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Sea Level Characteristics Referenced to Specific Geodetic Datum in Alexandria, Egypt

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***Abstract*—**Two geo-referenced sea level datasets (September 2008 – November 2010) and (April 2012 – January 2014) were recorded at Alexandria Western Harbour (AWH). Accurate re-definition of tidal datum, referred to the latest International Terrestrial Reference Frame (ITRF-2014), was discussed and updated to improve our understanding of the old predefined tidal datum at Alexandria. Tidal and non-tidal components of sea level were separated with the use of Delft-3D hydrodynamic model-tide suit (Delft-3D, 2015). Tidal characteristics at AWH were investigated and harmonic analysis showed the most significant 34 constituents with their amplitudes and phases. Tide was identified as semi-diurnal pattern as indicated by a “Form Factor” of 0.24 and 0.25, respectively. Principle tidal datums related to major tidal phenomena were recalculated referred to a meaningful geodetic height datum. The portion of residual energy (surge) out of the total sea level energy was computed for each dataset and found 77% and 72%, respectively. Power spectral density (PSD) showed accurate resolvability in high band (1–6) cycle/days for the nominated independent constituents, except some neighbouring constituents, which are too close in frequency. Wind and atmospheric pressure data, during the recorded sea level time, were analysed and cross-correlated with the surge signals. Moderate association between surge and wind and atmospheric pressure data were obtained. In addition, long-term sea level rise trend at AWH was computed and showed good agreement with earlier estimated rates.

***Keywords*—**Alexandria, Delft-3D, Egypt, geodetic reference, harmonic analysis, sea level.

I. INTRODUCTION

THE relationship between tidal and terrestrial vertical datum is of importance to provide essential data to many users including those who are involved in; hydrographic surveying, commercial shipping industry, marine construction, recreational boaters, coastal area planners, chart datum needed for nautical charts, and also military operations (amphibious warfare). So, updating oceanographic information especially sea level data is always needed for continuous validations of nautical charts production, and for laying harbours plans.

The observed sea level variation at any part of the world depends on many factors among which are storm surges, astronomical harmonic components, the seasonal cycle inter-annual to secular variability, and finally variations at geological and interglacial scales [1]-[3]. In Egypt, the geodetic vertical datum network has been set as the mean sea level (MSL) in Alexandria. This datum was first derived based on sea level observations for eight years from 1898 to 1906 [4], and found that this imaginary surface level (MSL) was 33.8 cm above zero of a fixed tide staff in AWH tide well. This MSL was named as Survey Dept. Zero Level Datum or zero of the Egyptian Survey Authority (ESA) datum 1906. In Alexandria, height of chart datum referred to the ESA was 34 m [5]. Since then, there were no additional researches which have been made in Egypt concerning the connection between terrestrial datum and tidal datum. Due to the global warming fact, the sea level has been risen in all over the oceans and specifically in the Mediterranean Sea according to [6]. However, records and measurements showed that sea level has been steadily rising since 1900 at a rate of 1 to 2.5 mm/ year. Moreover, it is projected for SLR to increase by the end of the 21st century to levels from 18 cm to 58 cm [7]. In Alexandria, the astronomical tide contributes with 0.005-37.63% while, surge contributes with 62.37-99.995% in the observed sea level as discussed by [8]. This might refer to the meteorological and climatic effects, developed at Alexandria region.

As in the whole Mediterranean basin, the observed sea level variation in Alexandria results mainly from the combination of two elevations: astronomical tides and surges. While the former is of minor importance; being ±20 cm, the latter may reach 1.0 m elevation under the effect of the meteorological factors such as air temperature, the wind system, the atmospheric pressure and the steric effect [9]-[11]. The effect of winds on the observed sea level varies from one location to another, and depends largely on the morphology and position of the location itself. Reference [12] concluded that MSL in Alexandria, Egypt has risen 11.6 cm from 1906 to 2003 with a rate of 1.7 mm/year, while [13] found that MSL rose significantly from 1993 to 2011 by approximately 3.0 cm/decade. However, zonal and meridional wind speed has only a small effect on the sea level variations as described by [14]. The effect of winds on the observed sea level within the AWH is generally related to wind with speed greater than 2 m/s as demonstrated by [15].

Consequently, and due to the temporary change in SL, accurate re-definition of the Egyptian tidal datum referred to a specific geodetic vertical datum is always essential, and it needs additional research investigation.

Generally speaking, wind will raise sea level in the direction towards which it is blowing, i.e. a wind blowing straight onshore will pile up the water shoreward building a setup.

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The main aim of this paper is to analyze geo-referenced sea level data inside AWH, Alexandria on the Egyptian Mediterranean coast to investigate the characteristics of its components.

II. DATA AND METHODS OF ANALYSIS

Alexandria Port is located at the west end of the River Nile between the Mediterranean Sea and Mariot Lake (Fig. 1). It is the second most important city and the main port in Egypt. The harbour handles approximately 75% of all ship-borne foreign trade cargo of the country. Alexandria port consists of two harbours (East and west) separated by a T-shaped peninsula. Eastern harbour is a semi-enclosed shallow basin and not used in navigation. Western harbour used for commercial shipping. Two converging breakwaters enclosed the harbour with an area of about 31 km^2. Harbour is connected to the open sea by a narrow entrance, and the basin is protected from the prevailing North West winds. The water depth inside the harbour ranges from 5.5 m to 16 m and lies between latitudes (31° 9.6′ & 31° 12′ N) & longitudes (29° 50.4′ & 29° 52.5′ E).

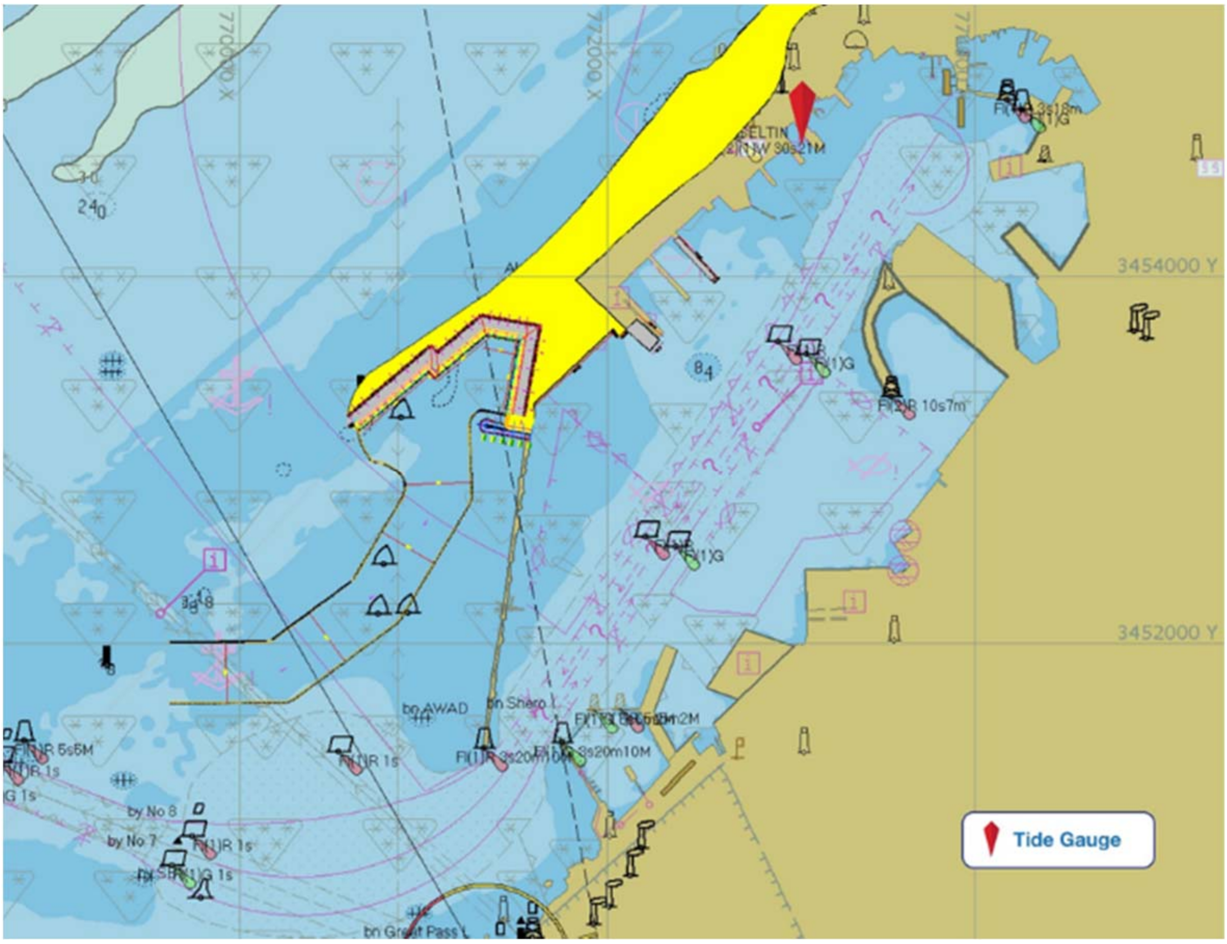

Fig. 1 Area of the study inside AWH and location of tide gauge

A. Data Collection

Two sea level datasets inside (AWH) were acquired in 30-minutes time step using Aqua-tide PS3100. The first set covered a period from 11th of September 2008 until 2nd of November 2010, and the second from 30th of April 2012 until 26th of January 2014. The study area and location of the tide gauge are shown in Fig. 1.

B. Geodetic Realization of the Tide Gauges Control Points (TGCP's)

According to the international federation of surveyors (FIG) and in order to increase the efficiency of bathymetric surveying, there is always a need for creating of offshore vertical reference surface [16]. That are referred to a specific geodetic vertical datum, which is a unified reference surface such as the International Terrestrial Reference Frame (ITRF) using GRS80 [17]. Therefore, recorded sea level datasets were referred to the (ITRF-2014). The International Global Navigation Satellite System GNSS (IGS) was precisely realized at the tide gauge control point (TGCP) from coordinate computations. Two geodetic sessions were made, after establishing two control points (CPs) at Ras El Tin Naval Base, in front of a stilling well, started first by choosing appropriate positions of the (TGCP), according to minimum requirements in manual of hydrography (M13, 2005). First session was made for establishing the geodetic information of sea level data set CP in 22nd of April 2012 for almost 6 hours, while second session was made in 28th of June 2015 for calculating coordinates of datasets.

Both control points coordinates were computed using Ashtech proflex-500 RTK dual frequency GPS receiver, processed using Australian positioning services online GPS (AUSPOS), to get Latitude, Longitude and Ellipsoidal heights of control points with positional uncertainty (95% C. L.). Levelling was made from the (TGCP) to tide gauges zero level (TGZL), using SOKKIA levelling instrument, in order to assign the ellipsoidal height of the (TGZL), and consequently the ellipsoidal heights of the observed sea levels and computed tidal levels referenced to ITRF-2014.

C. Methods of Analysis

The recorded sea level data at AWH were used, and both astronomical tidal constituents and residual elevations were obtained using Delft-3D hydrodynamic model tide suit [18]. The package permitted separation to time series of water level measurements into its tidal and non-tidal components using a selective least squares harmonic reduction resulting up to 34 tidal constituents. Delft-3D is principally based on the concept of the ability of expressing the tidal amplitudes at any location as the sum of all the harmonic components [19], as in (1):

$$\eta(t)=Z_0+\sum_n f_n A_n \cos((2\pi/T_{n)}t+\varphi_n+k_n) \qquad (1)$$

where, η(t): The vertical displacement of the sea surface as a function of time (m), Z_n: The MSL, F_n: The lunar node factor for nth constituent, A_n: The amplitude of a harmonic component (m), T_n: The period of a harmonic component (s), $\varphi_{\_n}$: The nodal phase of harmonic component, K_n: The phase of the nth constituent for the time origin in use.

The method used by Delft-3D to analyse a water level time series is known as Harmonic Analysis Method of Least Squares (HAMELS). This is a simple but powerful means of obtaining tidal constituent amplitude (A_n) and phase (k_n), the so-called tidal harmonic constants needed for tidal predictions using (1).

Classical harmonic analysis by means of least squares technique for the chosen tidal constituents for a period of time (782 and 636) days respectively were made, considering the Rayleigh Criterion (ω) of all data sets using the following equation to avoid criterion violation:

$$\Delta\omega=(360°)/T \qquad (2)$$

where T is the duration of the observation in hours, and (Δ ω) is the minimum frequency difference between two adjacent constituents that can be resolved for a given time series.

In the present work, the four main tidal components: O1, K1, M2 and S2 were produced using the output from harmonic tidal analysis, type of the tidal cycle off Alexandria was determined according to the value of the Form Factor [20].

Amplitude percentage calculated from sea level amplitude absolute values, power percentages of both tidal and residual signals were calculated referred to the total sea level signal using the following formulas:

Residual Power Percentage (RP %) = (Mean Residual Power) / (Mean Residual Power + Mean Tidal Power) *100

The most predominant tidal harmonic constituents were obtained from frequencies of highest significant peaks according to the output file acquired from Delft-3D tide analysis.

Results of sea level harmonic analysis used to acquire vertical tidal datum inside AWH, such as Highest Astronomical Tide (HAT), Lowest Astronomical Tide (LAT), MSL, Mean High Water Spring (MHWS), Mean Low Water Spring (MLWS), Mean High Water Neaps (MHWN), and Mean Low Water Neaps (MLWN) all referred to ITRF-2014.

PSD has been done by MATLAB package to acquire resolvability from the energy percentage of both tidal and non-tidal signals compared with recorded sea level.

Lastly, using hourly dataset of wind blowing over Alexandria from Ras El-Teen meteorological station during the investigated period of sea level data records, correlation coefficients were investigated between the obtained surge and wind components (alongshore & normal to shore), beside correlation with atmospheric pressure measurements. The trend of MSL was also investigated to recalculate the annual rates of sea level rise.

III. RESULTS

A. Recorded Sea Level

While the first sea level data set at AWH covers 782 days with 22 days of missing data, the second dataset was for 636 days with only 3 days of missing data. However, statistically speaking, the missed days do not critically affect the quality of the proposed investigation.

Fig. 2 shows the recorded sea level of the two observed sea level data sets. The basic statistics of sea level is represented in Table I. The half hourly minimum sea level record was -0.01 m and the maximum one was 0.95 m in the first data set, while in the second data set the hourly minimum sea level record from tide gauge was -0.06 m and the hourly maximum one was 0.76 m. The range of sea level variation in the first data set was about 0.96 m, while in the second data set was 0.82 m.

TABLE I
STATISTICAL RESULT VALUES OF ALL OBSERVED SEA LEVEL DATA SETS

Sea level data sets duration	Series length in days	Min. (m)	Max. (m)	Range (m)
11/09/2008 – 02/11/2010	782	-0.01	0.95	0.96
30/04/2012 – 26/01/2014	636	-0.06	0.76	0.82

B. Astronomical Tidal Elevations

The results of the present HAMELS analysis showed that the astronomical tidal elevations at AWH varied between 0.25 to 0.60 m and 0.19 to 0.53 m respectively (Fig. 3) during the period of investigation for the two data sets. The maximum tidal range in both data sets were 0.35 and 0.34 m.

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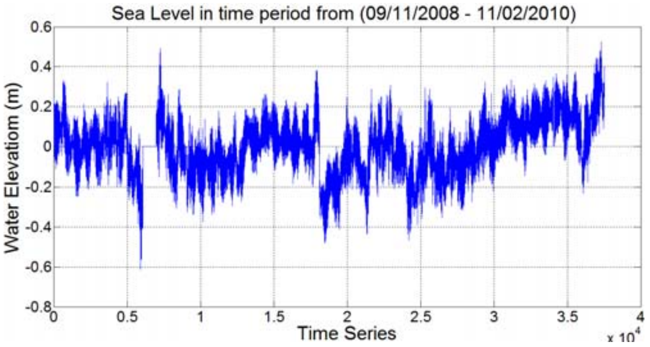

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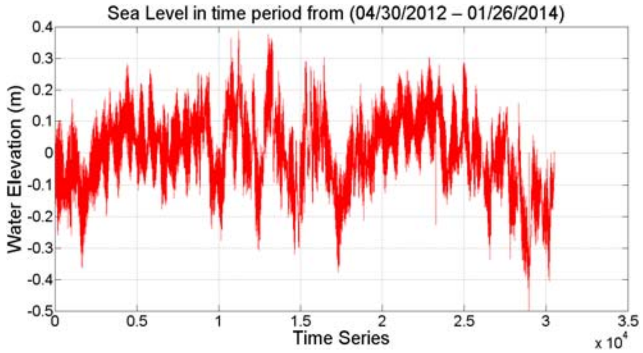
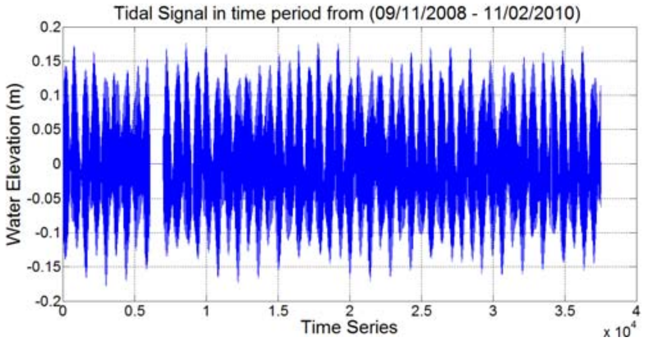


(b)

Fig. 2 (a) and (b) Sea level variation at the two data periods



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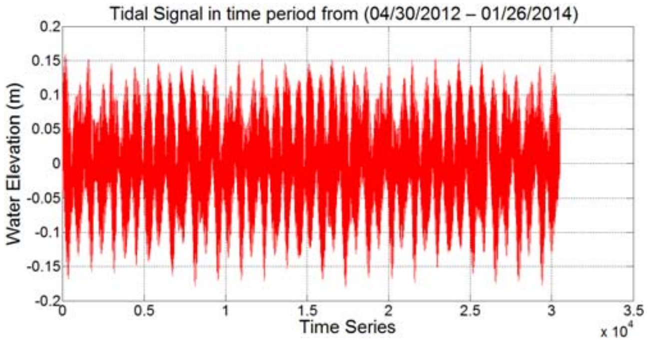


(b)

Fig. 3 (a) and (b) Astronomical tides at AWH during the two data periods

After harmonic analysis of the sea level data records, amplitudes and phases of the four main significant components in the harmonic signal were summarized in Table II and were compared with the findings of previous studies. It is clear from Table II that the obtained amplitude (H) and phase (σ) values of the four tidal major components in the two data sets are very close despite the discrepancies in data length duration. Results are also in good agreement with the values of the previous studies [21], [22]. Using the software outputs (Table II), the F factor for AWH is 0.24 0.25 in the two data sets respectively. The type of tides at the AWH has been, therefore, determined to be semidiurnal tides. Fig. 3 reflects this semidiurnal behaviour.

C. *Residual Tidal Elevations*

Residual tidal elevations are defined as the meteorologically induced components of the observed sea level, i.e. surge level [24]. This expresses the observed sea level after omitting the effect of the astronomical tides from the record data sets. At AWH, the residual tidal elevations varied from -0.05 to 0.87 m and from -0.13 to 0.71 m as shown in Fig. 4.

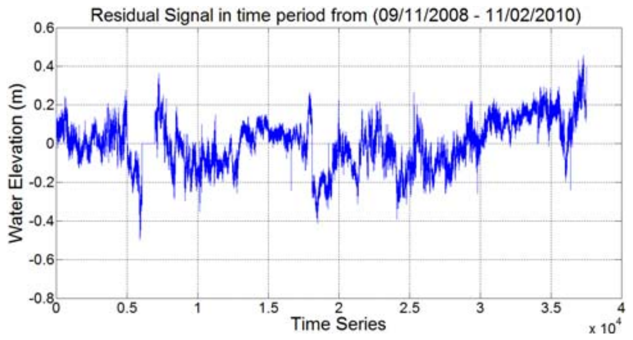
Table III shows that the surge in the first data set represented about 77%, while in the second data set was about 72% from the total sea level elevation. This result agrees with [8].

TABLE II
COMPARISON BETWEEN AMPLITUDES AND PHASES OF THE FOUR MAJOR CONSTITUENTS OBTAINED IN PRESENT WORK AND PREVIOUS STUDIES AT AHW

	HARMONIC	M2		S2		K1		O1	
	Reference	H (cm)	σ (Deg.)	H (cm)	σ (Deg.)	H (cm)	σ (Deg.)	H (cm)	σ (Deg.)
Previous	[23]	7.19	325	4.34	309	1.64	317	1.34	300
	[21]	7.09	256.1	5.20	225.8	1.66	280.5	1.23	249.8
Current Study	First dataset	7.4	301	4.5	315	1.7	303	1.3	272
	Second dataset	6.9	324	4.1	340	1.6	315	1.3	286

TABLE III
DATA SETS DURATIONS AND (GAPS) IN DAYS AND ASSOCIATED RESIDUAL AND TIDAL POWER AS PERCENTAGE OF THE TOTAL SEA LEVEL SIGNAL

Sea Level components		11/09/2008 – 02/11/2010 782 (22)	30/04/2012 – 26/01/2014 636 (3)
Datasets Power percentage	Residual Power	77%	72%
	Tidal Power	23%	28%



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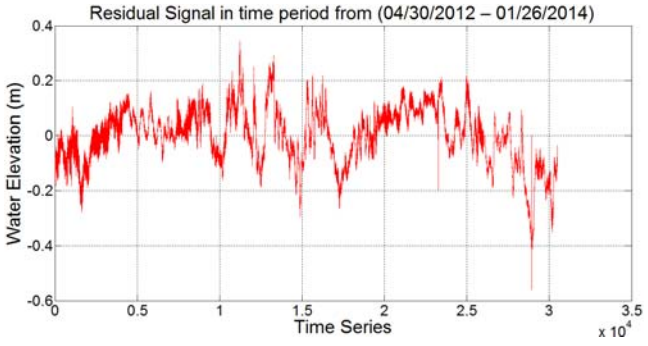


(b)

Fig. 4 (a) and (b) Residual elevations at AWH during the two data sets

D. Sea Level PSD

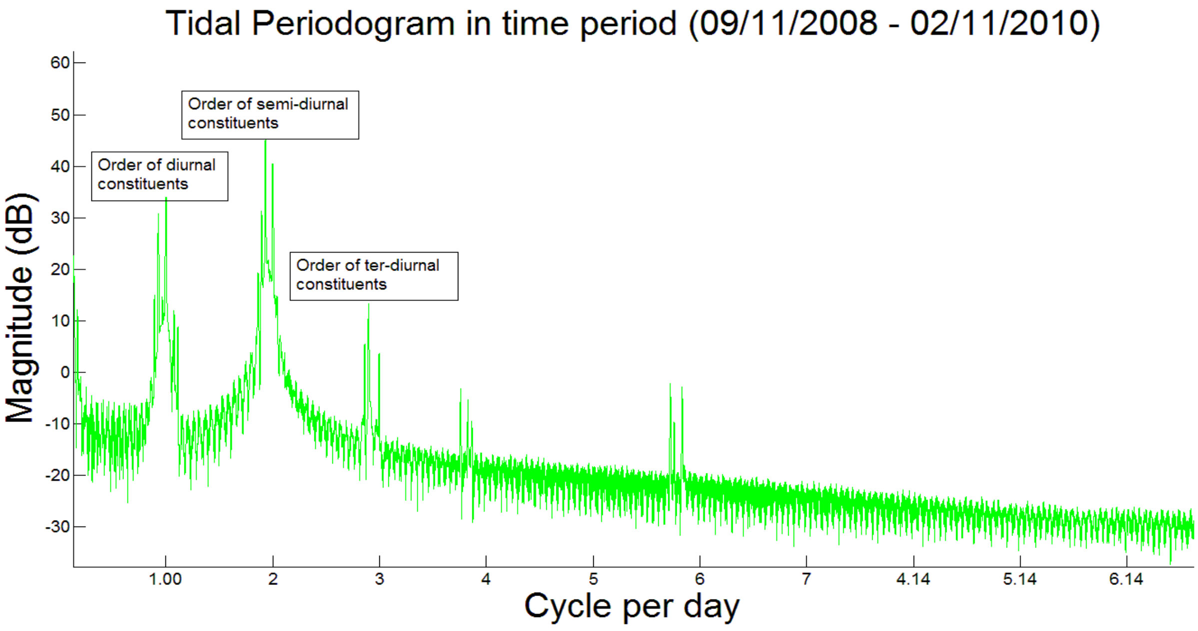
Fig. 5 displays the PSD or the tidal periodogram, with all significant tidal constituents up to a band of 6 cycles/day. In tidal analysis process, tide tool was forced to use the higher frequencies between neighbouring tidal components according to the use of Rayleigh Criterion status. From Fig. 5, it appears that the energy peaks associated with these significant frequencies are at the order of diurnal pattern such as Q1, O1, M1, P1, K1, J1, SO1, OO1 and semidiurnal such as 2N2, M2, S2, L2, K2, N2, MU2, NU2, and also in the terdiurnal such as MO3, M3, SP3 which are the dominant constituents.

E. Data

In the present work, tidal data in AWH were calculated referred to the ITRF-2014, using values of the four major harmonic constituents (M2, S2, K1, O1) appreciated from harmonic analysis, in addition to values of MSL ellipsoidal heights referred to the ITRF-2014. Based on the following theoretical terms by [25]:

1) Mean high water spring (MHWS) = MSL+ (M2 + S2).
2) Mean low water spring (MLWS) = MSL- (M2 + S2).
3) Mean high water neaps (MHWN) = MSL + (M2 - S2).
4) Mean low water neaps (MLWN) = MSL - (M2 - S2).
5) Highest high water level (HHWL) = MSL + (M2+ S2+ K1+ O1).
6) Lowest low water level (LLWL) = MSL - (M2+ S2+ K1+ O1).

Since 1906, there was no additional study made concerning the connection between terrestrial datum and tidal datum in Egypt. Therefore, tidal datum calculations referenced to ITRF 2014 were done for the first time to refer the tidal data in AWH to specific geodetic datum. It is clear from the calculated values that tidal levels are all within average values as illustrated in Table IV.



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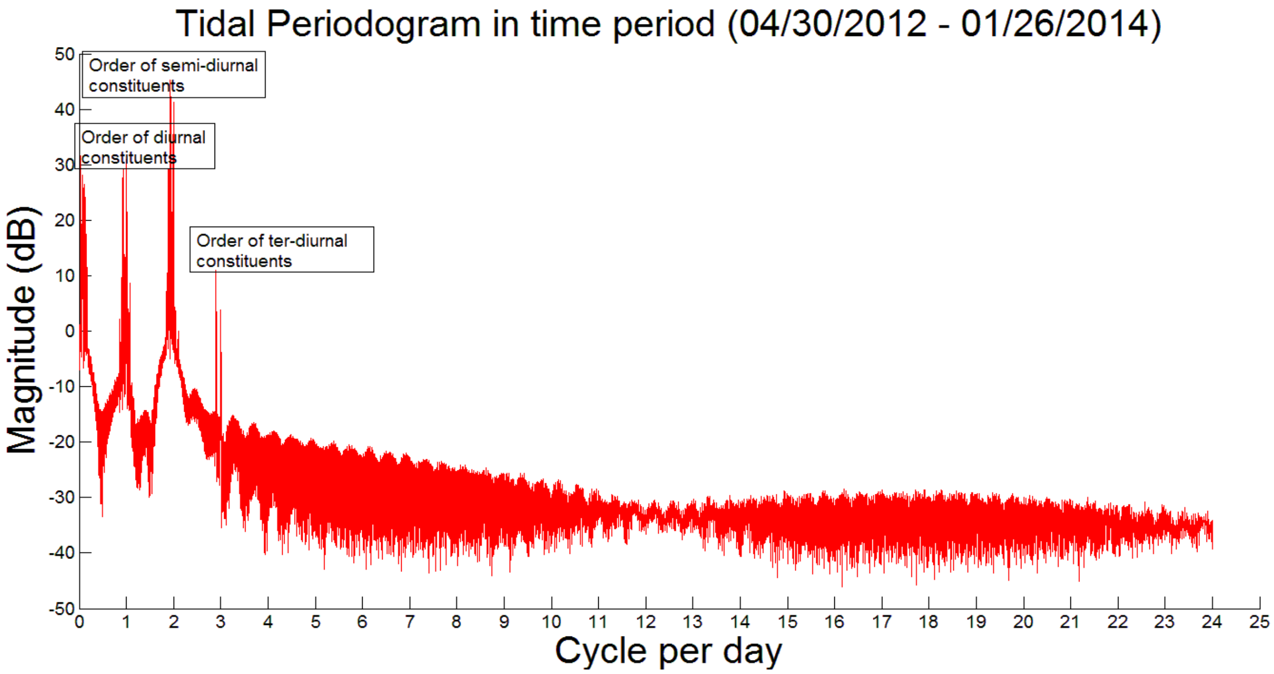

(b)

Fig. 5 Sea Level PSD for the two data sets

TABLE IV
TIDAL DATA REFERENCED TO ITRF-2014 IN AWH

	First Data Set	Second Data Set	Mean
M2	0.07	0.07	0.07
S2	0.05	0.04	0.04
MSL (Z0)	14.78	14.73	14.76
K1	0.02	0.02	0.02
O1	0.01	0.01	0.01
MHWS	14.90	14.84	14.87
MLWS	14.66	14.62	14.64
MHWN	14.81	14.75	14.78
MLWN	14.75	14.70	14.73
HHWL	14.93	14.86	14.90
LLWL	14.63	14.59	14.61
LAT	14.50	14.47	14.49
HAT	15.05	14.97	15.01

Realizing the ellipsoidal height of LAT level as chart datum is prominent in places where no homogenous vertical datum exists, and when there is scarce of constituent sea level data along coastline. In Egypt, there was no study made concerning relation between terrestrial datum and tidal datum since 1906, except in 2007 when [26] calculated the monthly tidal levels above Chart Datum. Reference [26] conducted that LAT level is -0.3 m refereed to Mean Low Water Spring (MLWS) which means relating two tidal data in their results, however in the present study LAT level value is -0.15 m from MLWS, beside it is referred for the first time in AWH to an accurate geodetic vertical datum which is the ITRF-2014.

F. Wind Pattern

The wind roses of hourly wind speed and direction during the two periods of investigation is shown in Fig. 6. During the two data sets, the average wind speed was 5.7 and 5.2 m/s respectively, and 25% of the blowing wind was Northwest (NW) during the first dataset while during the second dataset, 25% of the blowing wind was North-Northwest (NNW).

Correlation coefficients were calculated to examine the association of non-tidal component of sea level (surge) variation with both the wind blowing and atmospheric pressure at the same intervals. Correlation was also checked between residuals of sea level and long & normal to shore (U & V) components of the wind forcing. From Table V, it was concluded that there is a good inverse correlation between surge and atmospheric pressure, besides a weak direct correlation between surge and wind and wind components (U & V) as given.

TABLE V
CORRELATION COEFFICIENTS COMPARISON BETWEEN DATASETS

Correlated factors	First data set Correlation coefficient	Second Data Set Correlation coefficient
Wind Speed & Surge of tide-gauge	0.20	0.30
Surge (TG) & Wind (long-shore U-components)	0.19	0.19
Surge (TG) & Wind (long-shore V-components)	0.20	0.29
Surge (TG) & Atmospheric Pressure	-0.47	-0.50

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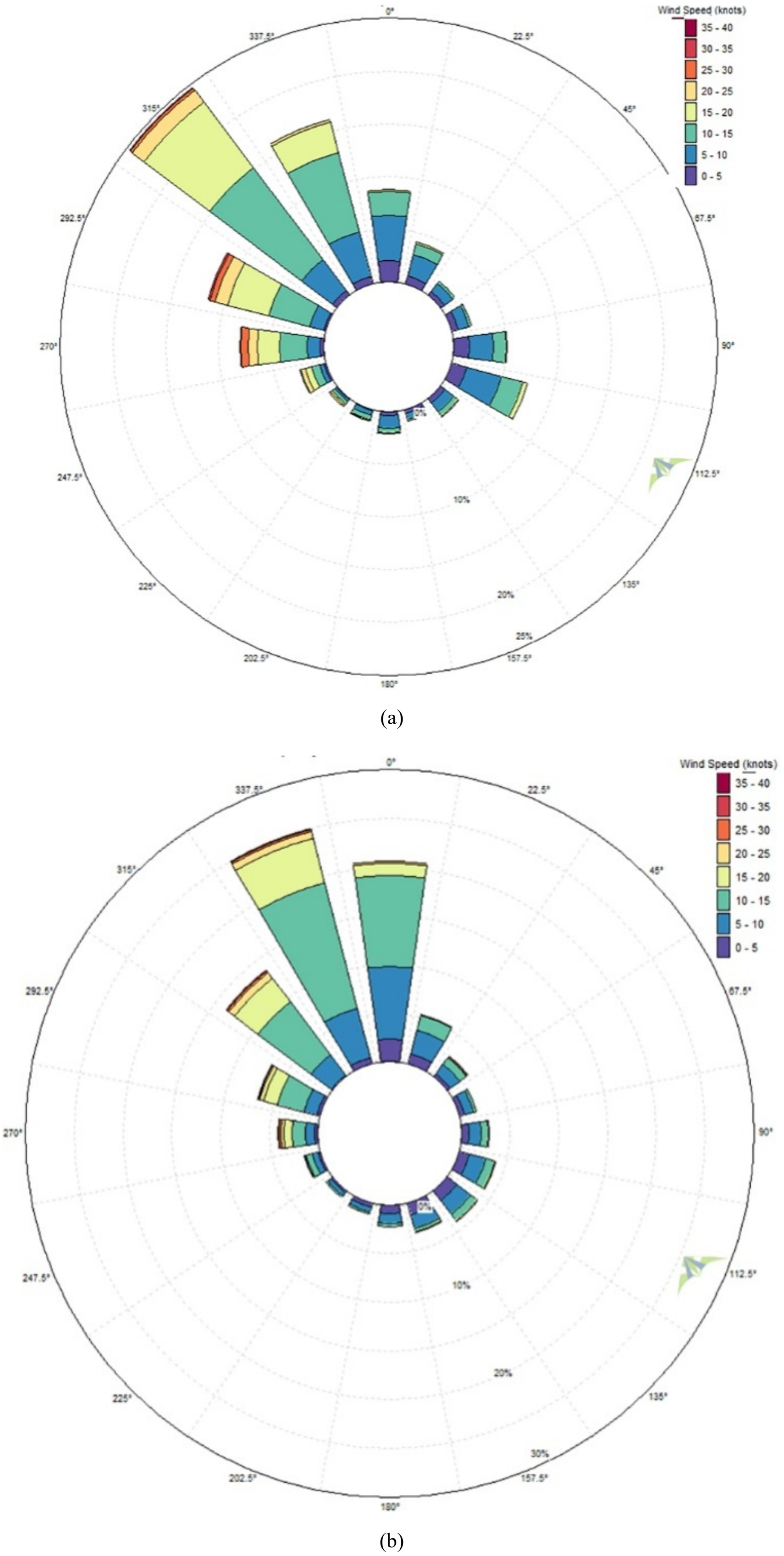

(a)

(b)

Fig. 6 A and B. Wind rose over AWH during the two datasets periods

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IV. CONCLUSION

The sea level variation within the AWH is the result of two contributors: astronomical tide and surge. Alexandria, along the Egyptian Mediterranean coast, is not an exception. The present paper draws the sea level pattern off Alexandria over two data sets. With the use of sea level data, astronomical tide and surge were separated

The obtained amplitude (H) and phase (σ) values of the four tidal major constituents in the two data sets showed close similar values despite the difference in data length duration. Results are also in good agreement with the values of the previous studies [21], [22]. The type of tides at the AWH has been determined to be semidiurnal tides.

The results of the present research show that astronomical tide contributes with 23% and 28% while, surge contributes with 77% and 72%% in the observed sea level. This might refer to the meteorological, oceanographic and climatic effects, which significantly affect Alexandria region. Moreover, the developed local seiches may have some impact on the observed surge elevation [8]. The greater contribution of surge over tidal elevation assures the nature of low tides at Alexandria, as in the whole Levantine Basin. The great impact and strong contribution of surge in sea level variation concluded in the present paper is, indeed, in agreement with [10], [22], [27], [11]. In the current study, it appears that the energy peaks of the tide are associated with these significant frequencies at the order of diurnal, semidiurnal and terdiurnal.

Despite of earlier studies in AWH, this study is the first to refer the tidal datum to ITRF 2014, a specific geodetic datum throughout the Egyptian Mediterranean coast.

In AWH, there is a good inverse correlation between surge and atmospheric pressure, besides a direct correlation with wind components. This means that surges in AWH are affected to less extend by the wind due to the sheltered location of the tide gauge inside the harbour and the constructed breakwaters that largely damps the effect of the wind.

Linear regression was made for the two data sets to calculate the sea level trend in the AWH as in (3):

$$\mathrm{MSL} = 41.3 + 0.16 * X \qquad (3)$$

where X is the month serial number, which indicates that there is a sea level rise in the MSL with annual rate 1.6 mm and 1 mm for the two datasets respectively, which agree with earlier studies [28], [29].

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