - {MSS_{alt}}^{(time\ span)}$$

$$atmospheric_{corr} = tropo_{wet} + tropo_{dry} + iono_{gim}$$

$$tide_{land} = tide_{solid\ earth} + tide_{load\ fes} + 0.468 * tide_{geo\ polar}$$

TWLE anomaly for tide gauge:

$$L_{tg} = level_{tg}\ - {MSS_{tg}}^{(time\ span)}$$

All the tide gauge data used in this study are referenced to the same local datum: the zero mareografico di Punta della Salute, ZMPS in short. Punta Salute is the official zero-height reference to which sea level heights are measured in the Venice and Marano-Grado lagoons by local and national agencies: the Centro Previsioni e Segnalazioni Maree (CPSM) of the Venice Municipality, and the Servizio Laguna of the Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA). It corresponds to the Venice mean sea level of the years 1884-1909 (conventionally referred to 1897). For such a reason it has been called Zero Mareografico di Punta Salute (ZMPS). It is known to be about 32 cm lower than the actual mean sea level in 2022 (AA.VV., 2022), because of eustatism and local subsidence.

The comparisons between altimetry data and *in situ* observations follow these rules:

1. The observations of each altimetry pass over the area of interest (AOI) are divided in two sets: the observations falling inside the LAGOON area and those falling inside the SEA area. For each of the two altimetry sets, the median value is chosen as representative for that satellite pass in the two regions of the AOI (LAGOON and SEA);
2. Tide gauge representatives of sea level (L)/wind speed (WS)/significant wave height (SWH) are chosen selecting the *in situ* observations matching the mean time of the altimetry flight over the AOI ± 26 minutes, so that at least 5 regular observation are selected if sampling period is 10 minutes, or 10 regular observation for sampling period of 5 minutes. The

selected *in situ* data are then linearly interpolated to the exact mean pass time of the satellite over the AOI;

3. The two time series, formed by one altimetry median value for each satellite pass, for each track (in case of S3) and each region of the AOI, and a single value of the *in situ* data identified by linear interpolation around the pass mean time, are then used for calculating the statistical indicators described in the following section.

2.2.5 Statistical indicators used to compare TWLE anomalies

Five statistical indicators have been used in the study, in order to give a solid picture of the different characteristics of the observations and of their differences. Indicated with X_i and Y_i the occurrences of two datasets to be compared pairwise, the five indicators are defined as:

- BIAS: $\underline{X} - \underline{Y}$
- MAE: median absolute error $MAD \ = \ median(|X_i - Y_i|)$
- RMSD: root mean square difference $RMSD \ = \ \sqrt{\frac{1}{N}\sum_{n=1}^{N} \quad [(X_i - Y_i)]^2}$
- MAD: median absolute deviation $MAD \ = \ median(|X_i - Y_i - (\underline{X - Y})|), \quad \underline{X} = median(X)$
- CRMSD: centred RMSD $CRMSD \ = \ \sqrt{\frac{1}{N}\sum_{n=1}^{N} \quad \left[(X_i - \underline{X}) - (Y_i - \underline{Y})\right]^2}, \quad \underline{X} = mean(X)$

BIAS and MAE are indicators of accuracy in the reproduction of one dataset by the other. While BIAS is sensitive only to the average-error magnitude, MAE also varies with the variability within the distribution of error magnitudes, thus combining both disagreement factors in a number.

MAD and CRMSD express the degree of precision in one dataset reproducing the other: while MAD weighs the errors in a linear manner, CRMSD is more sensitive to outliers as they count as squared terms in the error sum. Being MAD and CRMSD independent from the averages of the two datasets, they are complementary to BIAS and MAE.

RMSD is an expression of both the variability within the distribution of error magnitudes and the average-error magnitude. Moreover, it also gives higher weight to outliers. For such reasons RMSD is an indicator of accuracy, precision and dispersion.

2.2.6 Sea state bias

Having as objective the assessment of altimetry products in coastal lagoons, we have not used the sea state bias correction. The reason is that coastal lagoons are less affected than the open sea by strong winds and waves. Moreover, as coastal lagoons are subjected in general to shorter fetch, the usual global formulation of sea state bias based on the significant wave height could give biased results.

2.3 Results

Before getting HydroCoastal data, altimeter data collected along the two S3B tracks were scrutinised, with special focus on the impact of: a) reflectivity of the sea surface on radar echoes over lagoon; b) impact of geophysical corrections and vertical references on SLA; c) global vs local bathymetry. An *in situ* survey permitted to identify fish farms and enclosed bays not connected to the sea that were then masked. Results of these analyses were presented during previous project progress meetings and then summarised during the talk at the 13 Coastal Altimetry Workshop that took place in Cadiz (Spain) from 6 to 10 February 2023. Briefly, several specular and quasi-specular echoes were found inside the lagoon, with more specular echoes in S3B track 384 (ascending), especially in the northern part, than S3B track 250 (descending) where land interference can explain less pure specular behaviour. Clusters of similar surface levels over time were identified over specific land areas and are consistent with the underlying topography. Large number of echoes were also recovered inside narrow rivers (width of 50-100 m), predominantly along the Corno River because of its collinearity with the S3B track 384. The impact assessment of the geophysical corrections on the surface water levels within the lagoon shows that the Dynamic Atmospheric Correction (DAC) is the second source of sea level variability, while astronomical tides (from FES2014b model) are the first one. Residual SLA includes currents, residuals pressure effects not corrected by instantaneous IB (typical of Mediterranean basin). The consistency of data was confirmed by the inverted slope of the tide between the two S3B tracks, matching the expected latitudinal variability of tides with the pass direction. The performance assessment of FES2014b model showed that when Utide was forced to use the FES harmonics (32 out of 34) modelled tides agree at ~2 cm with those at tide gauge (FES assimilates Trieste TG but not Grado TG). DTU 2018 and CLS-CNES 2015 MSSs have been also assessed in the lagoon and results are summarised in a technical note (De Biasio and Vignudelli, 2023), where we suggested a preferable MSS (DTU 2018) based on literature and on consistency with local and global geoid slopes. A new methodology that makes use of the specular or quasi-specular reflections of the high-resolution radar signal was also tested for data selection in lagoons.

The performance of HydroCoastal data set was finally evaluated in comparison with in-situ observations from tide gauge located in Grado as well as L2 state-of-the-art products (SARvatore) from the former GPOD ESA service, using 82 cycles of S3B (41 track 250 + 41 track 384), over the SEA and LAGOON areas of the Marano-Grado region. The UBONN retracker provides range, significant wave height and backscatter; the DTU retracker provides only range. The comparison of results using UBONN and DTU has been presented at PM13 with statistics indicating low-bounds about precision and accuracy. As the HydroCoastal UBONN retracker needs a MSS as input, the same MSS has to be used when calculating TWLE anomalies, to be consistent. CLS-CNES 2015 MSS was fed to the UBONN retracker, so we have to adhere to the same protocol, and use the same MSS to compute TWLE and SLA anomalies. The remaining altimetric retracked ranges (ESA/ocean retracker, HydroCoastal/DTU, GPOD/SAMOSA+) can use any MSS for calculating the anomalies. To investigate the impact of the MSS used in the retrieved anomalies, and having in mind that the two available MSSs overlap off-shore, an experiment was done, calculating the histograms of the SLAs for the three HydroCoastal retrackers for the SEA and the LAGOON areas. Figure 2.2 shows these histograms: for the SEA area (left panel), the CLS-CNES 2015 MSS was used for all the retrackers. For the LAGOON area (middle and right panels), CLS-CNES 2015 MSS was used for UBONN, while ESA and DTU anomalies were calculated subtracting the CLS-CNES 2015 MSS (middle panel) and DTU 2018 (right panel). ESA/UBONN/DTU SLA relative frequencies are centred around the same SLA in the SEA zone; the official ESA SLA has a broader shape with respect to UBONN and DTU. It should be noted that UBONN retrieves 3% less measurements than ESA and DTU in such region. In the LAGOON area ESA/UBONN/DTU SLA relative frequencies are centred around different values, due to some extent to the MSS used. The official ESA SLA has a broader shape with respect to UBONN and DTU. UBONN retrieves 37% less measurements than ESA and DTU inside the lagoon. If DTU MSS is used for ESA and DTU SLAs (right panel), the histogram of DTU mostly overlaps that of UBONN, while that of ESA gets shifted by about half a metre towards UBONN.

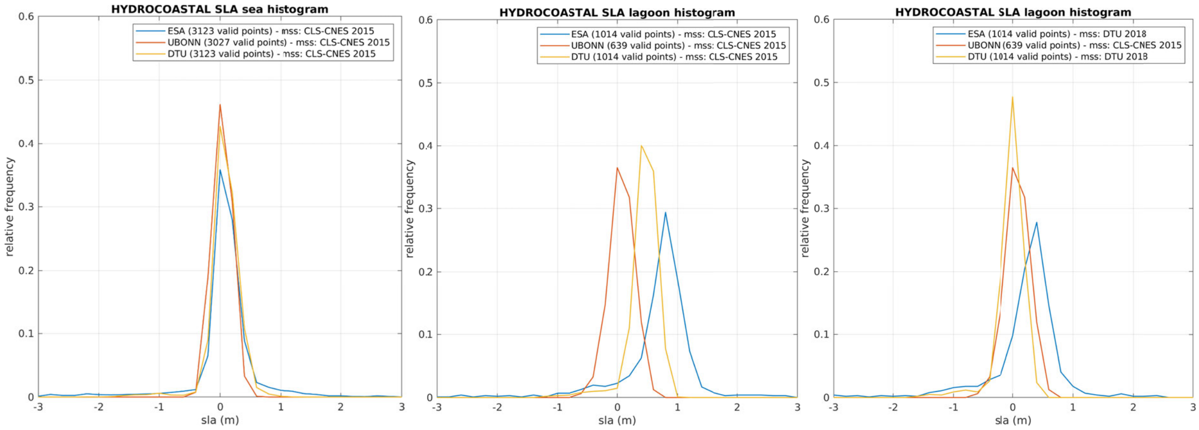


Figure 2.2: left:Histograms of HydroCoastal measurements in SEA area; middle:Histograms of HydroCoastal measurements in LAGOON area; right:Histograms of HydroCoastal measurements in LAGOON area (using DTU MSS for ESA and DTU retrackers)

The altimetry data registered during the 82 cycles along the two S3B tracks were compared to the tide gauge heights at the time of the satellite pass. The comparison has been made separately for the coastal region off-shore the Marano-Grado Lagoon, and inside the lagoon. The results of the comparison are depicted in Figure 2.3 for the SEA region, and Figure 2.4 for the LAGOON region. Five statistical indicators have been chosen to summarise the results of the study (see Methodology section). They are BIAS, MAE, MAD, CRMSD and RMSD. BIAS and MAE are good indicators of accuracy; MAD and CRMSD are more appropriate for evidencing precision. RMSD is an expression of both precision and accuracy.

Figure 2.3 shows the differences of altimetry and tide gauge TWLE averaged over each cycle, for HydroCoastal ESA (original) range, HydroCoastal UBONN range, HydroCoastal DTU range and GPOD SAMOSA+ range, in the SEA region. Measurements from both tracks are accumulated and shown with increasing time. All retrackers perform similarly at sea, agreeing well with TG in terms of BIAS, MAE and MAD , and ESA having the highest RMSD and CRMSD. It should be noted that UBONN has no outliers. This confirms what reported in the HydroCoastal Product Validation Report, where UBONN and DTU have been found to provide accurate range measurements in coastal regions, with the UBONN re-tracker showing lower levels of noise, but both the DTU and UBONN retrackers showing similar accuracy in comparisons against tide gauge data.

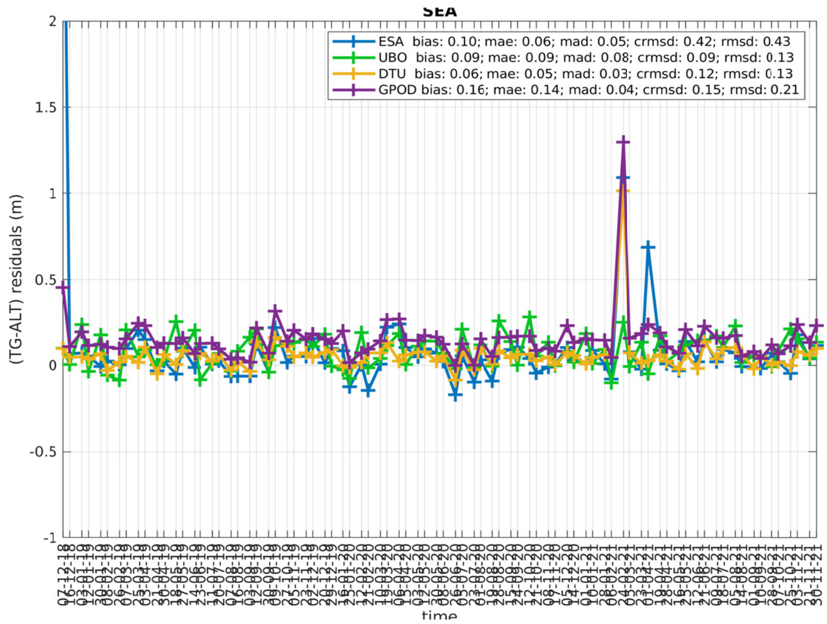


Figure 2.3: absolute values of the TWLE anomaly differences (L_{alt}-L_{tg}) for the SEA region, for both tracks S3B 250 and 384, in chronological order. Some outliers are visible for the ESA, GPOD and DTU retracked ranges. The absolute difference is generally within the ±25 cm range.

Figure 2.4 is the same as Figure 2.3 but for the LAGOON area. UBONN and DTU perform much better than (original) ESA. DTU has a bias of -37 cm, higher than UBONN and GPOD, but has the lowest MAD and CRMSD (inaccurate but precise). Using DTU 2018 MSS, DTU is both accurate and precise: BIAS 0.10, MAE 0.10, MAD 0.03, CRMSD 0.05 RMSD 0.12 (not shown), performing quite similar to UBONN. UBONN has the lowest bias (accurate) and MAD and CRMSD higher than DTU and similar to GPOD.

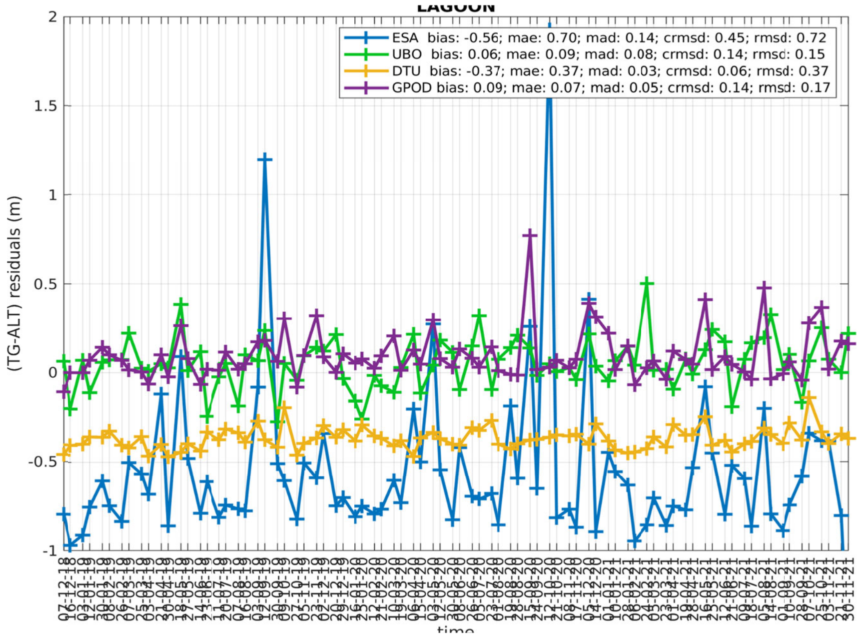


Figure 2.4: same as above, but for the LAGOON region. Outliers are still present, and significant biases are noted for DTU and ESA ranges.

The results graphically described in the two figures, are summarised in Table 2.1 and 2.2. In the SEA region, DTU and UBONN perform similarly well, with low values of all the five indicators. GPOD suffers for a small bias which penalises BIAS and RMSD, and for some outliers which enlarge the value of the CRMSD. ESA has very low values of BIAS and MAE, but the presence of more outliers than the other retrackers penalises both the CRMSD and the RMSD.

In the LAGOON region, ESA shows low precision and accuracy (high BIAS and MAE, high MAD and CRMSD). DTU exhibits scarce accuracy (high BIAS and MAE) but high precision (low MAD and CRMSD). GPOD and UBONN have similar performances.

Table 2.1: statistical indicators for the TWLE anomaly differences (L_{alt}-L_{tg}) in the SEA region. Values are in metres.

SEA	**ESA**	**UBONN**	**DTU**	**GPOD**
BIAS	0.10	0.09	0.06	0.16
MAE	0.06	0.09	0.05	0.14
MAD	0.05	0.08	0.03	0.04
CRMSD	0.42	0.09	0.12	0.15
RMSD	0.43	0.13	0.13	0.21

Table 2.2: statistical indicators for the TWLE anomaly differences (L_{alt}-L_{tg}) in the LAGOON region. Values are in metres.

LAGOON	**ESA**	**UBONN**	**DTU**	**GPOD**
BIAS	-0.56	0.06	-0.37	0.09
MAE	0.70	0.09	0.37	0.07
MAD	0.14	0.08	0.03	0.05
CRMSD	0.45	0.14	0.06	0.14
RMSD	0.72	0.15	0.37	0.17

2.4 Summary

State of the art products have demonstrated in a number of test coastal regions that it is possible to enhance the quality and quantity of the altimeter data exploitable close to the coast. For instance, comparisons of along track data to nearby tide gauge observations around Australian coast show RMSE accuracies in the range 10-20 cm in the 0-5 km coastal strip (Peng et al., 2021). Similar results (5-15 cm) are found using tide gauges located in West Africa, North East Atlantic and Mediterranean (Birol et al., 2021). On average, 30-40 cm in the 0-3 km along track coastal segment are found using several tide gauges along the Baltic Sea (Passaro et al., 2022). These studies are part of a larger effort in validating altimetry products around the world's coastline, e.g. in the Mexican Caribbean (Palma-Lara et al., 2023), Spanish coast (Aldarias et al., 2020), in the Southern Bay of Biscay (Vu et al., 2018), Hong Kong (Xu et al., 2018), etc.

With the HydroCoastal product, we show for the first time that Sentinel-3 is capable of retrieving data at land-sea-boundary and waters within land.

The scientific analyses show very good comparisons to *in situ* data, with MAD of the order of 3 cm and MAE of the order of 5 cm. There is a clear consistency between the three satellite-based independent products. UBONN and DTU comparisons against tide gauge are in a very good agreement. For GPOD RMSD are higher (17-21 cm). ESA has the worst performance with the highest RMSD of 43-72 cm. However better results were found when using suitable MSSs (DTU2018).

Altimetry measures sea level offshore, while TGs are in harbours: this has been a central issue in the coastal altimetry workshops. As part of the study, we have also proposed a new approach based on the PISA processor described in Abileah and Vignudelli (2021) to assess performances, using only bursts over LAGOON that are specular or quasi-specular. By using this approach, the precision is measured from burst-to-burst variability with respect to the TG. The accuracy is measured by matching altimetry and *in situ* measurements. Bursts inside the lagoon are found more accurate than bursts outside the lagoon: sea state is more complex offshore.

2.5 Highlight main findings

The case-study of Marano-Grado showed that altimeter data exploitation is now possible where previously not considered (lagoons). The study permitted better understanding of data, from echoes to sea level, as the radar altimetry is a system and not only an instrument.

From the technical note on MSS that has been submitted to ESA, we have suggested a preferable DTU 2018 MSS based on literature and on consistency with local and global geoid slopes.

Analyses of retrieved echos that were presented at the Coastal altimetry Workshop in Cadiz, highlighted some interesting findings that we mention hereinafter.

- An assessment of the FES2014 model in the lagoon showed good agreement in terms of statistics at TG in Grado;
- A survey in the lagoon showed that there are areas disconnected from the lagoon (e.g. fish farms) that need to be masked with novel methodologies. Using 80 hz instead than 20 hz would be more appropriate in lagoons;
- Flat land altimetry patterns and small rivers (Corno and Auser) were also consistent from cycle to cycle, demonstrating that S3 altimetry is promising to retrieve data in these areas;
- Icesat-2 is another independent data set that can be used to validate the radar altimetry products.

2.6 Potential Scientific / Operational Impact (“Benefit and unique value”)

Sheltered coastal regions are shallow transition zones characterised by slow water flow, low wind and waves, and intertidal marshes further protecting confined portions of the water surface from wind. Around 32,000 lagoons (Carter et al., 1996) are identified along 13% of the world's coastline (Barnes, 1980). Because of sparse *in situ* measurements, especially in developing countries, many coastal lagoons remain un-gauged in the world. The usage of satellite data is currently the only option to monitor sea level changes, besides the fact that *in situ* observations are expensive and need continuous efforts for monitoring and maintenance operations. Moreover, satellite altimetry in such an environment gives continuity of observations from open ocean through the coast and inland. The proposed approach can be applied globally where the altimeter crosses a lagoon. Altimetry measuring precisely coastal sea level inside lagoons is an emerging technology which could push this satellite measuring system further inland than ever.

2.7 Recommendations

The in depth altimeter data analyses outlined a number of topics to be addressed, including specific R&D investigations that deserve further consideration, with future projects to be implemented. Hereinafter some recommendations:

- Specular and quasi-specular echoes are seen as recurrent and precious for lagoon altimetry: they can be the key for bringing altimetry further inside sheltered areas (e.g., bays) than ever before. It is recommended to extend the analysis to other lagoons;
- Specular echoes in lagoons could be used for calibration of radar altimetry, as they can be seen as a handy laboratory for understanding the interaction of active microwaves, water and land;
- Marano-Grado Lagoon suggested as cal/val area for the Sentinel-3B, Sentinel-6 and ICESat-2 missions, a laboratory where a better understanding of radar reflectance at the sea is facilitated, thanks to existing infrastructures and easy logistics;
- Further analyses are recommended to investigate the physics of echoes and how they relate to surface types and wind conditions;
- Regionalization of range, wind and significant wave height algorithms, as the interface of sea and land, the coastal zone, has different characteristics than global ocean, and is also of paramount interest for the monitoring of sea level rise and for storm surge applications;
- An improved MSS is necessary and should be computed using the new reprocessed 20/80 Hz data;
- Consistent MSS and geoid are necessary to join sea and land properly. We recommend a dedicated study to assess MSS and geoid and the northern Adriatic sea is a good laboratory to test with the local ITALGEO geoid.

3. Venice coastal lagoon

The Venice lagoon rests in a fragile balance, subjected to physical, geological, and biological processes (e.g., shoreline erosion, subsidence, eustatism, habitat variability, ecosystem dynamics, storm surges). It is highly sensitive to changing environmental and climatic conditions. It is acknowledged as a spot of sea level variability in the region. Coastal lagoons have not been sufficiently explored yet with satellite radar altimetry.

Storm surge is a regional phenomenon due to the Sirocco wind, directed along the main axis of the Adriatic Sea basin and causing a stronger signal in the northwestern part, especially in the city of Venice. Here, the well-known “Acqua Alta” phenomenon (High Water) takes place. The challenge is to forecast the height of water at time of a surge event, as well as the extent to which it will inundate the city. The key quantity in surges is the TWLE, i.e. the Sea Level inclusive of ocean, polar and ocean load tides (omitting a fraction of the solid earth tide), atmospheric forcing, wave setup, etc (see section 2.2). Sea level anomaly (SLA) can be measured with precision of a few cm. We can also get wave height and wind speed at same time. A unique profile of these quantities is available from offshore to the coast when a satellite altimeter flies over the area affected by a surge. This profile shows the spatial structure of the surge that is not available from pointwise tide gauges. Of course there is a sampling issue, as the altimeter is not always where it is needed.

HydroCoastal project extends measurements to the coastal strip and within the lagoon, i.e. exactly where they would be useful for observing the surges and therefore relevant to storm surge research, applications and services. We can best use the TWLE fine-scale information and its variation at the coast. The high resolution wave field in the coastal strip is also relevant, as it helps development of more realistic wave models that can be used to estimate wave setup. We expect the new SAR altimetry to have intrinsically good coastal performances (i.e. good Signal-to-Noise, better along-track resolution).

The Venice lagoon is touched by one S3B track (327) crossing, with at least four tide gauges from sea to land. Other Sentinel-3 tracks crossing the area are S3A 193 and, marginally, S3B 193. CryoSat-2 (CS2) also crosses the area. Figure 3.1 shows the position of the mentioned Sentinel-3 tracks, as well as that of the meteo-marine automatic stations available to us and the SEA and LAGOON zones defined for this area.

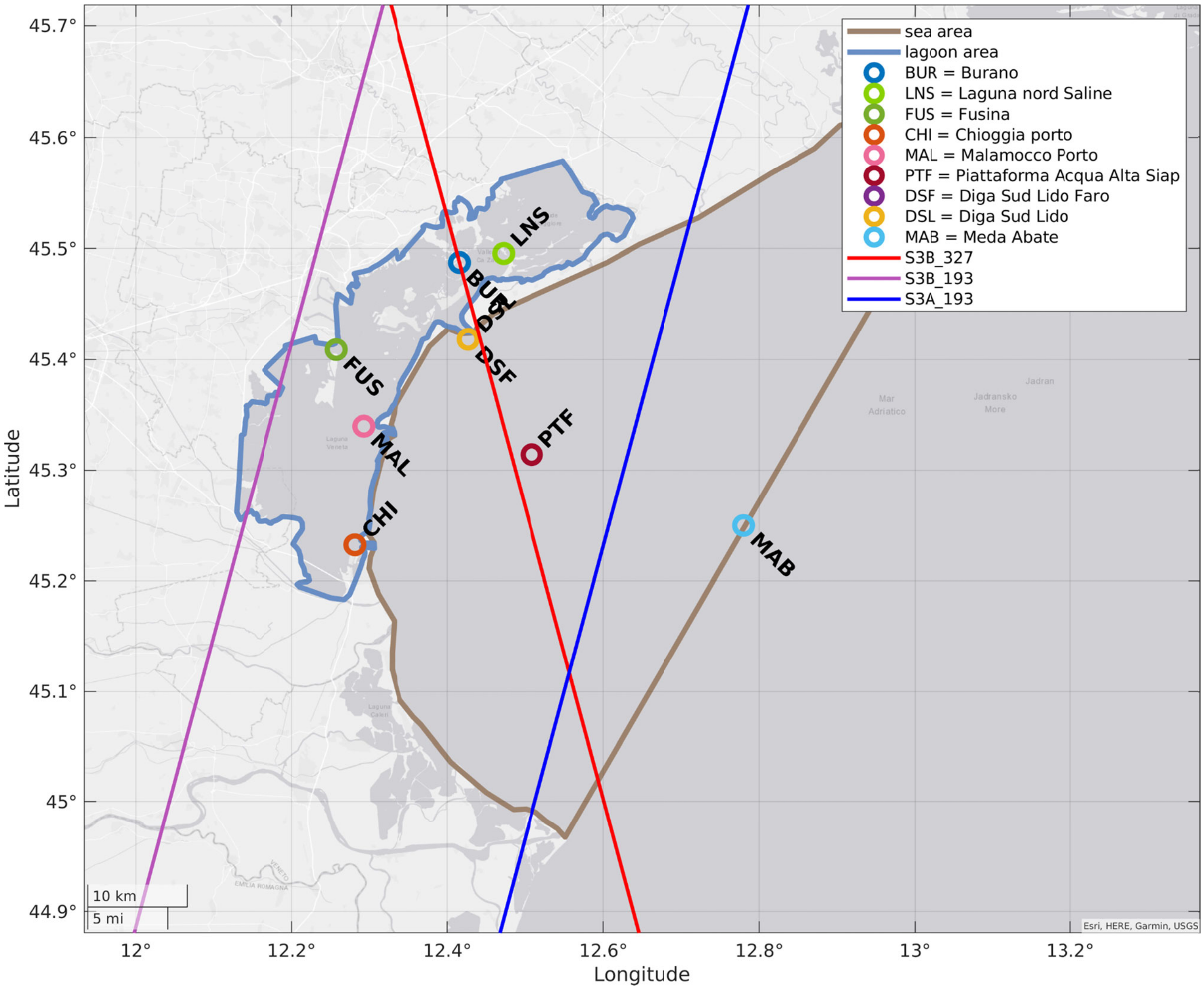


Figure 3.1: The position of the automatic meteo-marine stations related to this study, of the S3B tracks 327 and 193 and of the S3A track 193 in the Venice Lagoon. The sea and lagoon areas are also highlighted.

The network of the automatic meteo-marine stations in the Venice Lagoon AOI is owned by the Centro Previsione e Segnalazioni Maree (CPSM) of the Venice Municipality, which kindly provided us all available station data since 2010. Details about tide gauge/weather station geographic positions and instrumental equipment are reported in Table 3.1.

Table 3.1: list of the automatic tide gauge and weather stations in the Venice Lagoon AOI, with details on geographic position and instrumental equipment.

STATION	STATION LONG NAME	LAT (°N)	LON (°E)	SEA LEVEL	WIND SPEED	SWH
BUR	Burano	45.48750	12.41549	X		
LNS	Laguna nord Saline	45.49559	12.47197	X	X	
FUS	Fusina	45.40889	12.25694	X		X
CHI	Chioggia porto	45.23254	12.28060	X	X	
MAL	Malamocco porto	45.33980	12.29197	X	X	
PTF	Piattaforma	45.31425	12.50825	X	X	X
DSF	Diga sud Faro	45.41823	12.42655		X	
DSL	Diga sud Lido	45.41823	12.42655	X		
MAB	Meda Abate	45.25000	12.78000	X	X	X

3.1 Objectives

The main objectives of the impact assessment with reference to the Venice lagoon are:

- to assess the HydroCoastal product (TWLE, wind amplitude and SWH) in the Venice Lagoon and surrounding northern Adriatic Sea;
- to demonstrate the benefits and the scientific value of HydroCoastal product in the area for storm surge monitoring and forecast applications;
- to investigate the limits and the potential of novel altimetry products in a complex yet fragile environment, subject to profound and sudden developments led by anthropic drivers (tourism, commerce, navigation, industry and fishery).

3.2 Methodology / Data Processing

3.2.1 Total water level envelope anomaly local datum

The main procedural steps for the analysis of the data are the same described in section 2.2 Methodology. However, a noticeable difference resides on the calculation of the TWLE anomalies. While in the Marano-Grado Lagoon case study the anomalies were calculated over their respective MSSs, for the Venice Lagoon study we have adopted a different strategy. All the tide gauges in the Venice Lagoon share the same local datum, which is ZMPS (see section 2.2). We use a single MSS for all the tide gauges of the network, considering representative for all of them that of the PTF station, 14 km off-shore the Venice littoral. As already noted in section 2.2, an *in situ* MSS consistent with the altimetric MSSs is constructed averaging the *in situ* observations over the corresponding time range. For the tide gauge network we have thus two different MSSs, one consistent with the CLS-CNES 2015 altimetric MSS, and the other with the DTU 2018 MSS. We name them TG_{mss_cls} and TG_{mss_dtu}.

In the ALT-TG comparisons, we must pay attention in subtracting to the TG level time series the appropriate MSS: TG_{mss_cls} if the altimetry time series uses the CLS-CNES 2015 MSS, and TG_{mss_dtu} if the altimetric MSS is DTU 2018:

$$ALT - MSS_x \Leftrightarrow TG - TG_{mss\_x}$$

To avoid changing the TG MSS for calculating the sea level difference anomalies for every different altimetric time series, we can add to both members of the above expression the in situ TG_{mss_x}:

$ALT - MSS_x + TG_{mss\_x} \Leftrightarrow TG - TG_{mss\_x} + TG_{mss\_x}$, i.e.:

$ALT - MSS_x + TG_{mss\_x} \Leftrightarrow TG$.

We have finally defined the correct anomalies for both altimetry and in situ data, in a consistent MSS system (DTU 2018 for ESA and DTU; CLS-CNES 2015 for UBONN), and above the ZMPS local datum.

3.2.2 Mean sea surface

Auxiliary data, as the mean sea surface, are central for the exploitation of altimetry observations. In the Marano-Grado Lagoon study, we observed that different MSSs can differ substantially from each other, impacting the interpretation of geophysical variables, as for example the sea level and mean dynamic topography. The same situation is observed in the Venice Lagoon. Figure 3.2.1 shows the profiles of the DTU 2018 and CLS-CNES 2015 MSSs, as well as the profile of the EIGEN-6C4 geoid (Foerste et al., 2014), along track S3B 327 for all cycles. While at open sea the two MSSs differ by a limited quantity, near coast they rapidly diverge, reaching about 30 cm where the satellite track crosses land.

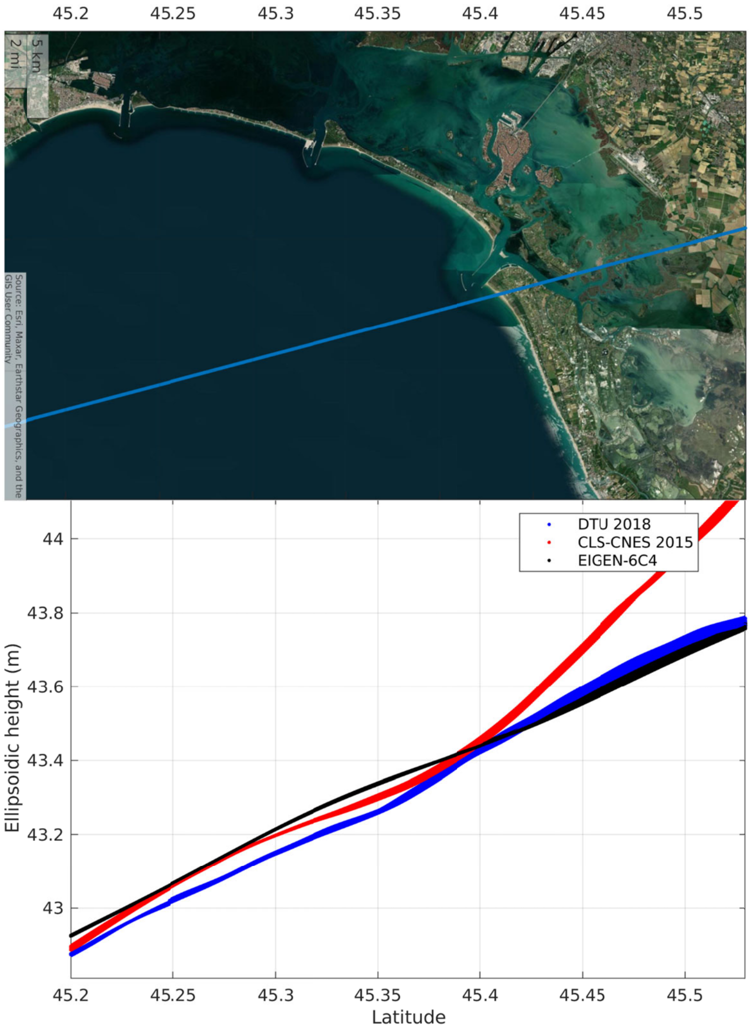
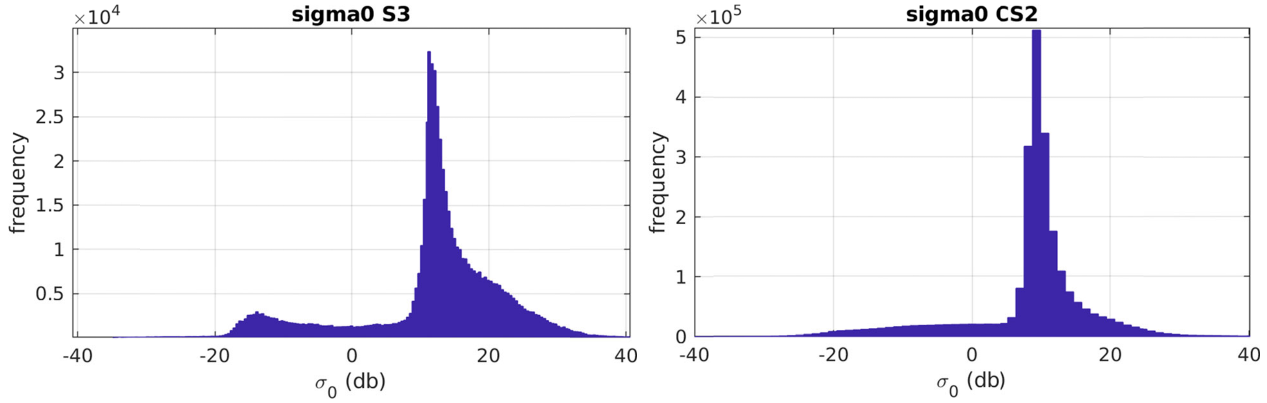


Figure 3.2.1: S3B track 327 DTU 2018 and CLS-CNES 2015 MSSs, along with EIGEN_6C4 geoid profiles, at the crossing between sea and land on the Venice Lagoon littoral.Top: the track position overimposed to the map. Bottom: the corresponding profiles of the two MSSs and of the geoid along the track.

3.2.3 Wind speed

The wind speed is calculated from the radar backscatter following Abdalla’s algorithm (Abdalla, S., 2007), applying the related formulas to valid values of retracked σ_0. Abdalla's original algorithm needs many *caveats* that cannot be fully respected in the context of this study, and with the available data. For this reason the wind calculated from S3 normalised radar backscatter values has to be considered as indicative. Moreover, CS2 files do not contain the atm_cor_sig0 parameter, and thus in principle the wind could not be derived at all for this mission. However, in order to provide at least an approximate value of wind speed also for the CS2 mission, we feed the wind algorithm with a constant atmospheric attenuation correction evaluated as the most probable one, in the median sense, from the S3 missions in the AOIs. The value of atm_cor_sig0 used here is 0.17 db. Unfortunately, for CS2 the calculated wind speed did not match that of the *in situ* stations. The main reason for this disagreement could be identified on the distribution of the σ_0 of CS2 in the northern Adriatic Sea, which significantly differs from that of S3 for the same area (see Figure 3.2.2). The CS2 distribution has a median of 9.6 db, a value much lower than that of S3 which is 12.7 db, giving rise to very different wind speed regimes (CS2 much higher than S3), due to the 3.1 db difference in their means.

Figure 3.2.2: histograms of the normalised backscatter values for S3 (left) and CS2 (right) in the northern Adriatic Sea.



3.3 Results

A selection of storm surge events when S3 and CryoSat-2 are flying at the same time is reported in Table 3.2. In order to highlight the utility of Hydrocoastal data, we show a selection of key results. Major details for each surge are reported in the same table (satellite, track, time of passage, nearby TG station, maximum level of the storm surge and related time, duration of the storm surge event).

Table 3.2: list of collocated storm surge events >= 95 cm and CS2/S3 satellite passes. Columns correspond, from left to right: mission name, orbit (CS2)/track (S3) mean time of satellite pass in the area, station where the 95 cm threshold was crossed, maximum level reached over the ZMPS, time of the maximum, duration in hours

mission	Orbit / track	sat pass time	Station	SEV max lev. (cm)	SEV time	SEV duration (h)
CS2	**19184**	**2013-11-20 11:30:00**	**BUR**	**108**	2013-11-20 10:45:00	3.8
CS2	**24260**	**2014-11-05 06:27:00**	**DSL**	**115**	2014-11-05 07:25:00	4
CS2	**2464**	**2010-09-25 08:54:00**	**DSL**	**104**	2010-09-25 09:20:00	2.5
CS2	57388	2021-02-04 00:58:00	MAB	99	2021-02-04 00:55:00	0.9
S3A	193	2018-01-03 09:44:00	PSA	97	2018-01-03 09:30:00	1.1
S3A	**193**	**2018-10-27 09:44:00**	**MAB**	**102**	2018-10-27 09:30:00	2.7
S3A	**193**	**2019-05-04 09:44:00**	**MAB**	**106**	2019-05-04 09:20:00	2
S3A	**193**	**2019-11-09 09:44:00**	**BUR**	**102**	2019-11-09 08:35:00	2.4
S3A	193	2021-01-14 09:44:00	MAB	121	2021-01-14 08:20:00	5.2
S3A	**193**	**2021-02-10 09:44:00**	**MAB**	**139**	2021-02-10 07:20:00	5.5
S3A	193	2021-12-04 09:44:00	PSA	100	2021-12-04 09:25:00	1.4

S3A	193	2022-09-27 09:44:00	DSL	99	2022-09-27 09:30:00	1.1
S3A	327	2021-05-11 20:33:00	MAB	102	2021-05-11 20:05:00	2
S3B	193	2019-12-16 09:46:00	PTF	121	2019-12-16 10:20:00	3.9
S3B	193	2020-12-28 09:46:00	DSL	138	2020-12-28 09:30:00	6.5
S3B	**327**	**2020-06-04 20:34:00**	**PTF**	**118**	2020-06-04 19:25:00	3.8

Table 3.3 lists the storm surge events when the MOSE barrier was in operation and the satellite was flying at the same time. There are only two cases since the MOSE started operating. Unfortunately, one refers to the S3B track 193 that crosses the lagoon only, while the other (S3A 193) flies over open sea.

Table 3.3: list of collocated MOSE barrier operation events and CS2/S3 satellite passes. Columns correspond, from left to right: mission name, orbit (CS2)/track (S3) mean time of satellite pass in the area, station of reference, maximum level reached over the ZMPS, time of the maximum, MOSE operation duration in hours.

mission	orbit / track	sat pass time	station	SEV max lev.	SEV time	MOSE operation duration (h)
S3B	193	2020-12-28 09:46:00	PTF	128	2020-12-28 09:05:00	19.1
S3A	193	2021-02-10 09:44:00	PTF	127	2021-02-10 07:05:00	8.5

Storm surge events recorded in Venice from 2010 to 2022 are shown in Table 3.2, when S3/CS2 are flying at same time. Seven events were selected for illustration. They correspond to the passage of CS2 on 25 September 2010, 20 November 2013 and 5 November 2014; S3A along track 193 (27 October 2018, 4 May 2019, 9 November 2019, 10 February 2021) and S3B along track 327 (4 June 2020). The selected passes are marked bold in Table 3.2. Two tracks of Sentinel-3 were also found in coincidence with the operations of the MOSE barriers, segregating the Venice Lagoon from the open sea during remarkable storm surge events. They are reported in Table 3.3. Unfortunately the two tracks do not cross the littoral dividing the lagoon from the open sea, a circumstance that would have allowed some interesting investigations to be conducted, and were not analysed.

As for the Marano-Grado Lagoon, two masks were generated to separate LAGOON from SEA. Four different ranges were used (ESA standard, UBONN, DTU and GPOD that uses SAMOSA+ at 80 hz). TWLE are referenced to the local reference ZMPS, as explained in the methodology section.

Two figures for each event are reported showing the full TWLE, SWH and wind profiles temporally collocated with the TG measurement at the time of satellite overpass. This allows a visual evaluation of how altimetry captures the variability of the sea level along the track.

Figure 3.3.1 shows the first example of a storm surge happening on 25 September 2010 that produced a surge of 104 cm measured at DSL at 09:20. CS2 is crossing the northern Adriatic sea, then approaching the land near DSL and finally flying over the eastern part of the lagoon. The altimeter has clearly captured the storm surge signal, which compares very favourably with the measured level at DSL on the coast at the exact time of observations. In the SEA region, the retrackers do a good job and the TWLE retracked profiles display a comparable behaviour with some spatial details. TWLE from the ESA official product is noisier than DTU and UBONN. At the interface between SEA and LAGOON, retrackers fail due to the need of a more precise land/water mask.

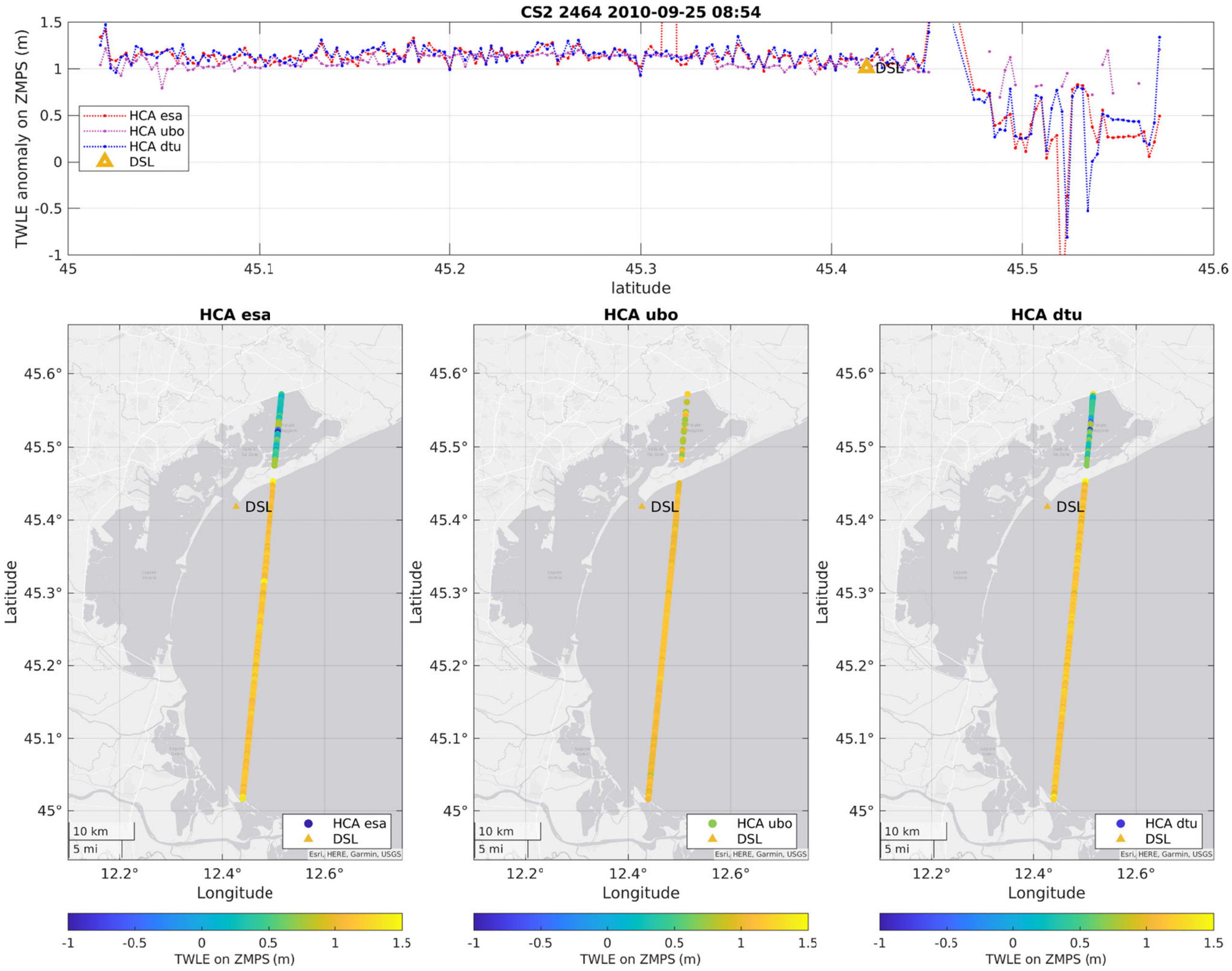


Figure 3.3.1: Total water level envelope as seen by CS2 orbit 2464 over the Venice Lagoon and the coastal zone, and by the tide gauge of Diga Sud Lido. Upper panel: plot of the TWLE from the three retrackers (ESA, UBONN, DTU) versus latitude. Bottom panels: same as above but geolocated on the map.

There is also a clear drop of the altimetric TWLE inside LAGOON that could seem unrealistic, and that is difficult to estimate in such a complex intertidal marsh environment, for which a detailed land/sea mask is not available. Grossly, the drop could be quantified as ESA ~55 cm, DTU ~-45 cm, UBONN ~-20 cm. On the other hand, inside the lagoon the tides propagate with variable delays and attenuations, depending on the geographic position and the wind. In general, the tidal wave delay and attenuation at LNS (which is one of the CPSM stations nearest to the altimetry track segment inside the lagoon) are estimated as +80 minutes and -20% of the signal registered at PSA. At the time of the satellite pass minus 80 min, the level registered at PSA was ~+60 cm on ZMPS (see Figure 3.3.2), and it is thus compatible with the drop observed inside the lagoon by at least two of the retrackers (ESA and DTU), if we consider an attenuation of about -6 cm (-20% of

30 cm). The difference in the MSS used by UBONN w.r.t. that used by the other retrackers could help to explain the remaining unexplained gap of UBONN. It should be noted that UBONN has several gaps at SEA and in the LAGOON.

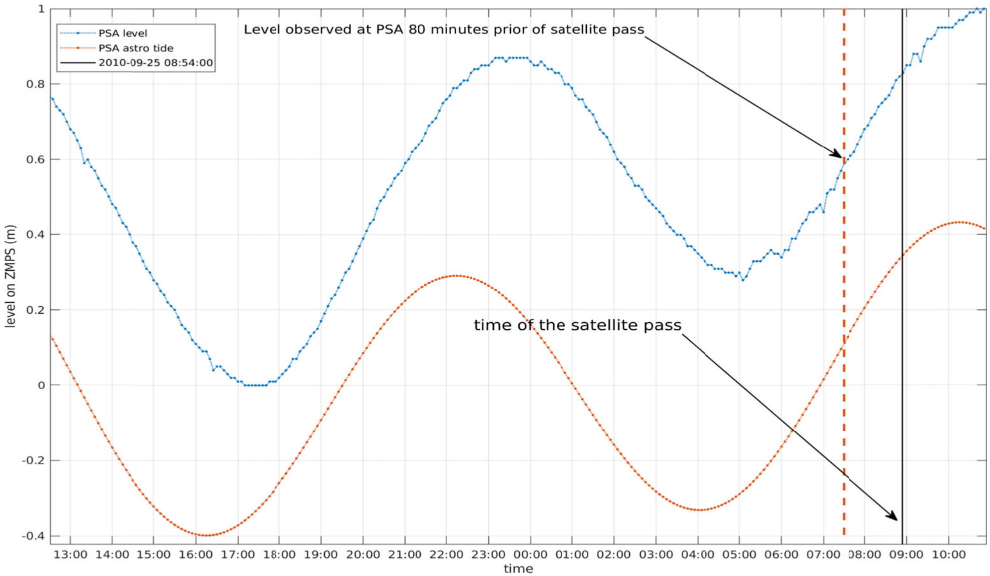


Figure 3.3.2: level registered at PSA station at the time of the surge observed at DSL. Blue and red dotted lines are sea level and astronomical tide (FES) respectively, The vertical black solid line represents the time of the satellite pass. The vertical dashed orange line marks 80 minutes prior to the satellite pass time.

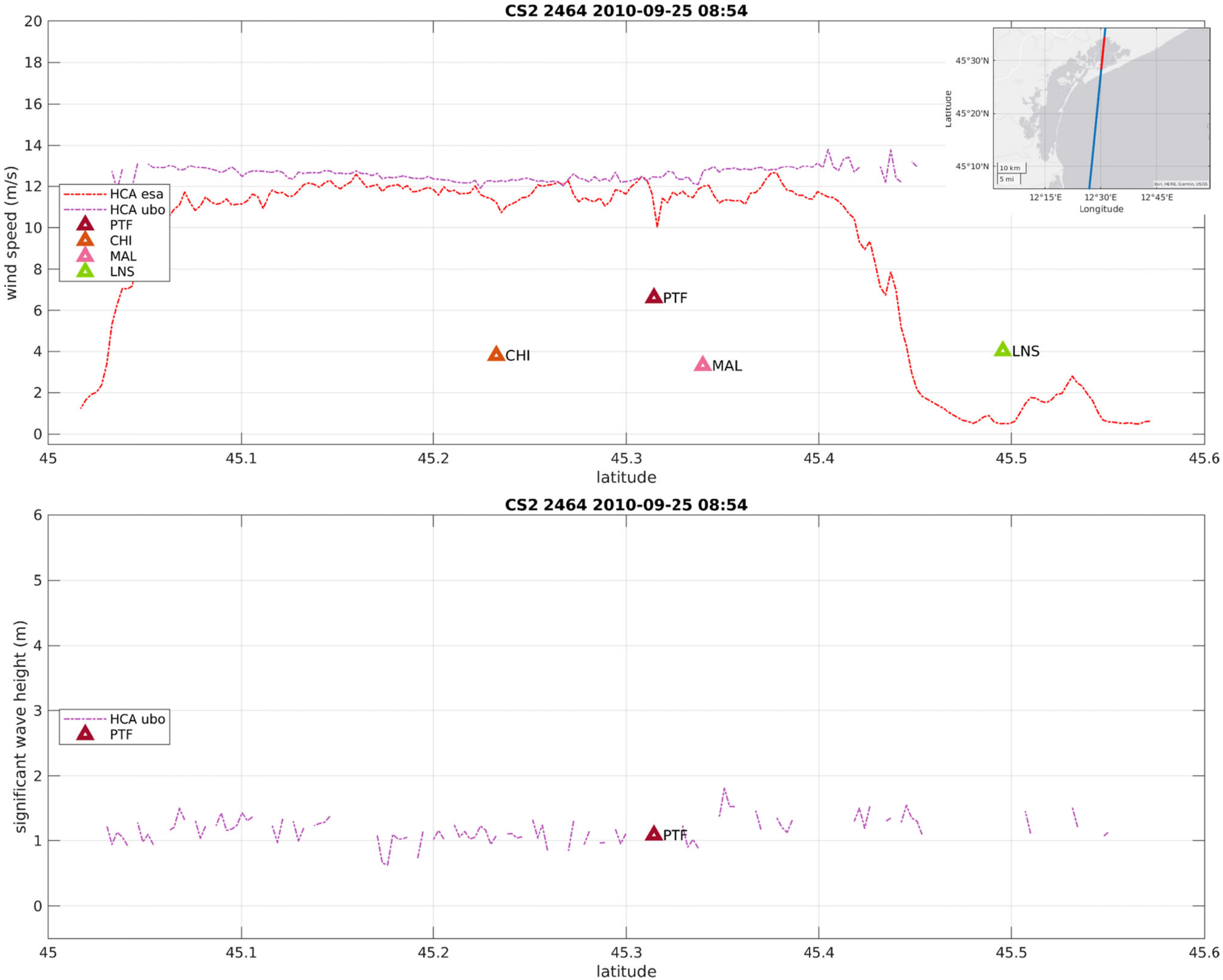


Figure 3.3.3: Wind speed and significant wave height measured by CS2 orbit 2464 over the Venice Lagoon and the coastal zone, and by several meteo-marine stations in the area. Upper panel: plot of the wind speed from the ESA and UBONN retrackers versus latitude. Bottom panel: same as above but for the significant wave height.

The set of plots in Figure 3.3.3 gives us an estimate for along track wind and SWH w.r.t the stations located in the surroundings. There is evident overestimation of the wind at SEA: as discussed in Methodology, section 3.2, the σ_0 retracked values for CS2 are about 3 db lower than the corresponding of S3, returning too high winds. In the LAGOON region the situation is opposite: a possible explanation could be that salt marshes not covered by water contribute positively to the returned backscatter. The gaps in UBONN data limit the assessment. SWH does not appear to be biased with the measured value at PTF. Despite UBONN data gaps, it is very interesting, and promising, that SWH can be measured with such spatial detail outside and inside LAGOON, and this is a distinct improvement compared to ESA official product. However, the few valid SWH values returned by UBONN retracker inside the lagoon, suggests a SWH higher than in open sea, which is quite unusual.

The second example concerns the storm surge event of 20 November 2013 at 10:45. CryoSat-2 at that time was flying over the northern Adriatic sea, then approaching the land near BUR TG and finally flying over the central part of the lagoon. BUR TG measured a peak surge of 108 cm. The storm surge event had a duration of 3.8 hours. The retracked altimetric profiles at SEA (Figure 3.3.4) show a similar pattern compared to the previous event, with the surge signal well captured and with a level closer to that measured at surrounding TGs, with the exception of a slight overestimation observed at PTF. As noted previously, ESA shows some outliers that are not in UBONN and DTU. UBONN retains less data than DTU, however, the along track profile is always notable.

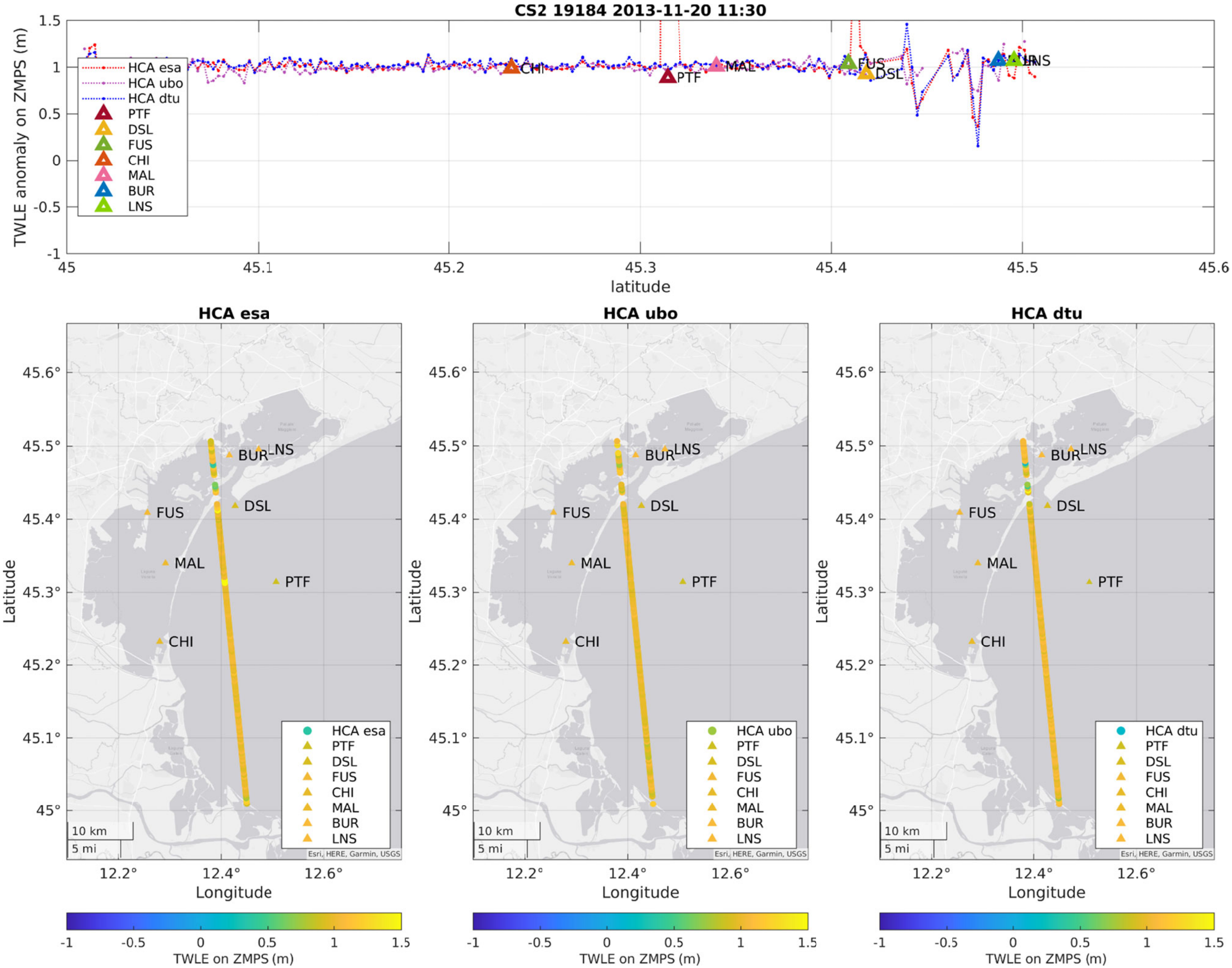


Figure 3.3.4: Total water level envelope anomalies as seen by CS2 orbit 2464 over the Venice Lagoon and the coastal zone, and by several tide gauges and weather stations. Upper panel: plot of the TWLE from the three retrackers (ESA, UBONN, DTU) versus latitude. Bottom panels: same as above but geolocated on the map.

Differently from the previous event, no sea level gaps are noticed passing from open sea to lagoon, even if the increased spread of the sea level values inside the lagoon expresses the presence of land contamination. The levels inside and outside the lagoon are similar for altimetry and *in situ* data, within a few cm. Two are the main reasons for the level agreement: first, the CS2 track crosses the lagoon more south than in the previous example, where the tide delay times are much smaller, if any. Second, the satellite crosses the AOI after the maximum tide has been reached at sea, and just before the maximum arrives in the lagoon at PSA. In such a period of time, changes in sea level are smaller, in the same time unit, than during the tide growth or decline. Thus, a small delay would not make a big difference (see Figure 3.3.5), being also the delays in that part of the lagoon varying from +15 min south of Murano, to +43 min at Burano (see: https://www.comune.venezia.it/it/content/la-propagazione-marea-laguna).

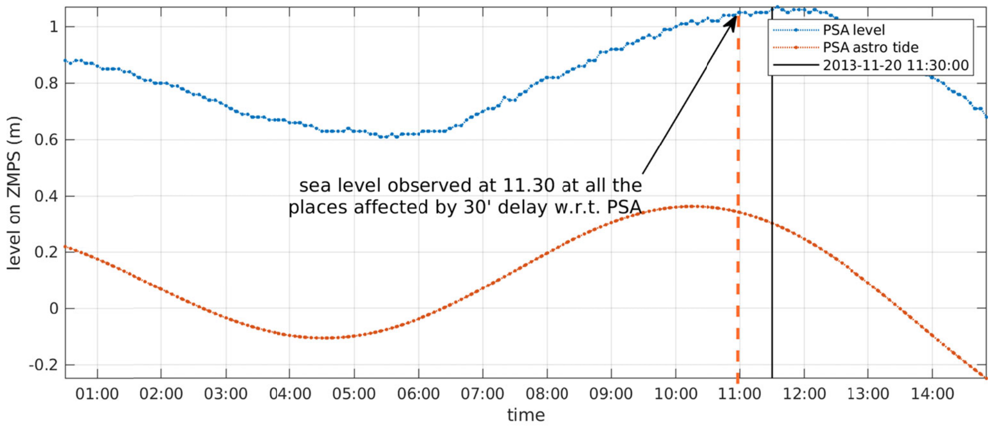


Figure 3.3.5: level registered at PSA station during and before CS2 pass. Blue and red dotted lines are sea level and astronomical tide (FES) respectively, The vertical black solid line represents the time of the satellite pass. The vertical dashed orange line marks 30 minutes prior to the satellite pass time.

At the interface between SEA and LAGOON, retrackers fail due to the need of a more precise land/water mask. In this example, we can better evaluate the capability of the Hydrocoastal product to detect the surge in the lagoon and reproduce the signal seen at the TG. There is a clear visual indication that the UBONN is less sensitive to land contamination than the ESA official product. UBONN and DTU provide the same level of TG in the last segment of the track inside the lagoon, while the ESA official product sometimes fails to estimate a realistic level.

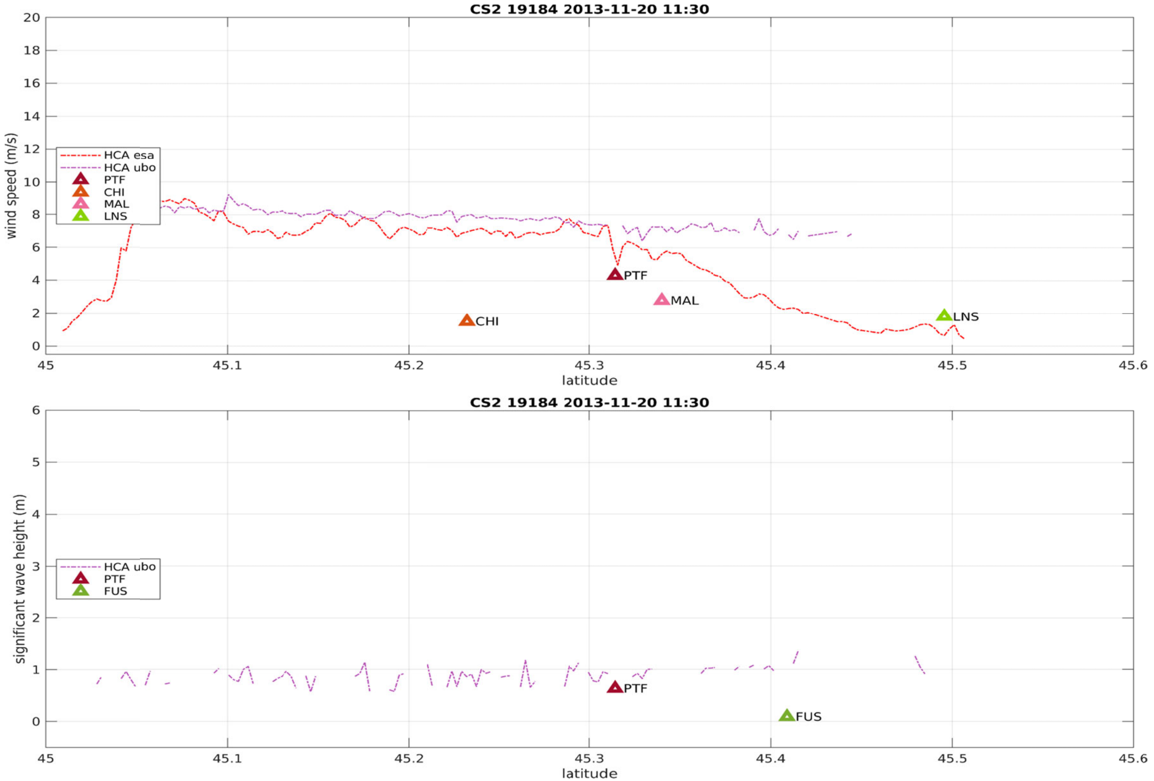


Figure 3.3.6: Wind speed and significant wave height measured by CS2 orbit 19184 over the Venice Lagoon and the coastal zone, and by several meteo-marine stations in the area. Upper panel: plot of the wind speed from the ESA and UBONN retrackers versus latitude. Bottom panel: same as above but for the significant wave height.

The wind speed measured by the HydroCoastal product is once again overestimated by ESA and UBONN. Once again, inside the lagoon, the land contamination affects the σ_0 values, causing a net drop of the wind speed below the is situ measurements. The SWH retracked by UBONN, albeit with several gaps, is compatible with the in situ values at PTF (open sea), but overestimates SWH inside the lagoon.

The third example concerns the storm surge event of 5 November 2014 at 06:27. CryoSat-2 at that time was flying only over the salt marshes in the western part of the lagoon. Here several fish farms are settled, and the water basins are not directly connected with the sea. The storm surge event had a duration of 4 hours. The measured level was 115 cm. The HydroCoastal retrackers (DTU and UBONN) provide reasonable levels, well comparable with those measured at nearby MAL and FUS TG stations. UBONN presents a few outliers north of PTF and before entering land at the FUS latitude. Unfortunately, no detailed land/sea mask is available in this sector of the lagoon. Investigation of the values observed by UBONN (but not by ESA and DTU, would require a survey in such a region. A remarkable finding is that by using specialised retrackers (UBONN and DTU) good quality measurements of TWLEs can be finally recovered also in the LAGOON.

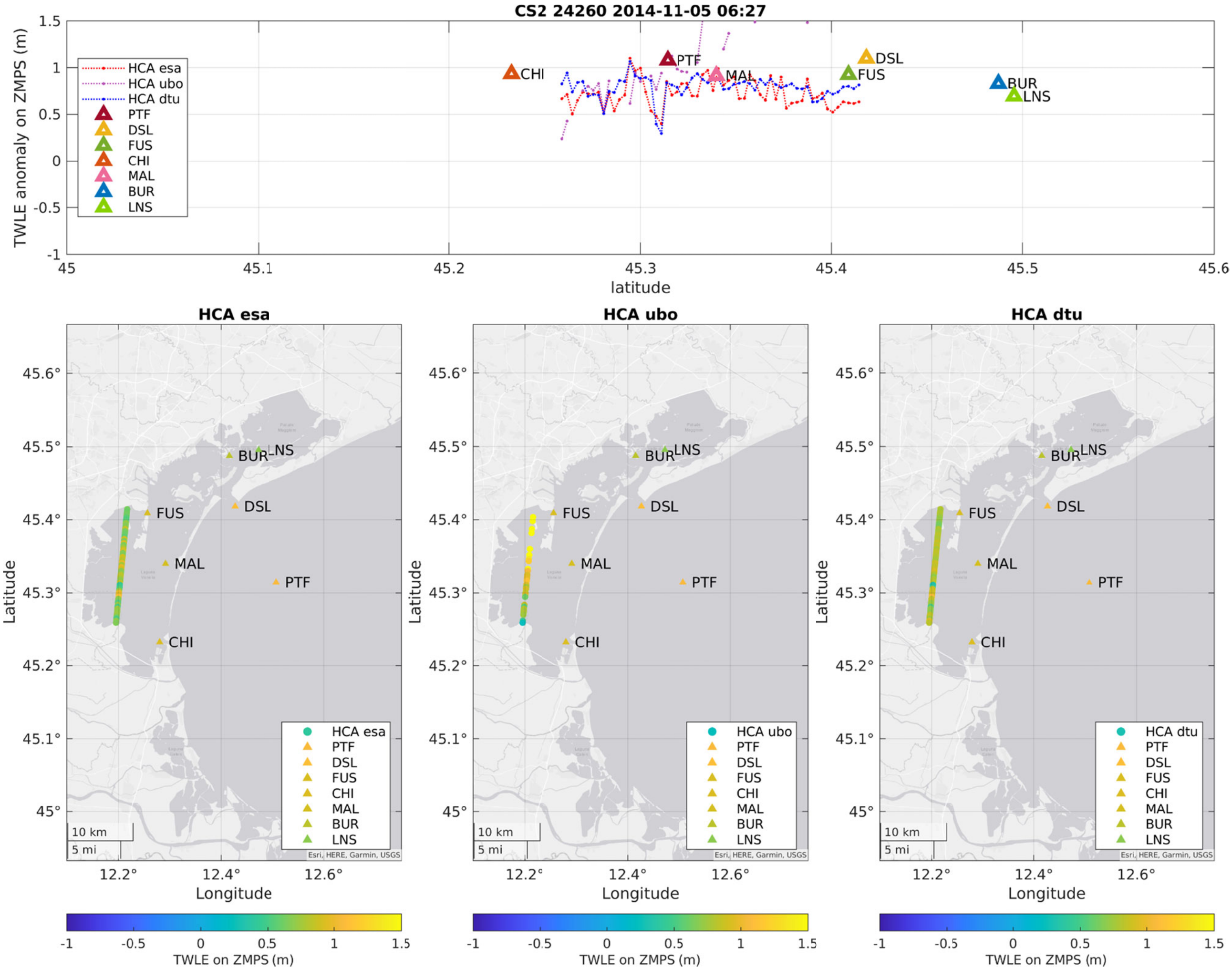


Figure 3.3.7: Total water level envelope anomalies as seen by CS2 orbit 24260 over the salt marshes inside the Venice Lagoon, and by several tide gauges. Upper panel: plot of the TWLE from the three retrackers (ESA, UBONN, DTU) versus latitude. Bottom panels: same as above but geolocated on the map.

Figure 3.3.8 shows that the only wind available for this CS2 pass is that from ESA (heavily underestimated), while UBONN does not provide any valid wind speed measurement. It should be noted in this particular event the reduction of SWH in the lagoon observed at FUS with respect to PTF. SWH is not supplied by any retracker.

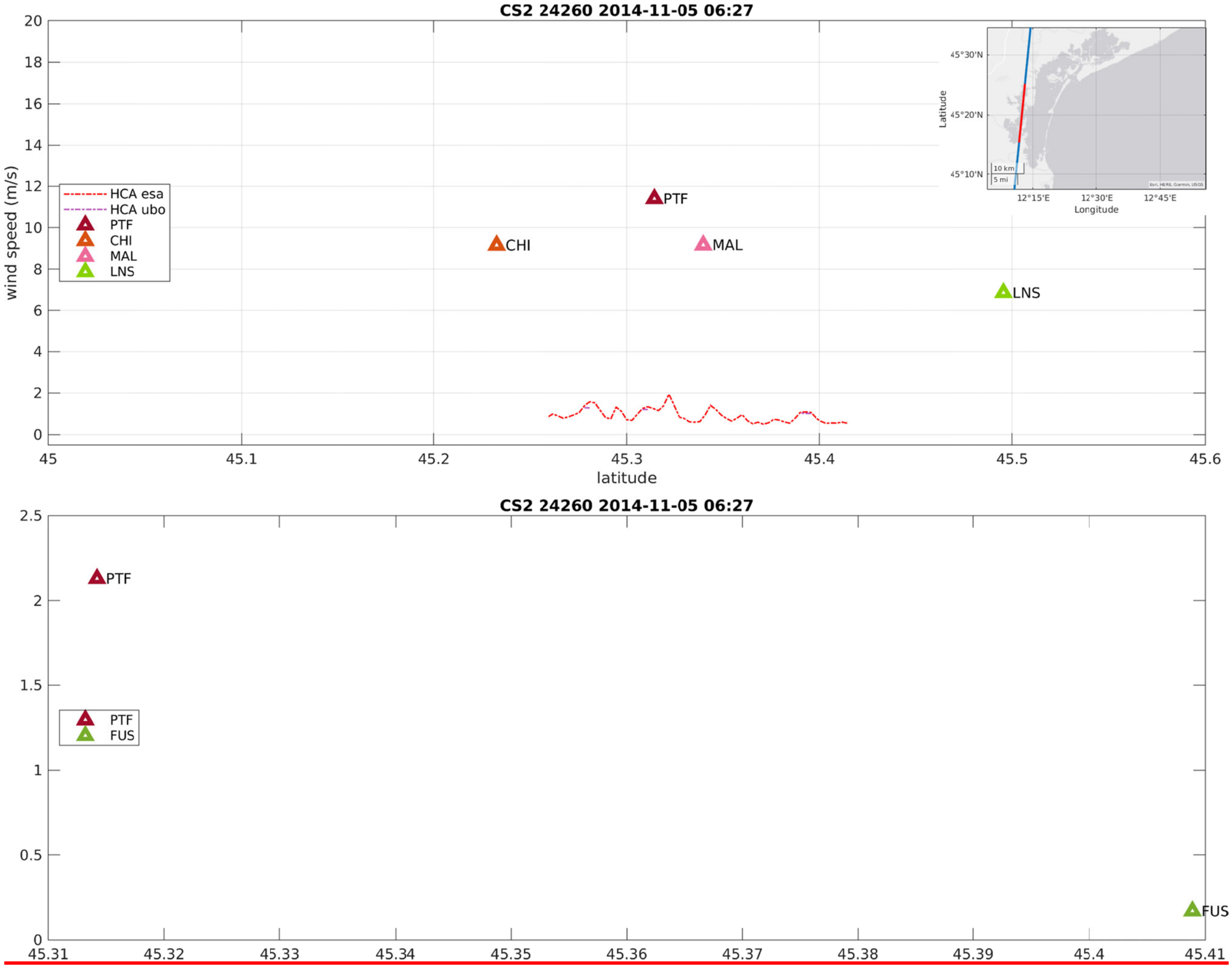


Figure 3.3.8: Wind speed measured by CS2 orbit 24260 over the Venice Lagoon, and corresponding values measured by several stations inside and outside the lagoon. The SWH measured at PTF and FUS is reported in the bottom panel. Upper panel: plot of the wind speed from the ESA retracker and some station versus latitude. Bottom panel: SWH at PTF and FUS stations.

The fourth example (Figure 3.3.9) is about the storm surge event of 27 October 2018 at 09:44. S3A is crossing the northern Adriatic Sea along track 193. The MAB station registered a storm surge event for 2.7 hours and a surge peak of 102 cm. There is good agreement between the levels measured by the satellite and those measured at the same time at MAB and PTF TGs. A somewhat degradation is observable on the edges of the track near the coast that is more remarkable for ESA than UBONN and DTU. UBONN drops, with respect to the other two retrackers, at the beginning and at the end of the coastal segment at latitudes [45.0-45.1] and [45.4-45.5]. The length of the drops is about 10 km on each side, and affects the agreement of the UBONN retracker with DSL that is the northernmost station.

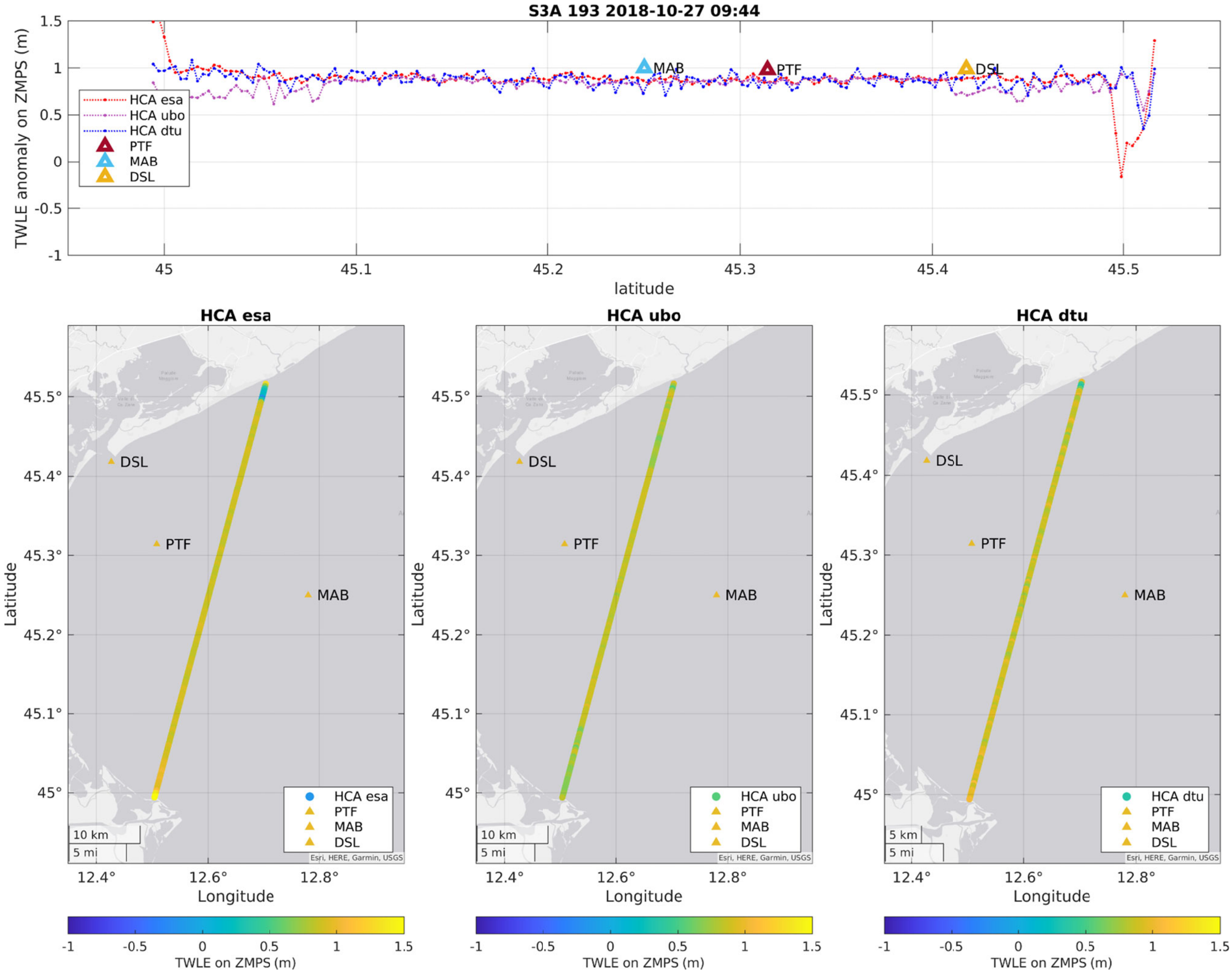


Figure 3.3.9: Total water level envelope anomalies as seen by S3A along the track 193 over the coastal zone in front of the Venice littoral, and by MAB, PTF and DSL tide gauges/weather stations. Upper panel: plot of the TWLE from the three retrackers (ESA, UBONN, DTU) versus latitude. Bottom panels: same as above but geolocated on the map.

During this storm surge event, along the central part of the segment, the wind speed measured by UBONN and ESA retrackers is underestimated with respect to ground truth, but in reciprocal agreement. As for the sea level, a strong drop is observed at the edges for both UBONN and SWH. No conclusion can be drawn if this spatial variability is realistic or is an artefact of the retracking processor, which acts differently passing from a distance to coast > 10 km to shortest distances.

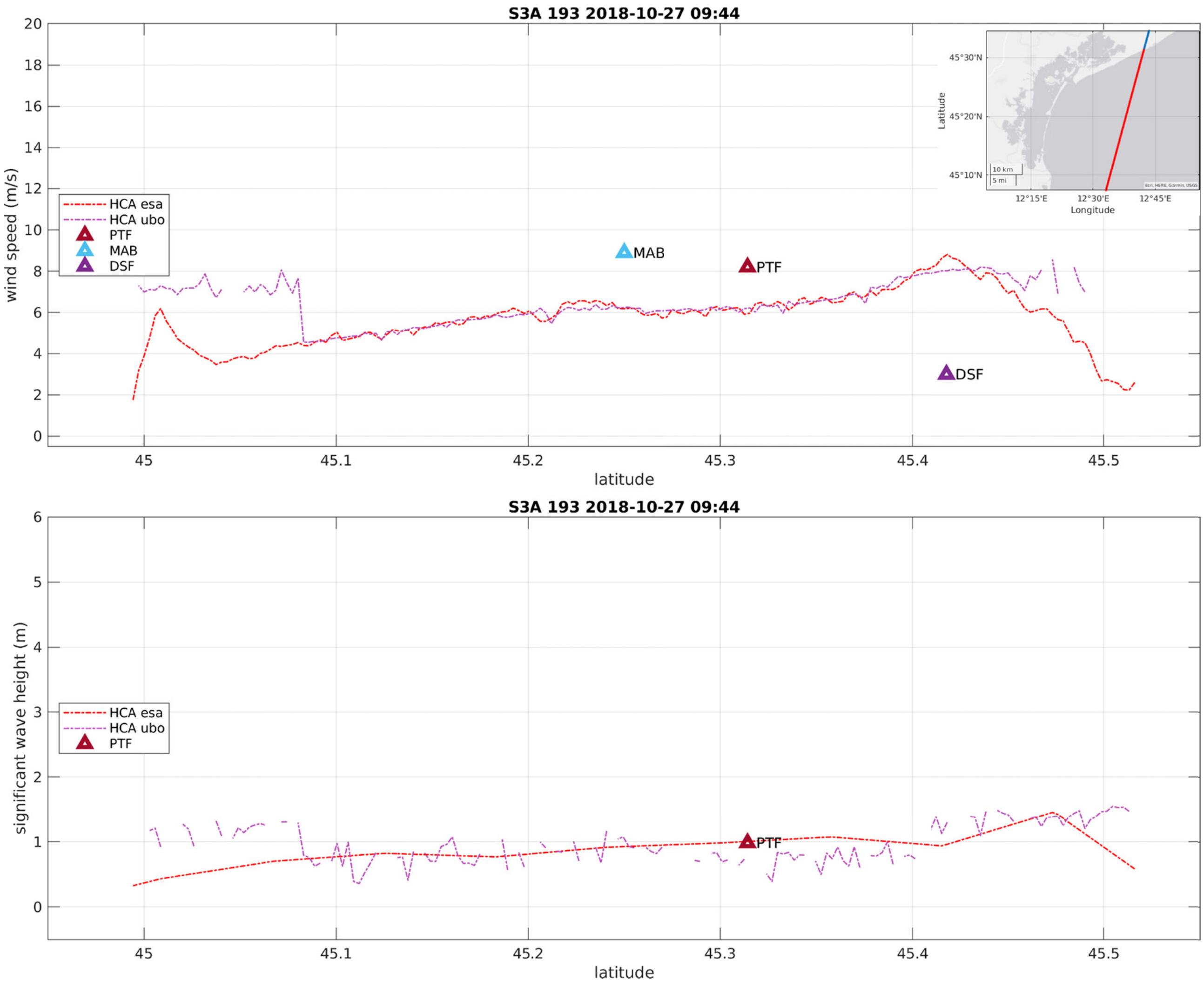


Figure 3.3.10: Wind speed measured by S3A along the track 193 over the Venice coastal zone, and the corresponding in situ values measured by MAB, PTF and DSF stations. The SWH measured at PTF is reported in the bottom panel, along with that measured by ESA and UBONN retrackers. Upper panel: plot of the wind speed from the ESA and UBONN retracker and the stations versus latitude. Bottom panel: SWH measured at PTF and as seen by ESA and UBONN retrackers.

The SWH field shows along track some spatial variability that is not observed in the ESA product, maybe because the ESA official SWH has been interpolated at 20 Hz from the 1 Hz product, while UBONN SWH is natively 20 Hz. Some UBONN data gaps exist as already observed previously. The comparison with PTF results is affected by such spatial variability. However, the average along track value is close to that value. The anemometer of DSF seems underestimating the wind with respect to the other *in situ* measurements and the altimetry observations. Actually, this is due to a delay in the wind to manifest himself at the three different stations, as can be seen in Figure 3.3.11, where the simultaneous time series of wind speed and direction of MAB (36 km off-shore) PTF (14 km off-shore) and DSF (in-shore) are shown.

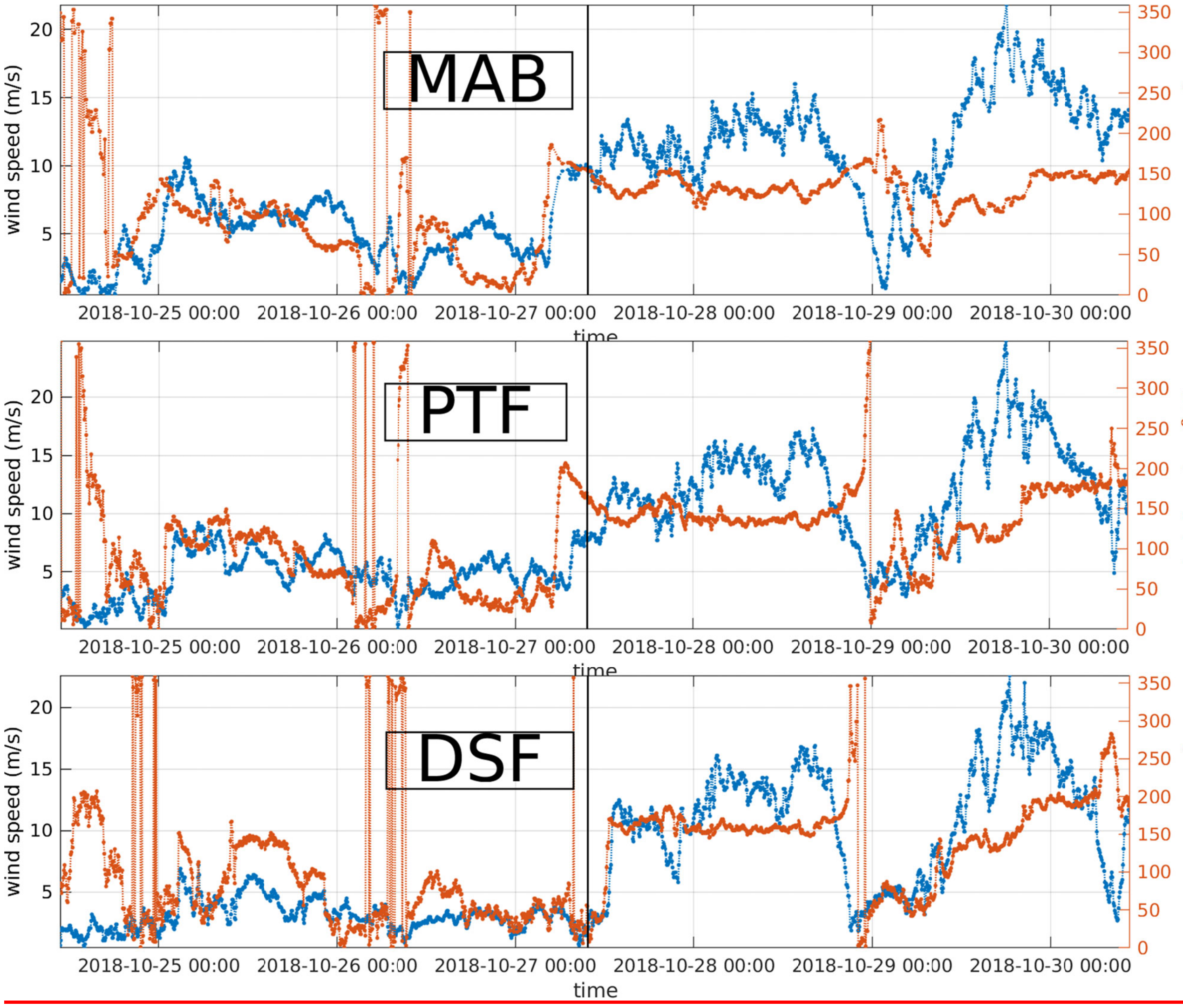


Figure 3.3.11: Wind speed and direction time series at MAB, PTF and DFS during the storm surge event of 2018-10-27 09:30. A strong increase in the wind can be seen to start at the beginning of 2018-10-27 at MAB (36 km from the littoral), affecting PTF (14 km from littoral) some hour later, and finally reaching DSF, on the littoral, one hour after the satellite pass time.

The storm surge event of 4 May 2019, which had a surge peak at MAB of 106 cm around 09:44, has been seen by the ESA, UBONN and DTU retrackers in a very similar manner from the S3A satellite (Fig. 3.3.12). The TWLE of the three retrackers is almost coincident in the central and longest segment of track 193, and in perfect agreement with the in situ levels registered at PTF and DSL. Only at the two sides of the track, near coast, some outliers appear, clearly induced by land contamination, for ESA and DTU. UBONN is not impacted by land at the extremes of the track, apart from a drop occurring around 10 km from the coast, more evident in the southernmost side.

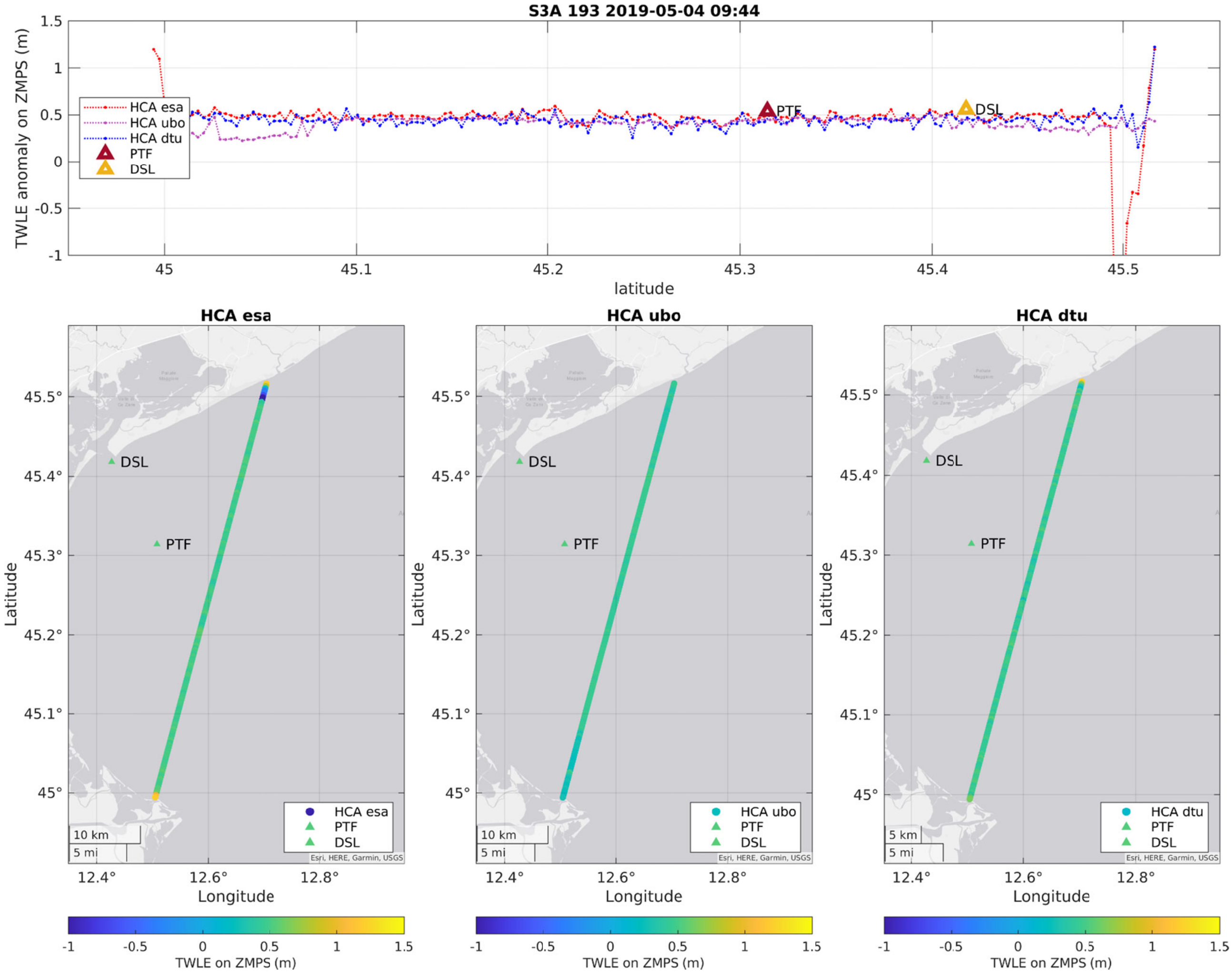


Figure 3.3.12: Total water level envelope anomalies as seen by S3A along the track 193 over the coastal zone in front of the Venice littoral, and by the PTF and DSL stations. Upper panel: plot of the TWLE from the three retrackers (ESA, UBONN, DTU) versus latitude. Bottom panels: same as above but geolocated on the map.

In this example, there is a good agreement of UBONN with respect to ESA about wind estimation at MAB and PTF (Fig. 3.3.13). Although it seems unnatural, the jump in WS corresponding to the drop in sea level of the UBONN retracker in the northernmost part of the S3A segment, lets UBONN WS agree well with the value measured at DSF. A reduced spatial variability is observed along track for UBONN, while ESA exhibits a n artificial SWH peak near the northernmost segment of the track. Both retrackers are in agreement with the SWH observed at PTF. The UBONN SWH seems to reflect the drops in SL and jumps in WS which appear at around 10 km from the coast on both sides of the track.

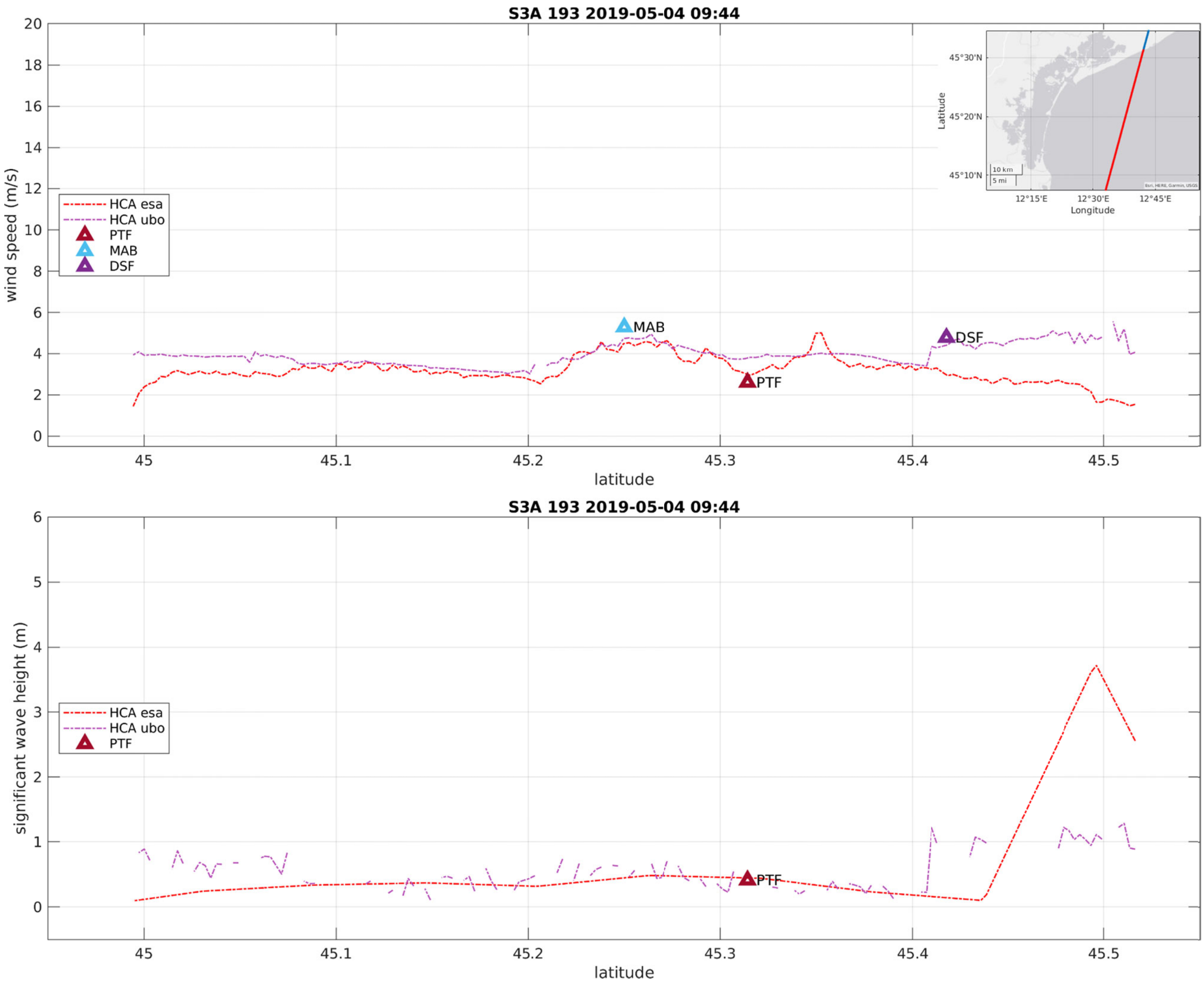


Figure 3.3.13: Wind speed measured by S3A along the track 193 over the Venice coastal zone, and the corresponding in situ values measured by MAB, PTF and DSF stations. The SWH measured at PTF is reported in the bottom panel, along with that measured by ESA and UBONN retrackers. Upper panel: plot of the wind speed from the ESA and UBONN retracker and the stations versus latitude. Bottom panel: SWH measured at PTF and as seen by ESA and UBONN retrackers.

The sixth example shown in Figure 3.3.14 is similar to the previous one. The storm surge event happened on 9 November 2019 at 09:44. S3A is crossing the northern Adriatic Sea along track 193. The BUR station registered the storm surge event for 2.4 hours and a surge peak of 102 cm. To be noted here that the satellite is measuring a lower level than BUR, but the level is similar to that observed at PTF. Here are again visible two *drops* in the UBONN TWLE, starting at about ten km from the coast at both ends of the track 193 segment. DTU and ESA do show some variability near shore, probably due to land contamination. In general the almost steady TWLE measured by the three retrackers is consistent with the *in situ* measurements of PTF and DSL.

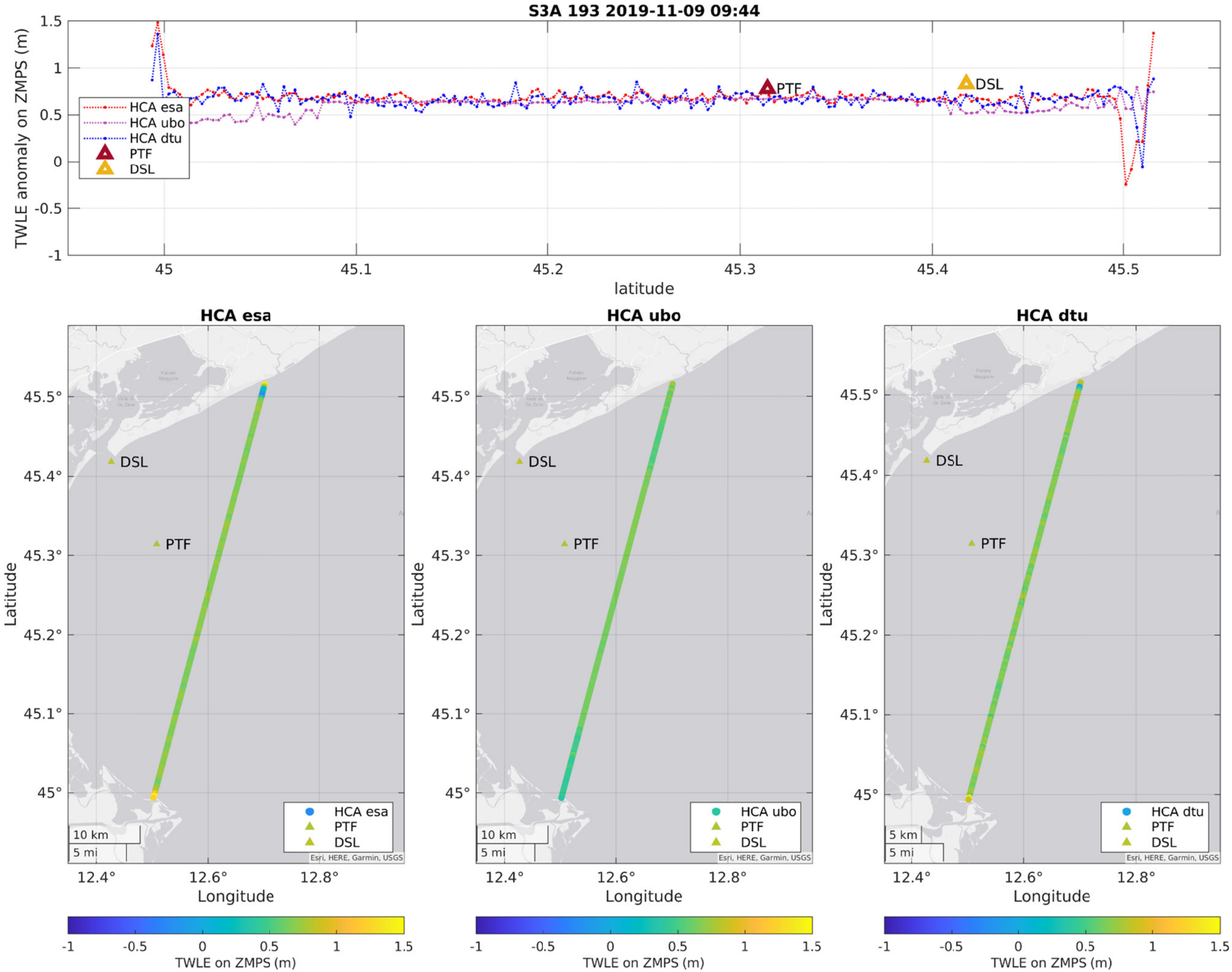


Figure 3.3.14: Total water level envelope anomalies as seen by S3A along the track 193 over the coastal zone in front of the Venice littoral, and by the PTF and DSL stations. Upper panel: plot of the TWLE from the three retrackers (ESA, UBONN, DTU) versus latitude. Bottom panels: same as above but geolocated on the map.

During this storm surge event, UBONN estimated wind amplitude and SWH more accurately than ESA (Fig. 3.3.15). In this example, there is a good agreement of UBONN with respect to ESA about wind estimation at MAB, PTF and DSF. A reduced spatial variability is observed along track compared to the previous example. The SWH is more variable along the track, and agrees well with that observed at PTF, resulting in better agreement with the ground truth w.r.t. ESA.

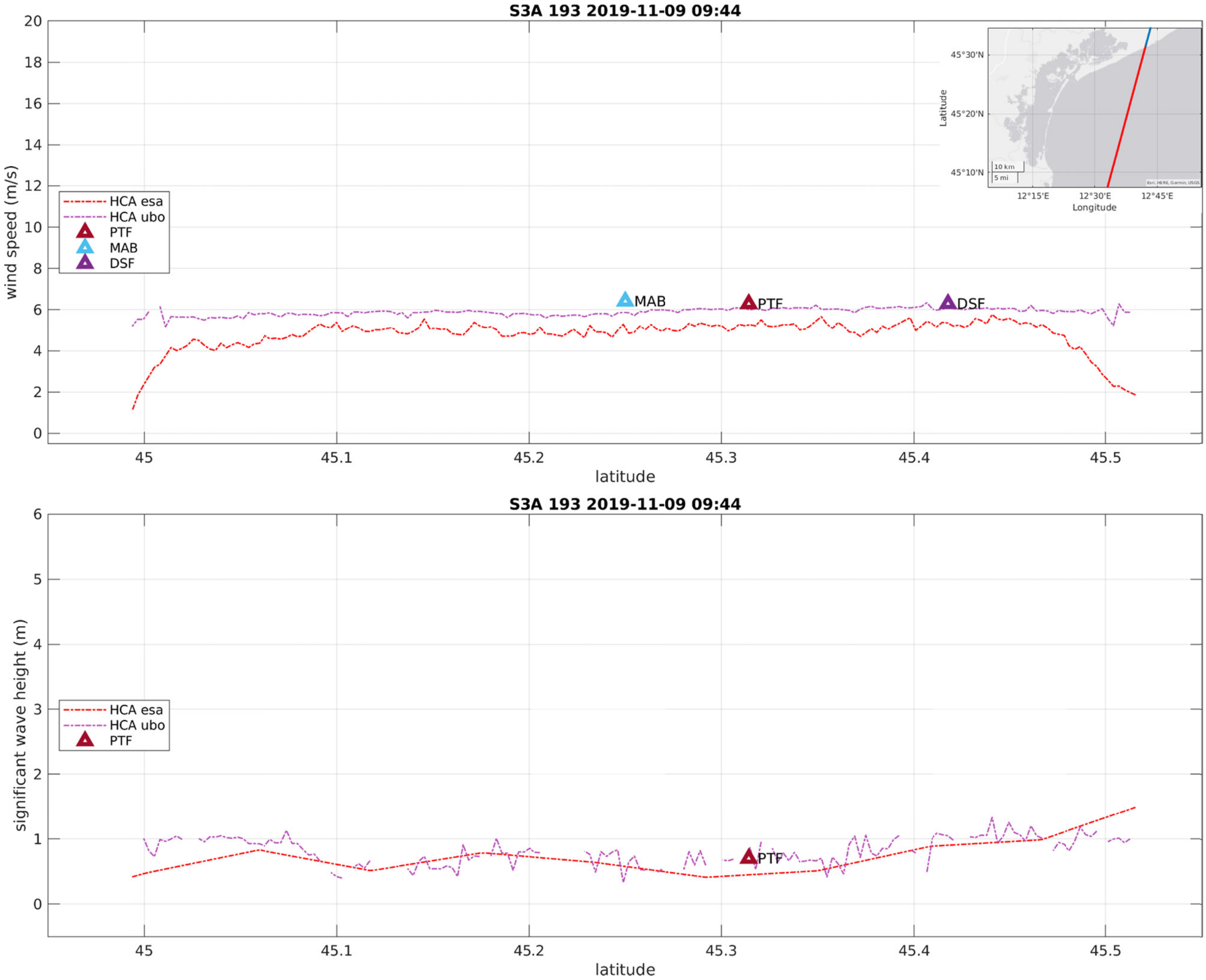


Figure 3.3.15: Wind speed measured by S3A along the track 193 over the Venice coastal zone, and the corresponding in situ values measured by MAB and PTF stations. The SWH measured at PTF is reported in the bottom panel, along with that measured by ESA and UBONN retrackers. Upper panel: plot of the wind speed from the ESA and UBONN retracker and the stations versus latitude. Bottom panel: SWH measured at PTF and as seen by ESA and UBONN retrackers.

The seventh example, shown in Figure 3.3.16, is about a storm surge event happening on 10 February 2021 at 09:44. Sentinel-3A is crossing the northern Adriatic Sea along track 193. The MAB station registered the storm surge event for 2 hours and a very high surge peak of 139 cm. At the time of the satellite overpass, the three TG in the region registered slightly different values of sea level: 120 cm at DSL, 118 cm at PTF and 129 cm at MAB. The satellite in this case is slightly underestimating the surge level when compared to MAB, PTF and DSL. The gap between the two measurement systems could be partly filled by correcting the altimetry range for the sea state bias: this would add 5 cm to the altimetric TWLE, reducing the gap between the PTF level (the nearest station to S3A 193 track) and the UBONN altimetry observation to 15 cm from the initial 20.

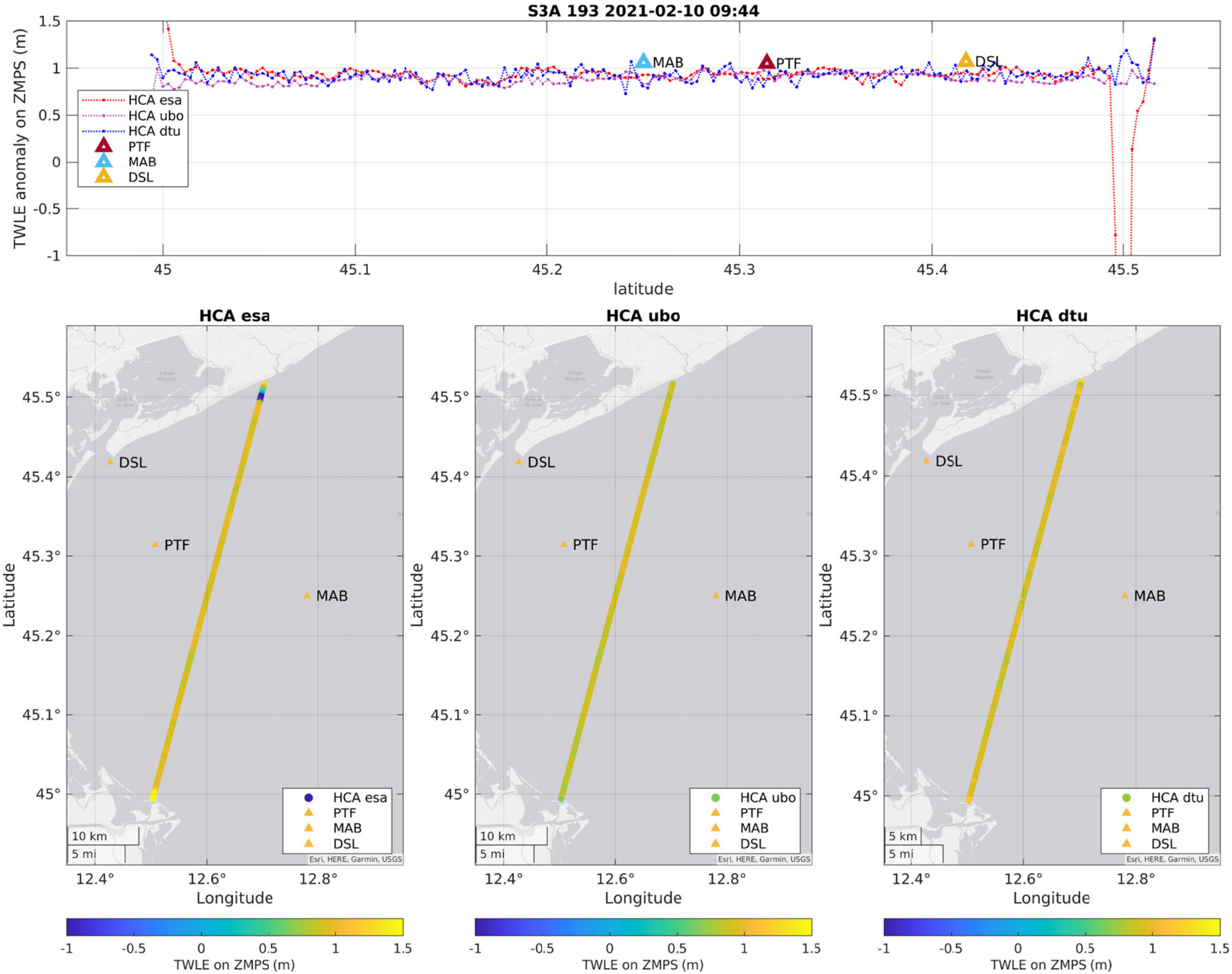


Figure 3.3.16: Total water level envelope anomalies as seen by S3A along the track 193 over the coastal zone in front of the Venice littoral, and by the PTF and DSL stations. Upper panel: plot of the TWLE from the three retrackers (ESA, UBONN, DTU) versus latitude. Bottom panels: same as above but geolocated on the map.

The wind and SWH filed at that time are shown in Figure 3.3.17. The wind estimated by UBONN is close to that observed at MAB while it is overestimated at PTF. There is little variability along track. The estimated SWH field agrees well with the value observed at PTF station, and some spatial variability is certainly more realistic than what ESA shows.

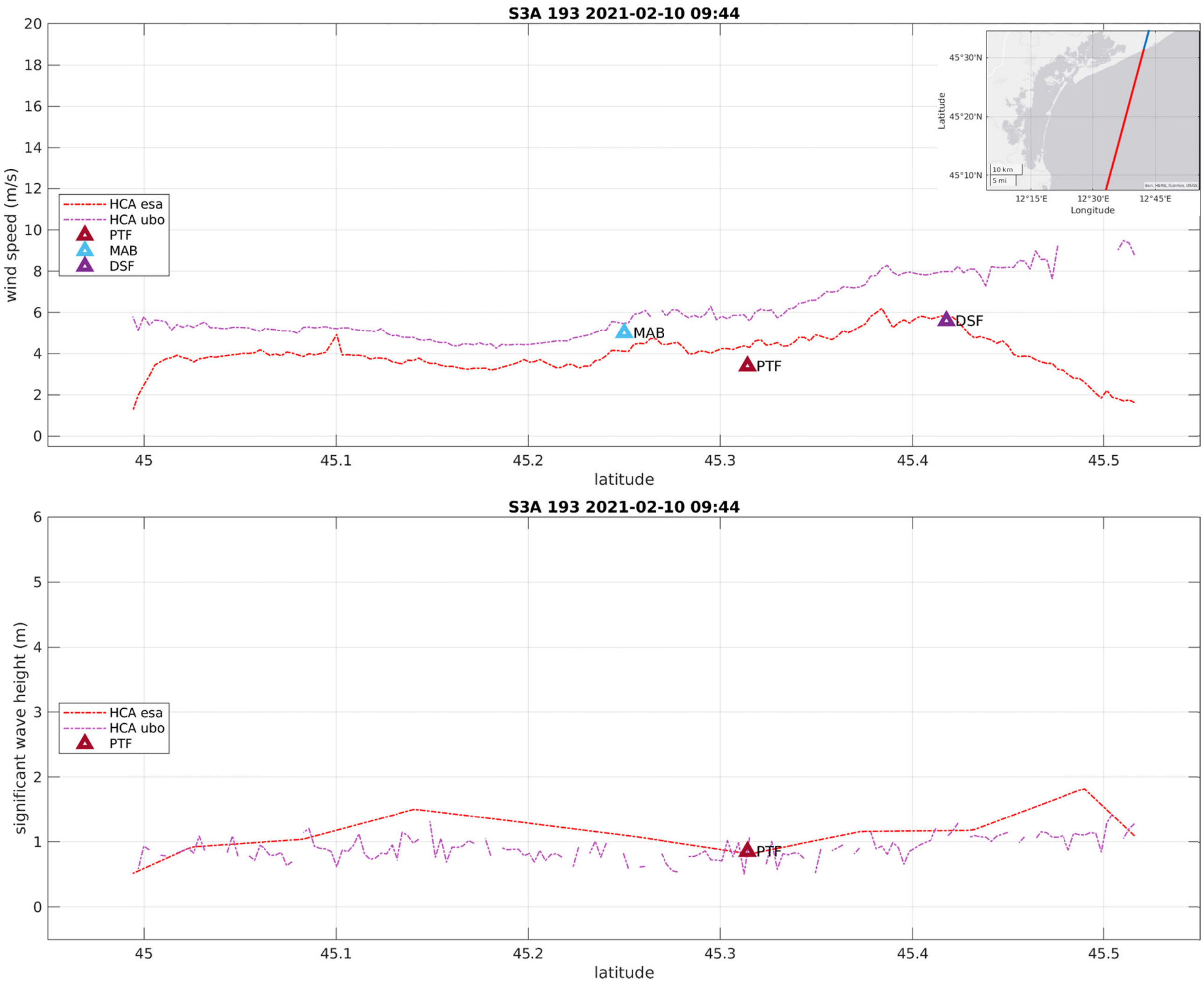


Figure 3.3.17: Wind speed measured by S3A along the track 193 over the Venice coastal zone, and the corresponding in situ values measured at MAB, PTF and DSF stations. The SWH measured at PTF is reported in the bottom panel, along with that measured by ESA and UBONN retrackers. Upper panel: plot of the wind speed from the ESA and UBONN retracker and the stations versus latitude. Bottom panel: SWH measured at PTF and as seen by ESA and UBONN retrackers.

The eighth example shown in Figure 3.3.18 is about a storm surge event happening on 4 June 2020 at 20:34. S3B is crossing the northern Adriatic Sea along track 193. The PTF station registered the storm surge event for 3.8 hours and the surge peak was 118 cm. This example is similar to previous CS2 events, with S3B crossing the northern Adriatic sea near PTF, then approaching the land near DSL and finally flying over the northern part of the lagoon. The altimeter clearly detects the storm surge signal, which agree very favourably with the measured level at PTF in open sea, DLS near coast and BUR/LNS inside LAGOON. The altimetric profiles show an interesting spatial variability at SEA. There is clear improvement with respect to the ESA product in the LAGOON. ESA and DTU retrackers fail in a specific place over the sea, while UBONN has gaps there. Similar cases are seen in other places and times and suggest an in depth investigation at echo level.

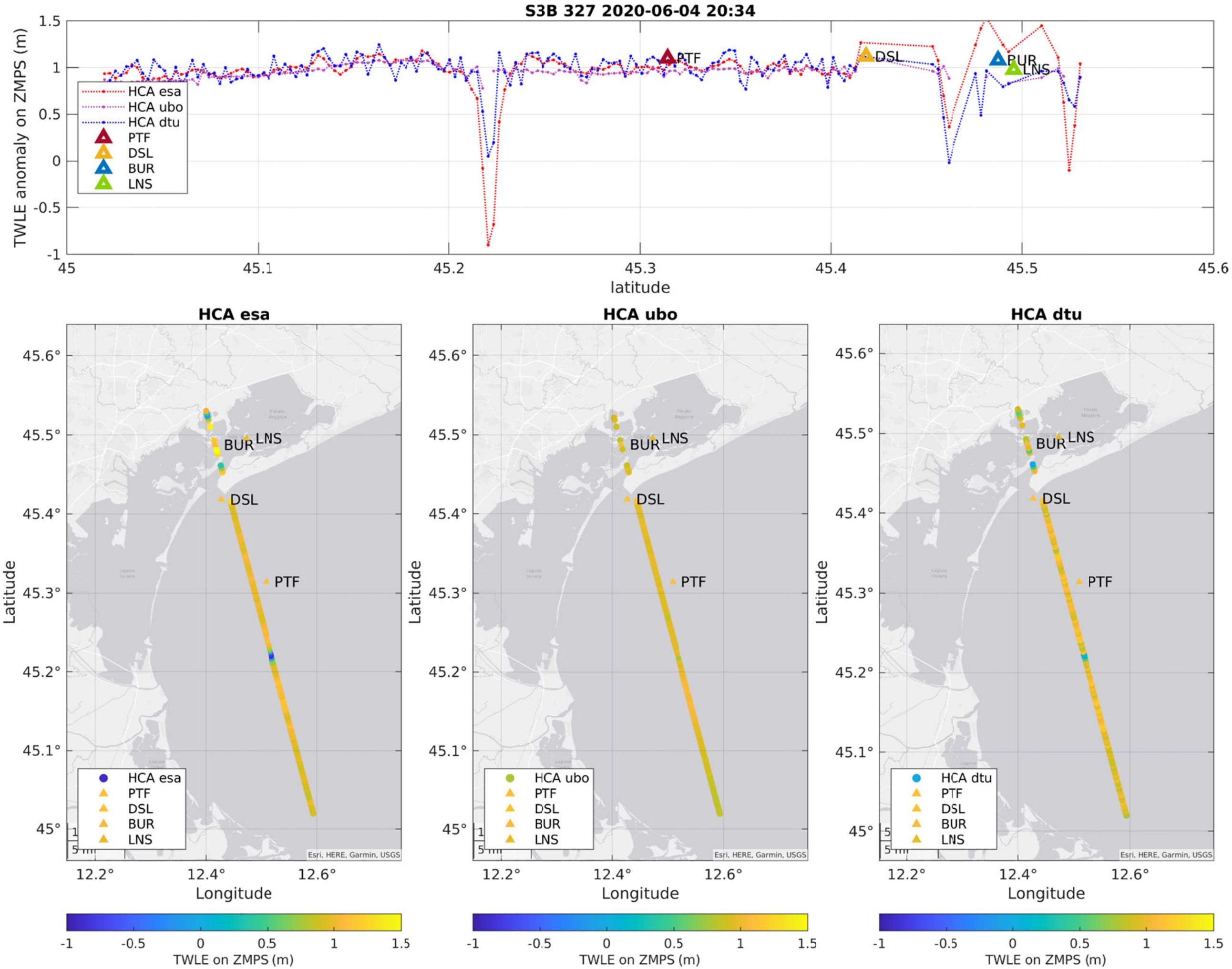
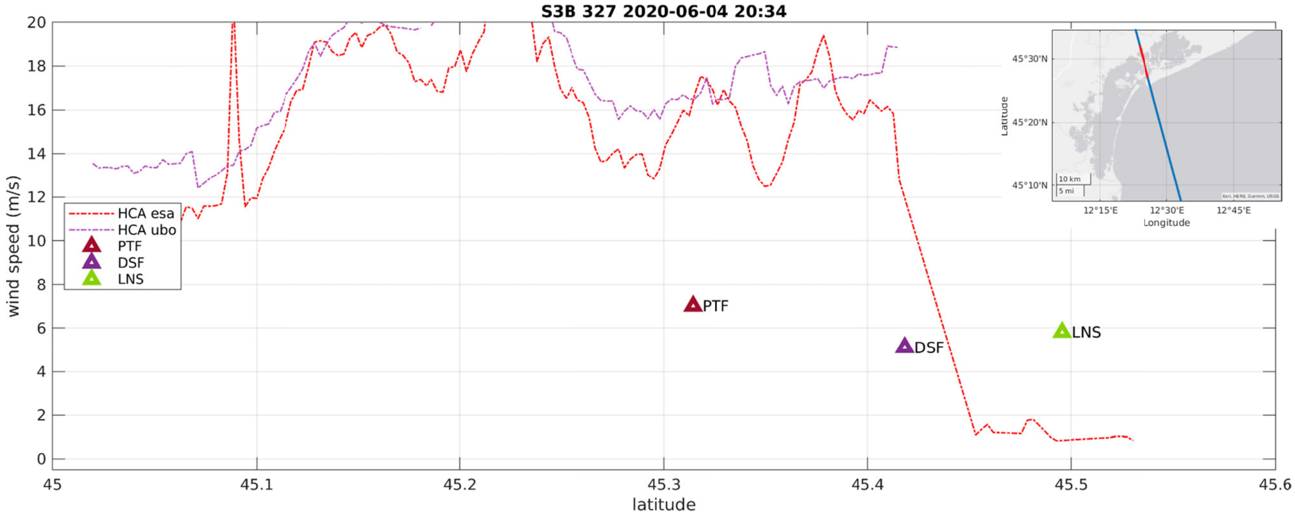


Figure 3.3.18: Total water level envelope anomalies as seen by S3A along the track 193 over the coastal zone in front of the Venice littoral, and by the PTF and DSL stations. Upper panel: plot of the TWLE from the three retrackers (ESA, UBONN, DTU) versus latitude. Bottom panels: same as above but geolocated on the map.

At the time of the storm surge event, the satellite-based wind does not agree with ground truth at SEA. There is a clear overestimation with respect to PTF and DSF, and only ESA has data in the LAGOON, albeit the underestimated altimetry wind speed in the LAGOON area are negatively influenced by land contamination, as seen before in similar cases. On the contrary, the altimetry SWH agrees well with that observed at PTF. Inside the lagoon, only ESA has valid SWH observations, but their values (~1 m) are too high for this region of the lagoon: the FUS station, at the same time, registered SWH of the order of 10-20 cm (see Fig. 3.3.18). All the profiles show a clear anomalous situation around 45.25°N, that needs to be investigated at echo level.


S3B 327 2020-06-04 20:34
wind speed (m/s)
latitude
0
2
4
6
8
10
12
14
16
18
20
45
45.1
45.2
45.3
45.4
45.5
45.6
HCA esa
HCA ubo
PTF
DSF
LNS
45°30'N
45°20'N
45°10'N
Latitude
12°15'E
12°30'E
12°45'E
Longitude
10 km
5 mi

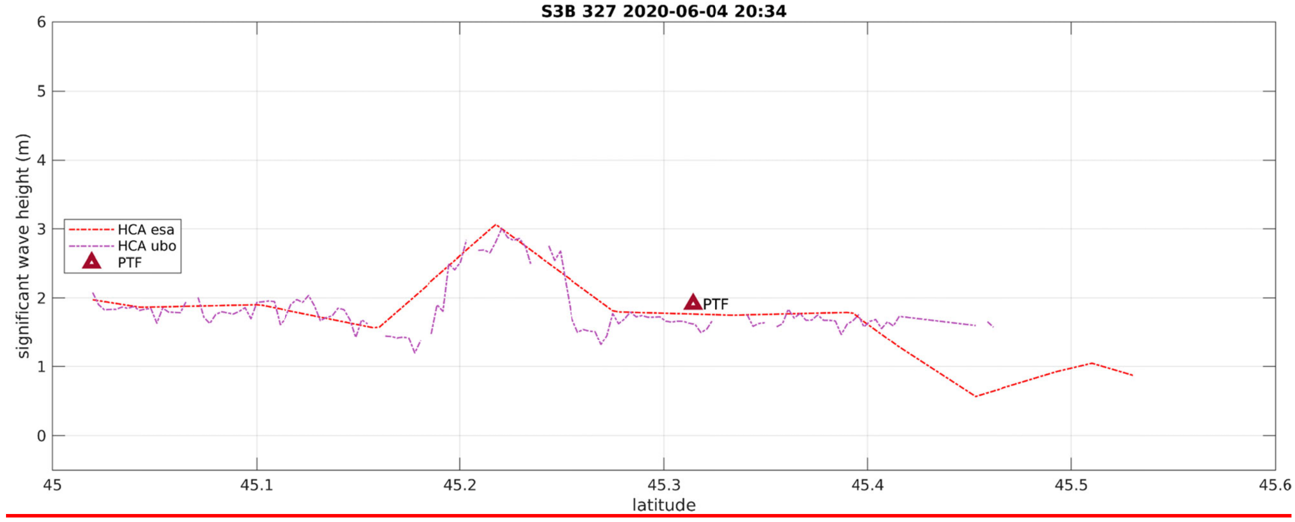

S3B 327 2020-06-04 20:34
significant wave height (m)
latitude
0
1
2
3
4
5
6
45
45.1
45.2
45.3
45.4
45.5
45.6
HCA esa
HCA ubo
PTF

Figure 3.3.17: Wind speed measured by S3A along the track 193 over the Venice coastal zone, and the corresponding in situ values measured at MAB, PTF and DSF stations. The SWH measured at PTF is reported in the bottom panel, along with that measured by ESA and UBONN retrackers. Upper panel: plot of the wind speed from the ESA and UBONN retracker and the stations versus latitude. Bottom panel: SWH measured at PTF and as seen by ESA and UBONN retrackers.

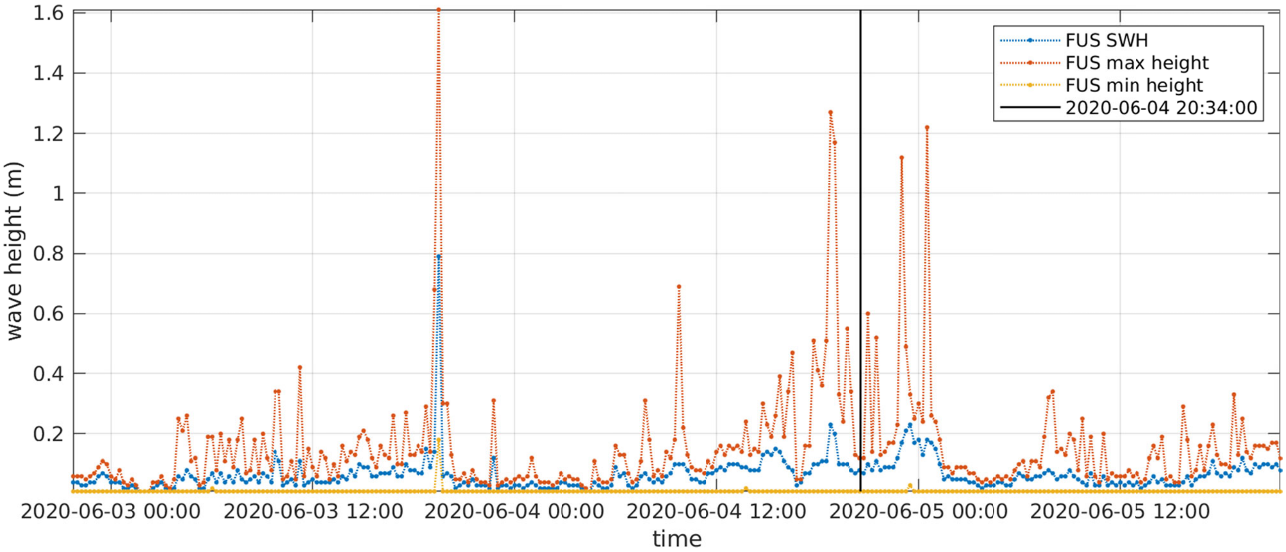


Figure 3.3.18: Significant wave height time series at FUS station during the storm surge event of 4 June 2020, 09:30. The SWH stayed under 20 cm during the event, despite the station was not sheltered from the south easterly wind, which had a long fetch.

3.4 Summary

We have demonstrated the potential usage of HydroCoastal data in the area of storm surge events, confirming what already seen with the past ESA eSurge Venice project, but with now the possibility of having sea level, wind and wave at same time and extending measurements closer to the coast and inside the lagoon.

The analyses in the Northern Adriatic Sea surrounding the city of Venice have provided qualitative and quantitative figures of the TWLE measurements generated by the Hydrocoastal altimetry processor. Overall, the results indicate that the TWLE is of good quality in the region at sea, near coast and within the lagoon, albeit the need is felt for a better land-sea mask for intertidal zones, maybe also with dynamic capabilities to follow the tidal cycles and offer the best mask in every tidal configuration. TWLE at the time of storm surge events is often comparable to the TG measurements and also much improved with respect to the state-of-the-art ESA product.

The analyses of the satellite-based winds are incomplete for various reasons and a definitive assessment at this stage cannot be provided. First, we could not use CS2 in the same way as S3 and we had to introduce an averaged attenuation value to exploit the $\square_0$ values supplied by the HydroCoastal retracker; second, there is no innovation in the algorithm to transform backscatter in wind amplitudes in the coastal environment. Nevertheless, comparisons with wind measured at stations showed in some cases some agreement. Some spatial variability needs additional investigation using other data (e.g. scatterometry) to better characterise the temporal and spatial variability.

The HydroCoastal processor also generated SWH data from retracked waveforms. SWH can be captured during the storm surge events, although UBONN shows data gaps. The estimated SWH is often in good agreement with observations.

3.5 Highlight main findings

A remarkable finding is that by using specialised retrackers (UBONN and DTU) good high-rate measurements of TWLEs can be recovered much closer to the coast and within the lagoon than for the ESA product. However, the altimetry system needs auxiliary information to transform radar measurements in sea level. An important confirmation of what is found in the Marano-Grado lagoon is that MSS vertical references can strongly differ from one dataset to the other, especially near the coast and within the lagoon.

The exploitation of wind amplitude and SWH is still at the early stage. Both variables can be measured, also inside the lagoon, but the results show some situations that need a more in depth assessment. Knowing the wind speed along track at the time of the storm surge event is important as no other instrument is capable of providing the same spatial variability with similar spatial resolution.

3.6 Potential Scientific / Operational Impact (“Benefit and unique value”)

The main users of the HydroCoastal product are the Centro Previsioni e Segnalazioni Maree (CPSM) of the Venice Municipality, and the Servizio Laguna of the Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA). The ESA eSurge Venice project showed good potentialities of altimeter data, now those are further improved in quantity and quality (with increasing spatial resolution), but for the operational usage of altimeter data, the need of frequent revisiting is a strong requirement. Satellite radar altimetry is not designed with in mind storm surge applications.

Satellite altimetry in the storm surge operational forecasting is still of limited use (because few altimeters are still flying in a constellation). Nevertheless some passages were available during storm surge events for an assessment. It should be noted that satellite radar altimetry has evident application in measuring storm surges, albeit currently limited by the number of simultaneous altimetry missions. Constellations of altimeters seem to be the more appropriate solution for the development of satellite radar altimetry services for storm surge forecasting. Satellite radar altimetry can compensate with available tide gauge measurements that provide only the temporal dimension at given coastal locations. The combined measurements can be used as an input for numerical models, and has been shown to improve predictions in the offshore part of the Adriatic Sea in the ESA eSurge Venice project (De Biasio et al., 2016).

The availability of S3 archived data represented a valuable opportunity for a retrospective analysis and testing. The HydroCoastal work establishes a more complete understanding of the performance of satellite radar altimetry, especially near coasts and within the lagoons, to work towards a better exploitation of these data. The actual scenario of S3 provides TWLE, SWH and wind profiles at the time of few storm surge events. The additional obstacle to further use HydroCoastal data operationally, is to count on faster data delivery to users. The additional post-processing is necessary to achieve the requested centimetric accuracy that needs to be transferred to the users in near real time.

3.7 Recommendations

Single altimetric along track profiles of TWLE, wind amplitude and SWH are useful for verification and support during the interpretation of storm surge events, in synergy with all the other data sets used by the forecasting services in Venice, to follow the spatial and temporal variability of the event in order to provide a proper forecasting for the population, in Venice as a first objective, but also all around the world, wherever coastal settlements are threatened by storm surges.

In particular, the following recommendations are advised for future scientific activities:

- We need all the parameters (TWLE, wind and waves) for storm surge applications. TWLE improved thanks to retracking. Wind amplitude and SWH are not mature for exploitation yet. The algorithm to transform backscatter in wind is tuned for the global ocean, and needs to be revisited at regional level, in the coastal zone and in coastal lagoons. SWH is not always agreeing with ground-truth. There is a need to understand the reasons for that. It should be noted that buoys and semi-mobile seamarks could not measure SWH well during the storms;
- Establishing a common vertical datum (geoid) for storm surge studies at regional level to integrate all height measuring systems and exploit satellite radar altimetry for inundation assessments;
- Re-computing a Coastal MSS with high-resolution SSH for better understanding ocean dynamics and for non-repeating tracks. Examining the effects of different MSS references and the opportunity of defining a MSS tuned for storm surge applications;
- Exploiting novel methodologies for sea surface height determination, based on specular reflection, as they can be more accurate for geodetic and cal/val applications in the coastal zone;
- Exploiting the extra resolution (80 hz or less) possible by reprocessing individual echoes;
- Improving the revisiting and exploring the possible advantage of constellation of small altimeters, as the storm surge signal is much higher than the background level and therefore might require a reduced radar payload;
- Investigate how the new Hydrocoastal product could be optimally exploited in the reanalyses of storm surge events and in the operational context if the satellite is flying at the time of the event;
- Stimulate the development of new high-resolution land-sea masks, possibly with a dynamic approach that could account for the tidal dynamics in the coastal strip and in coastal lagoons.

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