VALIDATION OF HIGH SPATIAL RESOLUTION WAVE DATA FROM ENVISAT RA-2 ALTIMETER IN THE GULF OF CADIZ COASTAL STRIP

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Abstract—Extending the applications of satellite altimetry to the coastal zone requires validate, quality controlled data. We present here a case study in the Gulf of Cadiz (SW Iberian Peninsula), an area of relevant social, economic and strategic ecological importance. We compare eight years (Dec 2002 - Jan 2010) of Significant Wave Height (SWH) data retrieved by the COASTALT processor along two Envisat RA-2 passes (one descending, one ascending) and the standard Geophysical Data Records (GDR, 1 Hz) against in-situ measurements. For the descending pass (land to ocean) the processor improves the retrieval of SWH respect to GDR in the coastal fringe with a strong reduction of the noise level. We estimated a decrease in rms and bias higher than 60% and 80%, using COASTALT data in comparison with the standard 1-Hz GDR product. In particular, the higher-rate COASTALT SWH products display accuracies in the sub-coastal strip (11 to 20 km from the coastline) of very similar magnitude of those further offshore, representing a clear improvement over GDR in this fringe. The ascending pass (ocean to land) indicates a smoother transition between ocean and land in terms of SWH retrieval. The validation of this new coastal-oriented product demonstrates that it is possible to build accurate wave height records much closer to the shoreline than routinely achieved, while also increasing the along-track spatial resolution.

Index Terms—Altimetry, Coastal Zone, COASTALT, Envisat RA-2, Gulf of Cadiz, Significant Wave Height, Validation.

I. INTRODUCTION

Satellite radar altimetry has been designed to give accurate information on sea surface height, significant wave height (SWH hereinafter) and wind speed at the sea surface over the open ocean. Past and current missions, however, encounter problems in coastal regions, where altimeter measurements are of lower accuracy and difficult to interpret due to two main factors: contamination of waveforms due to land or very calm waters entering the radar footprint, and inaccurate tidal and wet tropospheric corrections. Further region-specific complexity comes from the broad spectrum of spatial and temporal scales (in response to a variety of drivers and pressures) in the coastal domain [1]. Access to accurate information on coastal sea conditions is of great importance because of the enormous socio-economic-strategic interest of the coastal zone: this calls for new processing strategies to generate the optimized altimetric products suited to the diverse applications in such challenging conditions [2]. This demand is met by recent initiatives such as the COASTALT project: "Development of Radar Altimetry Data Processing in the Coastal Zone", funded by the European Space Agency (ESA), which developed, implemented and tested a prototype software processor to generate more accurate coastal altimetry products for Envisat.

Measurements of SWH and its variability in coastal areas are used for many purposes (sediment transport analysis, storm surges and coastal wave setup), and validation/calibration of models (wave forecasting, atmospheric, and ocean circulation). These applications serve a wide range of socially relevant purposes like the design of offshore engineering structures, the protection of coastal areas, ship routing, and the planning of operations at sea [3]. In this context, many studies have been devoted to validating altimeter SWH using ground-truth observations to ensure the accuracy of the products [4], [5], [6], [7], [3], [8], [9]. This work presents the first dedicated validation of high-rate wave data obtained from the new coastal product available in the COASTALT project. We validate the SWH data retrieved by the COASTALT processor along two Envisat RA-2 passes (descending and ascending) in the Gulf of Cadiz (Fig. 1) against independent ground-based observations from two stations (buoy and mooring). The validation was performed using along-track SWH at 18-Hz posting rate, i.e. much higher than the 1-Hz data in the standard products. We also assess the effect of various intermediate averaging rates in the COASTALT product.

II. MATERIAL AND METHODS

Altimetric data

Altimeter wave data come from two sources: (1) SWH at the standard resolution (usually referred to as “1-Hz” rather than the exact value of 0.9 Hz, see below), corresponding to about 7.5 km along-track: for this we used the standard Geophysical Data Records (GDR) products, distributed by ESA. The dataset corresponds to Version 2.1, which account satellite orbit evolution and implement the Ultra Stable Oscillator instrumental correction. The 1-Hz data are in fact generated by averaging a block of 20 samples at 18 Hz, so are spaced in time by ~1.11 s; (2) SWH at high-rate, i.e. 18 Hz, corresponding to 374 m along-track, from the processor developed under the frame of the COASTALT project. The COASTALT processor fits the 18-Hz waveforms of the Envisat RA-2 Sensor Geophysical Data Records (SGDR) with a suite of retrackers, some of which specifically designed for the coastal environment to capture unusual conditions like the presence of bright targets in the footprint [10]. However in the present paper, rather than putting the emphasis on unusual conditions, we focus on the investigation of the information contained in the high-resolution (18-Hz) wave data, which are normally not available in the SGDR; and in particular we try to assess the effect of averaging the data at various rates, and for this we use the output from the COASTALT Brown-model retracker (i.e. the same model used over open ocean based on [11]).

Both data streams were extracted for the 35-day repeating cycles 10 to 86, spanning about seven years in total (Oct 2002 to Jan 2010). The track segments are from descending pass 223 (land-to-ocean transition), and ascending pass 187 (ocean-to-land transition). Both cross the continental shelf in front of the Guadalquivir estuary mouth (Fig. 1). The quality-control procedures applied to both datasets to remove remaining spurious records included testing the land/sea flag, peakiness value (a measure of how ocean-like the radar waveform is), zero or default values in the wave height fields, and $N_{val} > 18$ (with N_{val} being the number of valid 18 Hz measurements per 1-Hz data block, which is between 0 and 20). The time series were further processed with the removal of all the observations for which SWH>15 m or SWH<0.15 m. To assess the effect of various averaging rates, we then averaged the quality-controlled 18-Hz data at "10 Hz" (actually 9 Hz, i.e. mean of 2 samples), "5 Hz" (actually 4.5 Hz, i.e. mean of 4 samples) and "1 Hz" (actually 0.9 Hz, i.e. mean of 20 samples as in the standard products).

In-situ measurements

The validation of altimeter wave data was made using measurements from two coastal stations deployed in the Gulf of Cadiz. (1) The SeaWatch buoy (36.28º N, 6.57º W, 54.4 km from coastline). SWH in this station was available at hourly intervals. (2) The Acoustic wave and current Doppler Profiler (ADP) AWAC (Nortek) (36.48º N, 6.30º W, 9.7 km from coastline), located in the coastal area in front of the Guadalquivir estuary mouth [12]. The AWAC is a bottom mounted system that uses Acoustic Surface Tracking (AST) moored (14 m below sea surface), which is basically echo-ranging to the surface with the vertically oriented transducer. The wave accuracy with respect to the resolution corresponds to SWH estimates <1% of measured value/1 cm (http://www.nortek-as.com/en). The wave measurements in this station were also available at hourly intervals. Rigorous quality control was undertaken, with complete removal of records containing default or null values, and of all the observations for which SWH<0.15 m and SWH>15 m. The accuracy specifications for buoy data are typically 5% for SWH, so that buoy measurements are considered the most reliable wave observations [13].

Validation of satellite altimeter wave data

Collocation of altimeter and concurrent buoy/mooring data was made for each station separately. The widely adopted criteria for match-ups (windows of acceptability of 50 km and 30 minutes), is based on assessments of the spatial and temporal variation of the wave field [14]. In our case Envisat, being in a sun-synchronous orbital configuration, overpasses the area at approximately 10:51 (pass 223) and 22:00 (pass 187). The time difference wrt the nominal buoy/mooring measurement is less than 10 minutes, which should have only a small effect on the comparison [14].

The track segments analyzed (about 90 km along-track) corresponded to 13 1-Hz track points with a maximum/minimum distances from stations of 72/11.5 km and 67/20 km (AWAC), and 57.7/18.5 km and 69.2/29.6 km (SeaWatch) for passes 223 and 187, respectively. The accuracy specifications for satellite measurements (10% or 0.5 m) are less stringent than for the buoy/mooring. Due to limitations in the in-situ data availability, we could only perform the comparison over 1.5 years of data for AWAC (May 2008-November 2009), and over the full seven years for SeaWatch (December 2002-January 2010), with a number of valid samples (satellite/in-situ match-ups) along-track of *N*=10/10 (AWAC) and *N*=55/57 (SeaWatch), for pass 223/187, respectively (COASTALT 1-Hz). The number of valid samples in GDR oscillates along-track between 7 and 11 (223-AWAC), 5 and 13 (187-AWAC), 40 and 54 (223-SeaWatch), 27 and 52 (187-SeaWatch). To perform this quality assessment exercise, conventional validation statistic tools were used, and differences between altimetry and ground wave data were quantified by computing some standard monitoring statistics such as the bias, root-mean-square (rms) error, and correlation coefficient (r). Observations that deviated out of the 95% confidence intervals of the scatter were identified as outliers and were discarded.

III. RESULTS

The wave climate at the SeaWatch site is close to open-ocean: the mean SWH for the study period was 1.2 m, ranging between 0.2 and 6.6 m. Instead, at the AWAC site conditions and variability are typical of a coastal semi-sheltered sea, with a mean SWH of 0.7 m and a range of 0.2 to 3.5 m over the study period.

Validation against the offshore SeaWatch buoy

Descending pass 223. The bias and rms difference (Fig. 2a and 2b) were estimated with respect to the buoy data using four along-track datasets: GDR (1-Hz) – COASTALT (1-Hz) – COASTALT (5-Hz) – COASTALT (10-Hz). A positive bias (i.e. an overestimation of SWH) can be observed in the 1-Hz COASTALT dataset (from P6 to P13), decaying to almost zero (P2 to P5), and significantly increasing in the closest point to the land (P1). The GDR dataset instead gives a negative bias along-track (P3 to P13), but rapidly increases in the two points closer to the coast (P1 and P2). Looking at the 5- and 10-Hz COASTALT rates, their bias show a similar behavior to the 1 Hz, with some negative but small bias between about 15 to 50 km along-track distance to the coast. The rms (Fig. 2b) estimated with the 1-Hz COASTALT wave data was lower than GDR inshore (6-60 km), while slightly higher rms was observed offshore. The rms greatly increases in the two points nearest to the coast, but this increase is much more pronounced in the GDR estimates. The bias around the points closest to the coast still indicate a strong overestimation of SWH in the coastal strip, but the overall statistics for the COASTALT data are significantly better (i.e. lower bias and lower rms) than for the GDR data.

Ascending pass 187. The bias (Fig. 2.c) indicates an underestimation of SWH in GDR and a smaller overestimation in COASTALT (almost zero in P3 and P4). One observes a smoother transition between ocean and land as the pass is moving from ocean to land. This is also confirmed by the lower rms obtained in P1 and P2 in both data sets (Fig. 2.d). The rms along-track is similar in GDR and COASTALT.

Validation against the inshore AWAC mooring

Descending pass 223. Fig. 3a and 3b show the along-track performance (again in terms of bias and rms) of both data streams when compared with the AWAC mooring, located in the sheltered zone close to the estuary of the Guadalquivir River. The bias and rms are similar in both GDR and COASTALT over the whole segment considered, except in the 20-km strip closest to the coast (points P1 and P2), where the latter compares much better with the buoy than GDR. The positive bias for both datasets indicates a common overestimation of altimetric retrievals with respect to the in-situ observations, especially in the proximity to land. Offshore, the bias and rms increase monotonically. Closer to the coast, at P2, the accuracy of COASTALT 1-Hz SWH is much better than GDR. COASTALT 5-Hz and 10-Hz SWH showed results a bit noisier than 1-Hz but with the same level of accuracy. It is worth noting that when approaching the coast both these higher-rate data remain on values of rms and bias lower than 1 m (that is not dissimilar from those observed further offshore) up to about 11–12 km from the land. In this sub-coastal strip the performance of the COASTALT SWH product, regardless of the degree of averaging, appears to be superior to the GDR.

Ascending pass 187. The bias (Fig. 3c) is positive in both data streams along-track (with the exception of P2 in GDR), with COASTALT showing a higher overestimation of SWH than GDR (excepting P3). The rms in GDR (Fig. 3d) is lower than COASTALT offshore with similar values as the track approaches the coast (P1 and P2). In P3, however, the GDR shows a strong deviation from the ground-truth data. The number of valid samples at this location is only 5 in GDR and 10 in COASTALT. As previously noted, the noisier results could be due to the lower number of valid points used in the comparison against the inshore mooring.

IV. DISCUSSION

This validation exercise shows that the processor developed under the frame of the COASTALT project retrieves along-track wave data from Envisat RA-2 waveforms with at least the same level of accuracy (in terms of rms) as obtained in the standard 1-Hz products of the GDR over the two passes analyzed. These two datasets present extremely consistent agreement (statistically significant at the 95% level), with similar and even better accuracy when compared to wave buoys than obtained in several studies over other ocean regions [4], [5], [15], [16], [17]. More importantly, the coastal-oriented processor retrieves accurate SWH closer to the land than routinely achieved in the land-to-ocean transition (descending pass 223). This improvement in the nearby coastal fringe has been observed in the comparison with both inshore and offshore stations, with a reduction of rms and bias values of 67% and 64% (w.r.t the AWAC mooring) and 65% and 83% (w.r.t. the SeaWatch buoy) in the COASTALT data with respect to the GDR estimates. We note that both COASTALT (at all rates) and GDR data systematically overestimate SWH with respect to the AWAC station, but this is in line with previous works on validation of altimeter SWH using in-situ buoy measurements in the ocean and coastal regions [18], [19], [8]. The COASTALT processor generates data with nominal along-track spatial separation of 374 m (18-Hz), which can be averaged to various extent. When compared to the SeaWatch data, COASTALT 5 Hz and 10 Hz data showed a level of agreement comparable to GDR 1 Hz and COASTALT 1 Hz records, with no significant difference between them. When comparing to the AWAC mooring, the 5 Hz and 10 Hz data clearly show a higher variability along-track compared to 1 Hz estimates, but remain at the same level of accuracy than the standard 1 Hz sampling (statistically significant at the 95% level).

In the Guadalquivir estuary, the effect of slight spatial variations in wave climate over the 10- to 50-km distances might affect the comparison between in-situ and altimeter data sets and could explain some of the bias obtained. In coastal systems the background energy may significantly vary within the region and affect the wave spectra differently [20]. This could reflect, at least in part, the noisier radar returns from a generally rougher sea surface condition than usually found in deep oceans. Thus, these effects associated with the remaining noise in the bias and rms are interpreted as due to local variations in wave climate because of the proximity to land (coastal shape), the bathymetry (low slope in the 30 km coastal fringe) or attributed to oceanic stability effects and phenomena at different temporal-spatial scales (e.g. wave/current interactions).

Some of the systematic bias found could be also due to buoy measurement inaccuracy, collocation errors, and also contamination on altimeter returns in the land-to-ocean/ocean-to-land transitions, or to the Envisat altimeter requiring some time to 're-lock' the ocean surface after coming off land [21]. Indeed COASTALT works better than GDR in terms of data quality for points near the coast of the descending pass 223 coming off land, both for the SeaWatch and AWAC stations (see fig. 2b and 3b). This is much less pronounced in the ocean-to-land transition (pass 187). Therefore, and despite the above difficulties, the COASTALT Brown retracker seems less affected by the proximity of the shoreline when the satellite comes from land than the standard retracker used for the GDR. The high bias and large noise of the data over the 4-12 km distances to coast (pass 223) demonstrate that, in addition to the dynamical coastal processes, land effects on the footprint impact negatively on the retrieval of SWH, but this effect is clearly greatly manifested in GDR SWHs than in COASTALT. The degradation of SWH measurements is common in the coastal strip [18], [21], and we cannot provide optimized SWH right up to the coastline [22]; getting closer than the 10-km threshold at the levels of accuracy seen offshore will probably require processing by dedicated retrackers that take into account the land contamination in the waveforms [2].

V. CONCLUDING REMARKS

The SWH from the COASTALT processor (1-Hz, 5-Hz and 10-Hz averaging rates) is of the same level of accuracy than the standard GDR when compared against both inshore and offshore stations. The processor improves the retrieval of SWH respect to GDR especially coming off land. We observed a decrease in rms and bias higher than 60% and 80%, respectively at all averaging rates (COASTALT data) in comparison with the standard GDR product. In particular, the higher-rate COASTALT SWH data display accuracies in the sub-coastal strip (12 to 20 km from the coastline) of very similar magnitude of those further offshore, representing a clear improvement over GDR in this strip. The ocean-to-land transition seems to be smoother in terms of SWH retrieval.

These results show that it is possible to build accurate wave height records closer to the shoreline than before, while also increasing the along-track spatial resolution, and encourage further research on coastal-oriented processing. The use of wave data at higher along-track spatial rates would improve the capture of dynamical processes of smaller spatial scale and their variability such as river plumes, coastal upwelling and circulation. Thus, it would allow a better characterization of coastal regions by taking into account the non-uniform conditions, e.g. local SWH gradients induced by fetch, or sheltering effects bathymetry, land morphology, and the local tides and wind.

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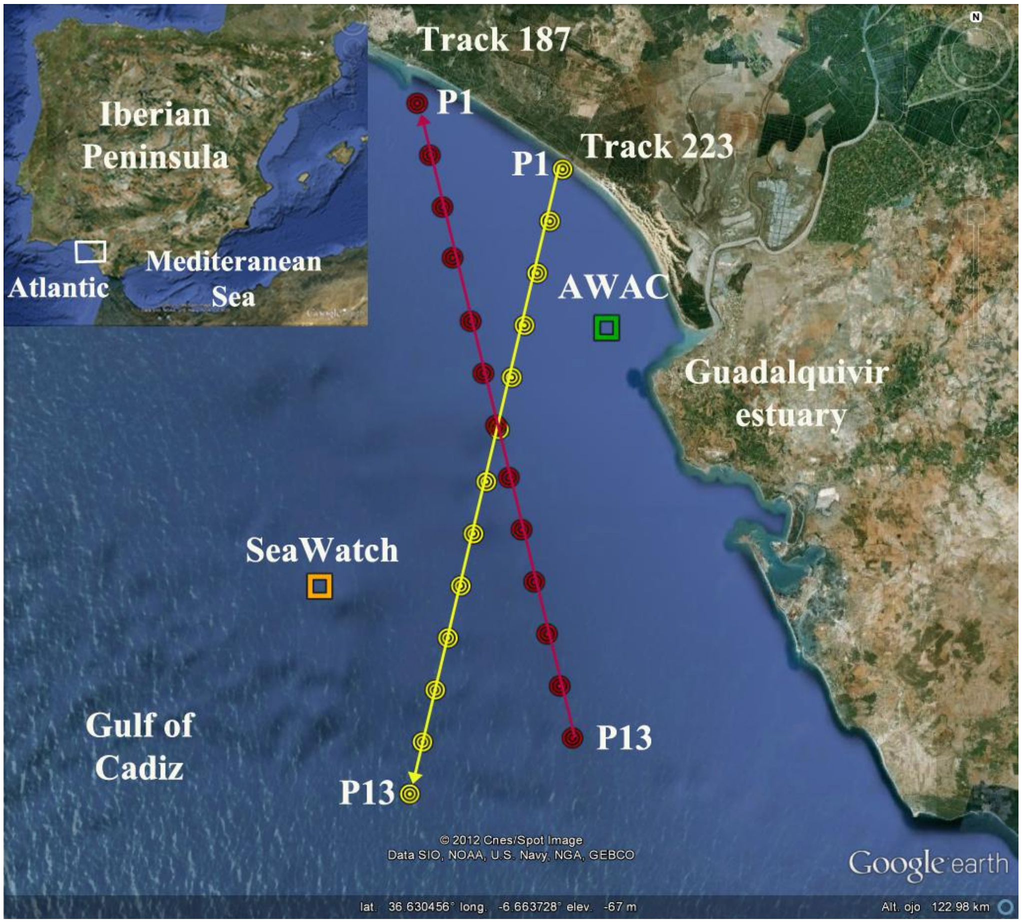

Fig. 1. (a) Location of study area (southwest Iberian Peninsula).
(b) Zoom of region showing descending and ascending altimetric passes 223 and 187 (yellow and red lines, respectively), and AWAC (green square) and SeaWatch (orange square) coastal *in-situ* stations. Yellow and red dots along ground tracks indicate mean position of 1-Hz averages.

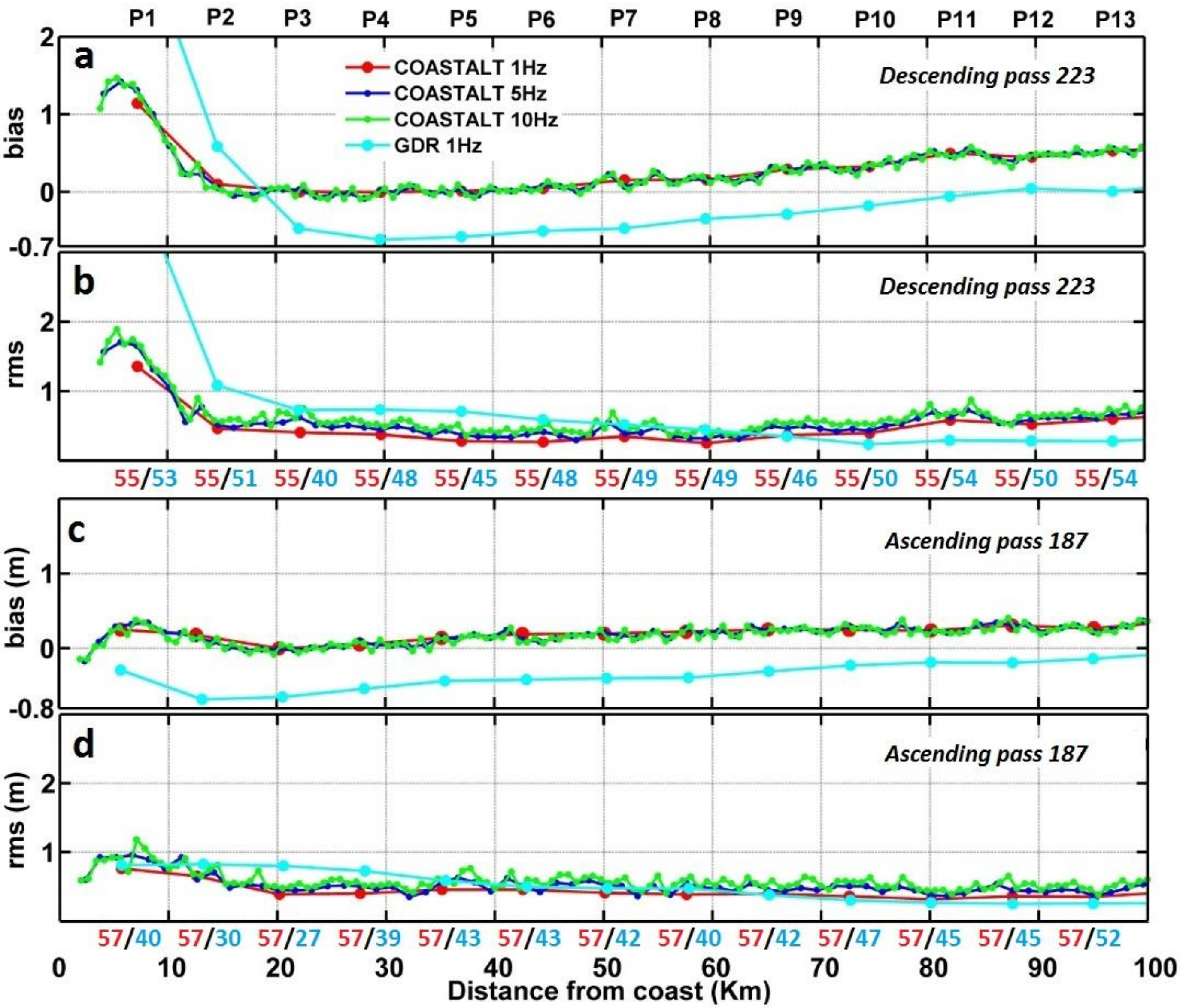

Fig. 2. Along-track SWH bias (m) and sdd (m) of four altimeter datasets for passes (a) and (b) 223 and (c) and (d) 187 respect to (along-track) distance from coast for comparison against SeaWatch station. Cyan line corresponds to GDR 1-Hz data; red, blue, and green to 1-Hz, 5-Hz and 10-Hz COASTALT data, respectively. Red and cyan numbers in bottom of (b) and (d) indicate number of valid samples used for 1-Hz COASTALT and GDR data, respectively (satellite/*in-situ* match-ups). Black vertical arrow on panels (a)–(d) indicates the location of SeaWatch station.

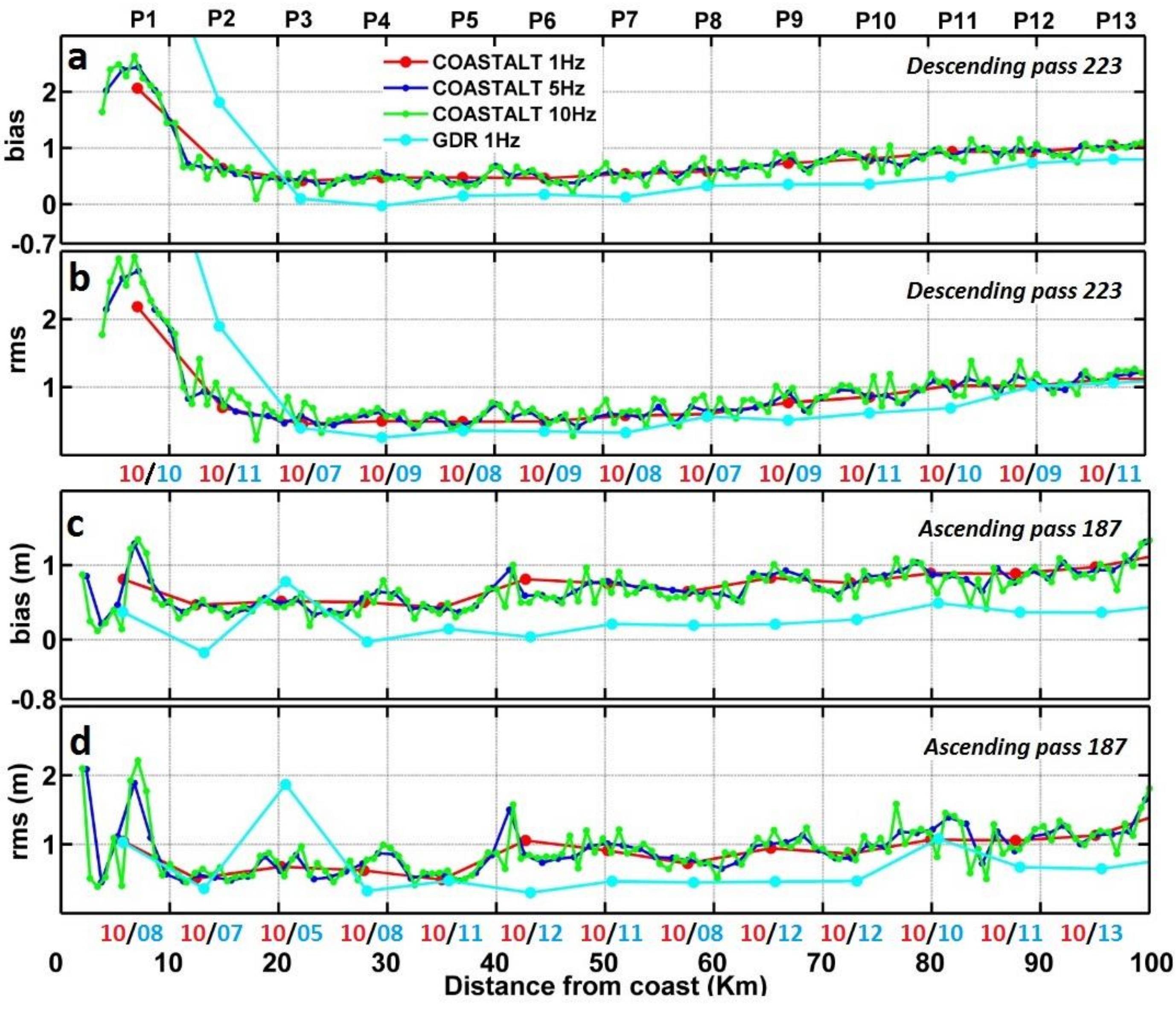

Fig. 3. Same as Fig. 2 for comparison against AWAC mooring station. Black

vertical arrow on panels (a)–(d) indicates location of AWAC station.