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Analysis of multi-sensor sea level measurements in the Adriatic Sea

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Abstract – **The aim of this study is a preliminary analysis and comparison of a ten years, multi sensor co-located observations of sea level. Starting from data collected by the Italian tide gauge network, we report the description of recurring errors, some statistics for the compared signals and a comparison between closed stations.**

I. INTRODUCTION

Sea level monitoring networks are necessary for many applications, ranging from shoreline protection and coastal flood control to planning and design civil infrastructure that insist on the coast, from the navigation support to the climate change studies, from the sea safety and circulation to the validation and calibration of forecasting models. Most of these activities require both real-time data and multiannual time series.

The principal applications of sea level observations are: the evaluation of the tidal cycles, the estimation of the effects of meteorological contributions, the study of extreme events, the tides prediction, the validation of forecasting models. Moreover, sea level data are used for determining seiches and can support the identification and characterization of tsunami and storms tides.

ISPRA manages the national tide gauge network "Rete Mareografica Nazionale" (in the following RMN), currently counting 36 stations located along Italian coasts. Each station provides sea level measurements and also main meteorological parameters. Some stations also provide data used for the qualitative characterization of environmentally sensitive marine areas.

During the last decade, sea level data have been fundamental in the evaluation of the effects of climate changes on marine environment, in particular on the study of sea level rise acceleration. In this framework the levelling activities assume the same importance then the sea observation and the correct definition of a reference system is a critical step.

For each measurement station the local reference system is directly linked to the Italian IGM high precision leveling network, built in the years between 1950 and 1971, therefore sea level values are referred to the official altimetric system for the mainland Italy (Genoa 1942).

Nowadays the standard high precision leveling has been replaced by GPS measurements of the vertical displacements of the measurement stations. However, the discrepancies between these two approaches, the discontinuity of these operations, suggest the use of continuous monitoring of the vertical displacements through new technologies (e.g. GNSS).

As many other types of measurements, sea level observations collected by tide-gauges, are affected by different types of error.

The problem of sea level error has been addressed by several authors to estimate the measure uncertainty and determine reliability at studies on sea level changes [1].

Since tide-gauges are isolated instruments no comparisons with other independent records were possible, for this reason all the RMN measurement stations are equipped with two sensors that acquire sea level data simultaneously, a guided radar sensor and a float with encoder.

Following [2] we used the differences between the two collocated sensors to identify and classify errors and bias, particularly in relation to the vertical variation of the tide gauges benchmarks.

The aim of this study is then a preliminary analysis and comparison of a decadal multi sensor observations of sea level measured from two different sensors at six RMN stations. These stations are located along the northern and the central sector of the Adriatic basin. The investigated area is representative of 400 km of coastline, consisting of lagoon systems, sandy shorelines and rocky promontories, combining different hydraulic conditions and geographic environments.

II. RMN NETWORK

The RMN is the hugest network of sea level measurement in the Mediterranean Sea (Fig. 1), collecting real time series of sea level and meteorological parameters. Sea level data are collected with the very high frequency of 1 observation per minute and experimentally for some stations with a frequency of 15 seconds. The RMN also provides weather data that integrates the National meteorological system.

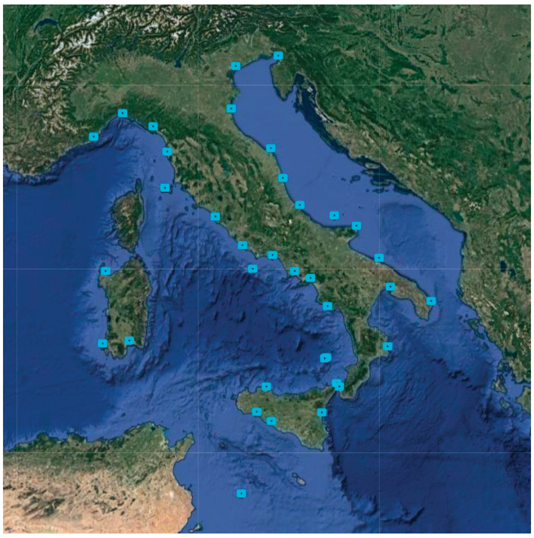


Fig. 1. RMN stations (www.mareografico.it).

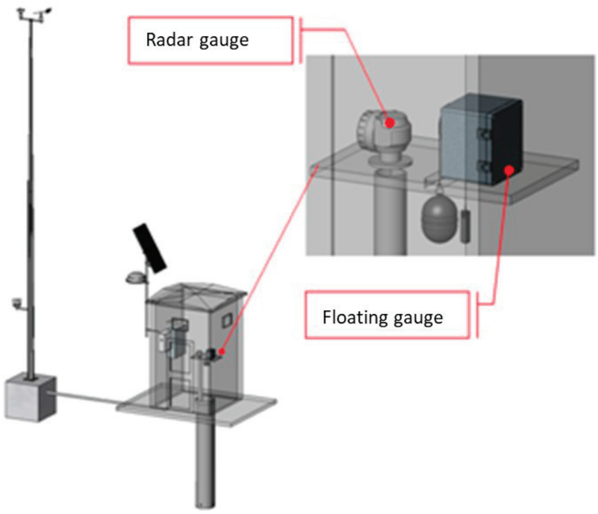


Fig. 2. Layout of RMN station.

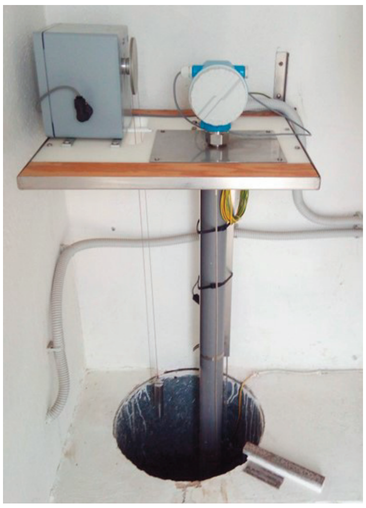


Fig. 3. Radar and floating gauges in RMN station.

Data used in this study range from 2010 to 2020, which are priory checked to ensure their highest possible accuracy.

III. METHODS

Standard procedures have been applied to remove errors in the time series of measurements and the resulting differences (Δ) calculated as follows:

$$\Delta = SL_r - SL_f$$

where SL_r is the sea level calculated trough the radar and SL_f is the sea level calculated trough the float.

The Δ differences have been calculated at the six stations, on the entire considered period and yearly, and then analysed respect to the amplitude and pattern.

Therefore, an algorithm for multiple change point analysis have been implemented to detect any possible discontinuity in the time series of Δ. This algorithm uses a dynamic programming and pruning approach [3] and detect a suitable number of change points according to the E-statistic as a goodness-of-fit measure.

Moreover, Van de Casteele test [4] has been implemented to analyse the magnitude of the expected error in the recorded sea levels and to provide a qualitative illustration of the type of error involved. Van de Casteele tests [5,6] allow to easily visualise the differences of recorded tidal levels between a sensor and another selected as reference. Following results of previous studies (e.g. [7,8]) which suggest that the radar sensors appear to have a more stable behaviour respect to the pressure gauges, radar sensors have been used as the reference gauge and the floater with encoder as the sensor under testing.

Tidal analysis and prediction have for long been an important issue for different applications such as safe navigation and hydrographic surveys. Because the tide is a periodic phenomenon, it can be modeled by a series of periodic functions such as sinusoidal ones. The influence in the tidal analysis of the presence of 'steps' in the sea level data, has been investigated to suggest an ideal time interval so that the analysis it is not invalidated by misalignments.

Finally, the spatial variability of sea level measurements obtained by radar sensors has been compared among neighbouring stations during selected time intervals.

IV. RESULTS AND DISCUSSION

In the following, results of described analyses are reported and discussed.

A. Descriptive statistics of Δ

Table 1 contains some descriptive statistics of differences Δ at the six gauges listed in the first column.

The second column of Tab. 1 reports the percentage of Δ values less than 2cm that for all gauges always represent more than 83% of the time series analysed. The number of null data is reported in the third column. The ten-years averaged values of differences (fourth column) vary from 0.001 to 0.008. In 2 the main representative percentiles of the annual difference's distribution are shown to investigate the occurrence of leveling errors and/or drifts between collocated measures. As highlighted in Fig. 4, the representation of the annual difference's main percentiles allows to point out different behaviour between the 10 years otherwise not noticeable with the same statistics calculated on the entire period.

Van de Casteele plots allow to quickly inspect whether time shift errors or instrument and system malfunction affect data during the time period selected. Fig. 5 shows the differences, at Tremiti gauge, respectively averaged with a five minute (on the left) and hour time span (on the right). The hourly averaged series is useful to remove high frequency variations and to simplify the identification of trends. In particular, at this station the test does not highlight a systematic deviation since the difference values remain around zero at all tidal altitudes.

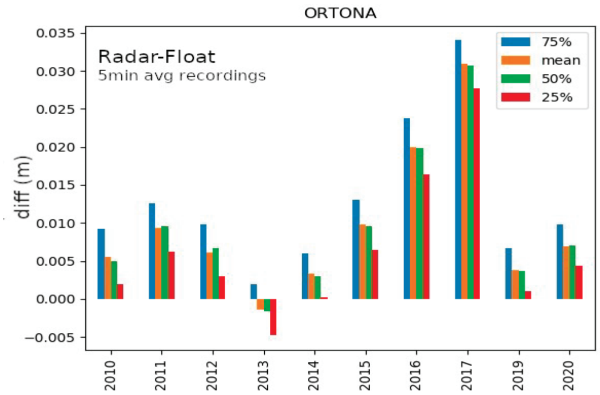


Fig. 4. Annual descriptive statistics of sensors differences.

Table 1. Descriptive statistics of differences between sensors.

Gauges	% (Δ < 0,02m)	# null data	Avg
Venezia	91,3	2	0,002
Ravenna	84,7	1018	0,002
Ancona	98,4	2	0,003
SBTronto	87,1	209	0,007
Ortona	83,1	780	0,008
Tremiti	99,9	2353	0,001

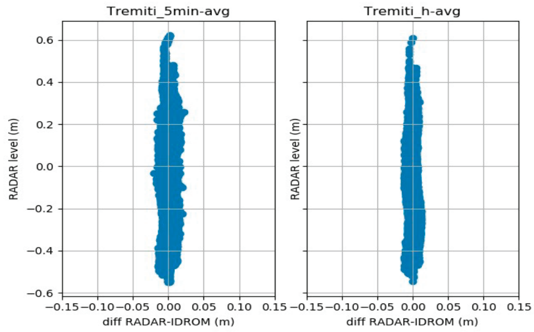


Fig. 5. Van de Casteele plot at Tremiti gauge. On the left 5minutes and on the right hourly averaged time series.

B. Type of errors

The differences between sensors at each station fall into one of the proposed categories by [2], with major importance of drifting evidenced by a linear trend (Fig. 6) and sudden 'step' in the recordings (Fig. 7). Sensor or data logging system malfunctions are concentrated in specific stations. The interpretation of the causes of the drifts in the differences between the levels measured by the two sensors needs various considerations since it is not possible to identify a reference measurement method. Although commonly radar-measured levels are considered to be very precise, in the present study we have carried out standard procedures to statistically

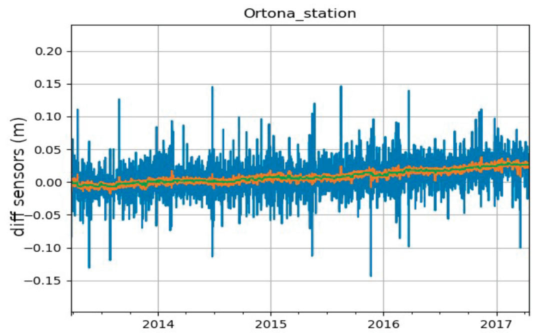


Fig. 6. Drifting of differences. In blue, orange and green the 5minutes, hourly and daily averaged values, respectively.

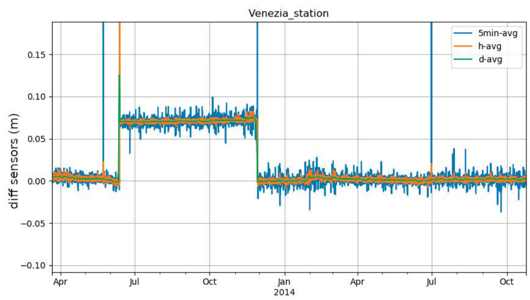


Fig. 7. Sudden change of values at Venice station.

analyse such differences in measurement between two sensors located in the same station.
The differences in levels statistically indicate a greater occurrence of float measurements that underestimate radar measurements (positive variations). These differences follow linear trends (drift) of increase, whose velocities are consistent with nearby stations and in particular with stations in the South Adriatic. For this reason, at present, a progressive underestimation of the float measurements due to biofouling induced system malfunctions is assumed. Similarly, the sharp decrease in deviations (sudden steps) could be due to maintenance work. Marine biofouling could generate indeed several problems for oceanographic instruments enhancing sensors and causing corrosion. This process depends on both biotic and abiotic factors such as: temperature, pH, dissolved oxygen and organic matter content. The effects of these factors are related to their spatial and temporal variability. Another relevant influence on increasing biofouling problems could be considered the sea primary production.

Table 2 reports some statistics about the amplitude of steps detected through the change points analysis in terms of real value (A) and absolute value (|A|).

The influence on the tidal analysis caused by the presence of ‘steps’, as the one reported in Fig.5, has been investigated. In Figure 9, main tidal components (illustrated in Table 3) calculated at Venice station respectively for radar, float and adjusted float levels measured in 2018, are reported; float adjusted series means that gaps in the float measurements due to maintenance operations were removed. The Z0 is the mean level, whereas the others 8 components (from SA to O1) are principally of long period while the others represent daily and semidiurnal components.
The amplitudes obtained for daily and semidiurnal components didn’t show relevant changes between the three series (radar, float and adjusted float). Instead the long period components show greater variations between the three series. These are the results when the analysis is performed on a single year of data while if the same analysis is performed over a longer period (more than two years) such differences are weaker and irrelevant. These results suggest to use a time span longer than one year, as usually is done, in order to avoid a negative influence of jumps presence in the sea level time series.

C. Spatial analysis of level data

Radar sea level measurements were used to analyse the coherence of the tidal signal in the northern part of the Adriatic Sea. An example of the differences in radar level among Venezia and the other stations is provided in Fig. 8, which highlights the increase of both the median and the deviation from it of the difference values moving away from Venezia, starting from Ravenna (ven-rav) until to Tremiti Islands (ven-trm).

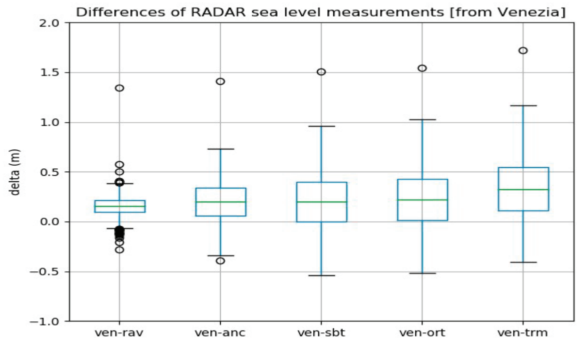


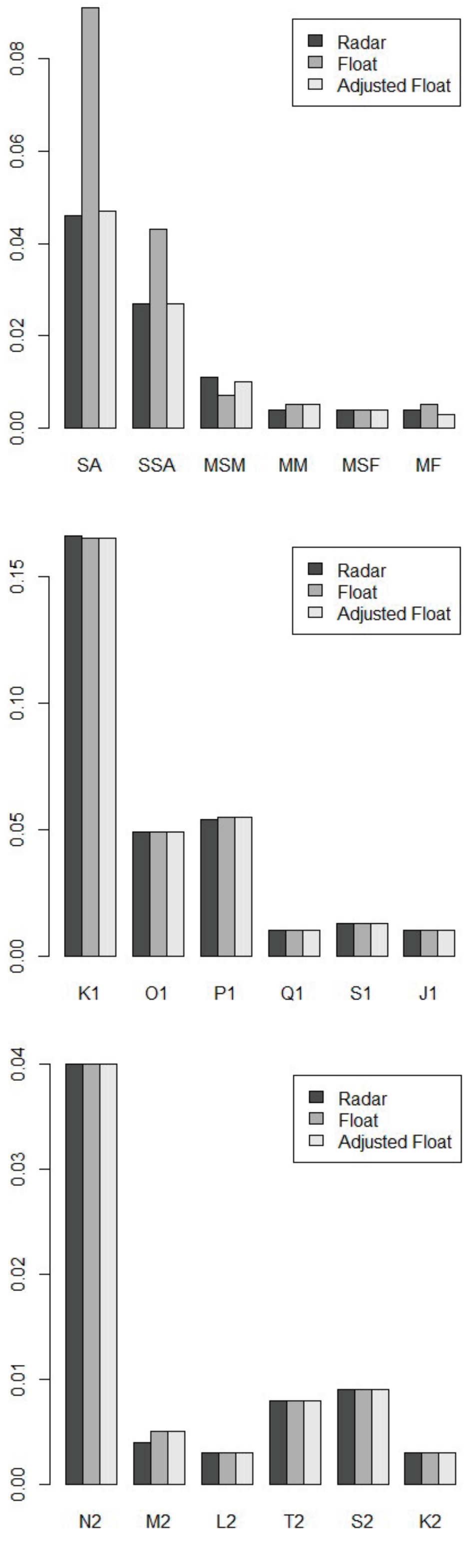
Fig. 8. Distribution of 2014 differences of RADAR recordings relate to Venezia (reference) station.

Table 2. Change points in differences.

Gauges	N	Mean(|A|)	Max(|A|)	Sum(|A|)	Sum(A)
Venezia	2	0.34	0.61	0.68	0.53
Ravenna	2	0.03	0.03	0.05	-0.05
Ancona	1	0.01	0.01	0.01	-0.01
SBTronto	0	-	-	-	-
Ortona	4	0.01	0.03	0.06	-0.04
Tremiti	0	-	-	-	-

Table 3. Calculated tidal components.

	Component name
Z0	Mean sea level
SA	Solar annual
SSA	Solar semiannual
MSM	Lunar monthly evectional
MM	Lunar monthly
MSF	Lunisolar synodic fortnightly
MF	Lunisolar fortnightly
K1	Lunisolar diurnal
O1	Lunar diurnal
P1	Solar diurnal
Q1	Larger lunar elliptic diurnal
S1	Solar diurnal
J1	Smaller lunar elliptic diurnal
N2	Larger lunar elliptic semidiurnal
M2	Principal lunar semidiurnal
L2	Smaller lunar elliptic semidiurnal
T2	Larger solar elliptic
S2	Principal solar semidiurnal
K2	Lunisolar semidiurnal



(a)

(b)

(c)

Fig. 9. Long period (a), diurnal (b) and semidiurnal (c) tidal components in Venice in 2018 for radar, float and adjusted float time series.

V.CONCLUSIONS

All the stations are influenced by a prevalence of positive differences between sensors, indicating that the floater often underestimates.

Moreover, the presence of jumps in the sea level time series suggest the use a time span longer than one year when performing a tidal analysis, in order to avoid great instability in the results.

In order to integrate the tide gauge network of the sector analyzed, GNSS stations will be integrated co-located with some tide gauges, as it has already been done for the Venice station, aimed at discriminating potential altitude reference errors in areas where the subsidence problem is particularly present and then refer the detected level to a global reference datum. This preliminary work is oriented to determine the stations that will be equipped with GPS equipment. A procedure for the validation and elaboration of the GPS data and an integrated analysis with the tide gauge data will be proposed, both in the framework of the Project AdriaCLim "Tools of information, monitoring and climate change for the adapting strategies in the Adriatic coast areas" funded by the cooperation program Interreg Italy-Croatia.

In this project ISPRA will review and apply validation procedures to historical time series related to meteo-marine parameters and build up a new homogeneous sea level data base.

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