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The Time Series Spectral Analysis of Satellite Altimetry and Coastal Tide Gauges and Tide Modeling in the Coast of Caspian Sea

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Abstract

This study endeavors to deal with the least square spectral analysis on the time series, to find present significant frequencies, to analyze 40 tide components using harmonic methods and to show relationship between discovered frequencies and 40 components of tide. For the purpose of collecting data of altimetry satellites of Topex/Poseidon (T/P), Jason 1, Jason 2 and coastal tide gauges of Bandar Anzali, Noshahr, and Nekah were utilized. In this time series formed by cross over points of altimetry satellite and then using least square spectral analysis on time series derived from altimetry satellite and coastal tide gauges the significant components were found and annual, biannual, and monthly components were discovered. Then, analysis of 40 tide components was conducted using harmonic method to find the amplitude and phase. It represented that solar annual (Sa) plays the most significant role on Caspian Sea corresponded to the least square spectral analysis of the time series. The results shows that the annual (Sa) and semi-annual Solar (Ssa) constituents on all of the ports listed have the highest amplitude in comparison with the other constituents which are respectively 16 cm, 18 cm and 15 cm for annual constituent and 2.8 cm, 5.4 cm and 3.7 cm for semi-annual constituent.

Keywords

Least Square Spectral Analysis, Harmonic Analysis, Altimetry Satellite, Coastal Tide Gauges

1. Introduction

Knowing the reason behind changes in seawater level is a great challenge in the scientific fields and causes of

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seawater level were interested issues that have been studied by scientists. Five influential factors that are effective in changing sea level are meteorological effects, oceanic effects, tide, climate change, and vertical motion of the crust [1]. The effects of tide as a result of significant changes in sea level are of particular importance and researchers have been looking for modeling this effect. So much effort has been made to model this phenomenon. In this study, the effect of tide components using observations of altimetry satellite and coastal tide gauges was investigated, and harmonic analysis method was utilized to specify the amplitude and phase of 40 tides components, and the least square spectral analysis method to find the present significant component.

Caspian Sea is surrounded by five countries including Islamic Republic of Iran, Russia, Republic of Azerbaijan, Turkmenistan, and Kazakhstan. The sea is the largest remaining part that emanated from dissolving the old Tethys Sea and extended from North Pole to Indian Ocean in the first to third period of geology. And in the third period it was disconnected because of folding, and mountain ranges such as Caucasus and Minor Asia and following upcoming the European continent and Iran Plain some seas were constructed like Caspian Sea. Caspian Sea is located in the North and East areas in 47˚57', and 36˚33', respectively. Also, from west and East it is restricted to meridians of 46˚43', and 54˚53', respectively. The length of Caspian Sea is about 1030 kilometers, and its width varies from 435 to 196 Kilometers [2] (**Figure 1**).

Data of T/P, Jason 1, and Jason 2 were prepared using binary form in the different cycles through NASA spatial site and AVISO organization. Data were gathered from 1992 to 2014 and updated cycles by NASA spatial organization site and AVISO site will be available in the following addresses: http://Podacc.jpl.nassa.gov and http://www.aviso.altimetry.fr/en/home.html. As periodicity of T/P, Jason 1, Jason 2 satellites is approximately 10 days (precisely 9.915 days), the least observation interval of data is 10 days.

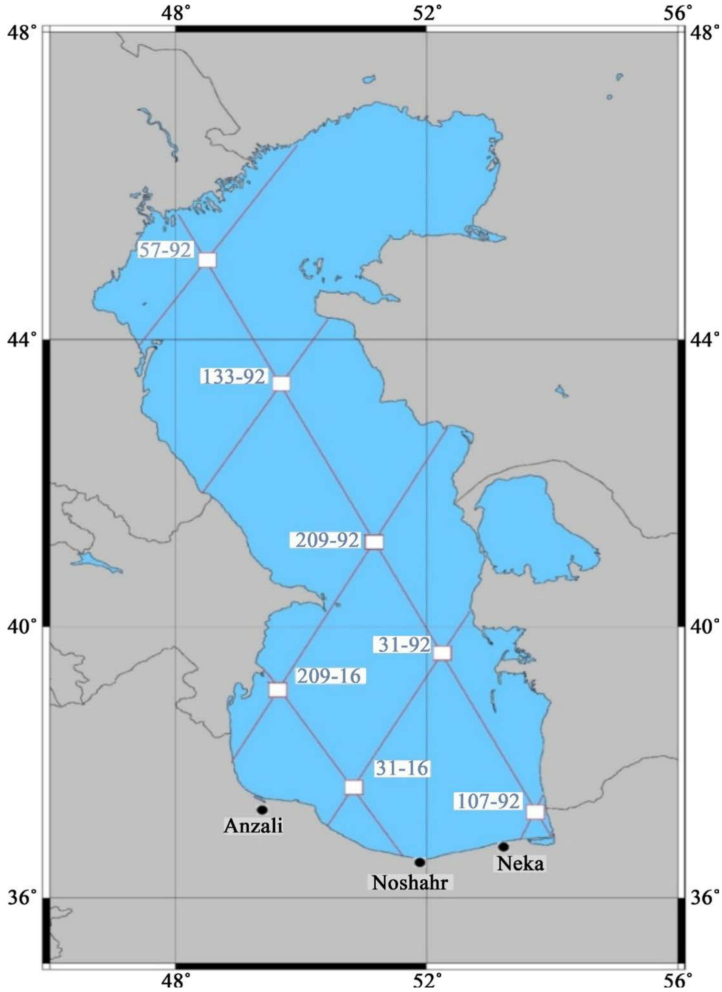

Figure 1. Caspian Sea and altimeter cross over points.

2. Methodology

Principle of Satellite Altimetry Method

The quantity of observation in satellites altimetry is the length of satellite to the surface of water, namely Satellite Range. When the length of satellite in the circuit in the Reference Ellipsoid can be specified using some methods, it is possible to achieve Sea Surface Height in the observation points to reference Ellipsoid as follows [3]:

$$\text{SSH}(\lambda,\varphi,t) = H_{\text{sat}}(\lambda,\varphi,t) - \text{Range}(\lambda,\varphi,t) \tag{1}$$

In the stated equation $\text{SSH}(\lambda,\varphi,t)$ the seawater surface height in a point with (λ, φ) coordinate in the moment t, $H_{\text{sat}}(\lambda,\varphi,t)$ the height of satellite to Reference Ellipsoid at the same moment of t and $\text{Range}(\lambda,\varphi,t)$ satellite distance to water surface in the observation point is at the same t moment that a series of corrections should be applied on them. These corrections are as follow:

$$\begin{aligned}\text{Corrected Range} = {} & \text{Observed Range} + \text{Wet Troposphere Correction} \\ & + \text{Dry Troposphere Correction} + \text{Ionosphere Correction} \\ & + \text{Electromagnetic Bias Correction} + \text{Ocean Tide Correction} \\ & + \text{Inverse Barometer Correction} + \text{Pole Tide Correction} \\ & + \text{Center of Gravity Movement Correction}\end{aligned}$$

After calculating the corrected height, having altitude from Reference Ellipsoid level the Seawater Surface height can be achieved to Reference Ellipsoid as follow:

$$\text{SSH}(\lambda,\varphi,t) = H_{\text{sat}}(\lambda,\varphi,t) - \text{Corrected Range}(\lambda,\varphi,t) \tag{2}$$

Important points: as in this study we deal with tide modeling of waters; therefore, in the modeling calculations the corrected value from this phenomenon would not be applied on observed height. Therefore, to prepare data and to model calculations the entire stated corrections were conducted except tide corrections applied in observations.

Formation of times series of observing satellite altimetry and coastal tide gauges:

Position of tide gauge stations in which time series were formulated via such stations as follow (**Table 1**).

The position of time series in the cross over points of satellite altimetry are documented below (**Table 2**).

3. Aliasing Phenomenon

According to sampling theorem to rebuild a signal from its sample the signal with a higher cost twice more than its most frequency should be sampled [4]. If the most present frequency in a signal is υ then sampling

Table 1. Coastal tide gauge station features of the Caspian Sea.

Location	Latitude	Longitude	Duration (time)
Anzai	37.478˚	49.4623˚	21/3/2005-20/3/2014
Noshahr	36.6584˚	51.5047˚	21/3/2006-21/3/2014
Neka	36.8502˚	53.3656˚	1/1/2000-31/8/2012

Table 2. Features of altimeter cross over points.

Name of station	Position	Duration (time)	Considerations
Anzali-Cross Over	Lat: 39.20˚ Lon: 49.59˚	1992-2014	Cross over of passes 16 and 92
Noshahr-Cross Over	Lat: 37.09˚ Lon: 51.02˚	1992-2014	Cross over of passes 16 and 32
Neka-Cross Over	Lat: 37.09˚ Lon: 53.85˚	1992-2014	Cross over of passes 19 and 107

frequency should be $f_N = 2\upsilon$ that f_N is called Nyquest frequency. In other words, in the case of periods, a connected time signal with T_w period can be totally rebuild from value of samples that might have been obtained in the intervals less than $\frac{T_w}{2}$. Therefore, if the value of sampling is more or less than this amount, then signal with T_w period will be converted to a Ta period that is called Aliasing period.

Aliasing period can be calculated by the following equation:

$$T_a = \frac{2\pi\Delta t}{2\pi\left(f\Delta t - \left[f\Delta t + 0.5\right]\right)} \tag{3}$$

Here, f is the frequencies of tide components, Δt is sampling period on the basis of day, for satellite Jason 2, 9.9156, [.] inside Bracket we use function (fix) that is a function of decimal numbers that round toward zero [5].

For example, for the component of half daily month (M2) that the main frequency is 1.9305 cycles per day according to stated alias frequency 0.0161 cycles per day corresponds to 62/107 days.

For satellite Topex, Jason 1, Jason 2 to divide the two great components of half days M2, S2 with period of 62 days and 59 days, at least we need 3 years of data for this satellite. But for separating components of P_1, K_2 also S_{sa}, K_1 from each other at least we should have 9 years of repetitive observations of this satellite [6].

The following table shows periods and alias frequencies related to the main components of half days, dailies, half months, monthly, biannual and annual of tide (40 components of tide) about observations of T/P satellite (**Table 3**). Spectral analysis on altimeter time series was done that aliasing frequency has been shown in **Figure 2**.

4. Least Square Spectral Analysis

The least squares' spectral analysis is a modeling method for approximate behavior of natural and physical behaviors [7]. To determine the included part a limited number of 1 periodic component to observe periodic sinuous and cosine base functions were used for modeling [8]. Estimating the least square dissolves each observation measurement that is equal to traditional method of specifying the value of power spectral density (PSD) that is a Fourier analysis. Though the traditional method of Fourier analysis maintains some limitations we can refer dependency of this method to using co-distanced data that most of the observations are dispersed and are not at the same distance that are sensitive to information gap [8]. To overcome such limitations [7], the spectral analysis method according to estimation of the least squares can be developed. This method is known widely as spectral analysis of the least squares [9]-[11].

Here $f_{n\times 1}$ is the vector of observations including observed n of momentum sea surface height by satellite altimetry or tide gauge. $\{\omega_1, \omega_2, \cdots, \omega_m\}$ Of the set of real and positive angular frequencies that have spectral values for observation vector should be specified. For each angular frequency ω_i, the base functions $\Phi^c(\omega_i)$ and $\Phi^s(\omega_i)$ are defined.

$$\Phi^c(\omega_i) = \left(\cos\omega_i t_1 \cos\omega_i t_2 \cdots \cos\omega_i t_n\right)^{\mathrm{T}} \tag{4}$$

$$\Phi^s(\omega_i) = \left(\sin\omega_i t_1 \sin\omega_i t_2 \cdots \sin\omega_i t_n\right)^{\mathrm{T}} \tag{5}$$

$$P(\omega_i) = \hat{c}_1 \cos\omega_i t + \hat{c}_2 \sin\omega_i t \tag{6}$$

That here $t_1, t_2, \cdots, t_n$ is the time of observations

Vectors $\Phi^c(\omega_i)$ and $\Phi^s(\omega_i)$ formed Vandermond matrix.

$$\Phi(\omega_i) = \left[\Phi^c(\omega_i)\Phi^s(\omega_i)\right] \tag{7}$$

$$\hat{c} = \left(\Phi^{\mathrm{T}}\Phi\right)^{-1}\Phi^{\mathrm{T}} f \tag{8}$$

Therefore, (Vanicek, 1969) is spectral value for each frequency that can be calculated via the following equation:

$$S(\omega_i) = \frac{f^{\mathrm{T}} P(\omega_i)}{f^{\mathrm{T}} f} \tag{9}$$

Or

$$S(\omega_i) = \frac{f^{\mathrm{T}}\Phi(\omega_i)\left(\Phi^{\mathrm{T}}(\omega_i)\Phi(\omega_i)\right)^{-1}\Phi^{\mathrm{T}}(\omega_i) f}{f^{\mathrm{T}} f} \tag{10}$$

Finally, a set of entire spectral values for the entire frequencies can be achieved.

$$S(\omega) = \left\{S(\omega_1), S(\omega_2), \cdots, S(\omega_m)\right\} \tag{11}$$

Table 3. Main periods and alias periods of them on the basis of samples from satellites altimetry of T/P, Jason 1, Jason 2.

Components	Frequency (cpt)	Period (day)	Frequency (cpd)	Alias period (day)
K2	2.005476	0.498634738	0.01154768	86.59748212
L2	1.96856526	0.507984175	0.04845842	20.63624862
M2	1.932274	0.517524947	0.016101504	62.10599902
N2	1.895982	0.527431168	0.020190496	49.52825362
Ma2	1.935011527	0.516792787	0.018839031	53.08128696
R2	2.00273778	0.499316491	0.0142859	69.99909071
S2	2	0.5	0.01702368	58.74170616
T2	1.99726222	0.500685383	0.01976146	50.60354889
J1	1.039029553	0.962436532	0.030517713	32.76785475
K1	1.002738	0.997269476	0.00577384	173.1949642
M1	0.966136807	1.035050102	0.042375033	23.59880154
O1	0.929536	1.075805563	0.021875344	45.7135667
P1	0.997262	1.002745517	0.01124984	88.89015367
Q1	0.893244	1.119514937	0.014416656	69.36421348
S1	1	1	0.00851184	117.4834123
M3	2.89841	0.345016751	0.026274336	38.05995355
S3	3	0.333333333	0.02553552	39.16113744
M4	3.864547	0.258762541	0.032202008	31.05396383
S4	4	0.25	0.03404736	29.37085308
M5	4.8306839	0.207010026	0.010172932	98.3000804
M6	5.796821	0.172508346	0.048303512	20.70242825
S6	6	0.166666667	0.049780144	20.08833063
M8	7.729094	0.12938127	0.036447167	27.43697439
S8	8	0.125	0.032756465	30.52832512
Mf	0.073202	13.66082894	0.027649184	36.16743265
Mm	0.036292	27.55428194	0.036292	27.55428194
Msf	0.067726	14.76537814	0.033125184	30.18851156
Oo1	1.075940113	0.929419758	0.033422911	29.91959654
Ssa	0.005476	182.6150475	0.005476	182.6150475
Ms4	3.932273613	0.254305803	0.000922562	1083.937532
Mn4	3.82825558	0.26121558	0.004089412	244.5339491
Mk3	2.935011527	0.340714164	0.010327191	96.83175341
Sa	0.002738	365.230095	0.002738	365.230095
Mo3	2.86180932	0.34942929	0.037976168	26.33230385
No3	2.825517673	0.353917447	0.001684522	593.6403785
2N2	1.85969032	0.537723937	0.044369008	22.53825457
So3	2.929535707	0.341351019	0.004851371	206.1273043
Sk3	3.002737907	0.333029399	0.022797613	43.86424117
SO1	1.070464293	0.934174083	0.038898731	25.7077979
Mk4	3.937749433	0.253952167	0.004553258	219.6229789

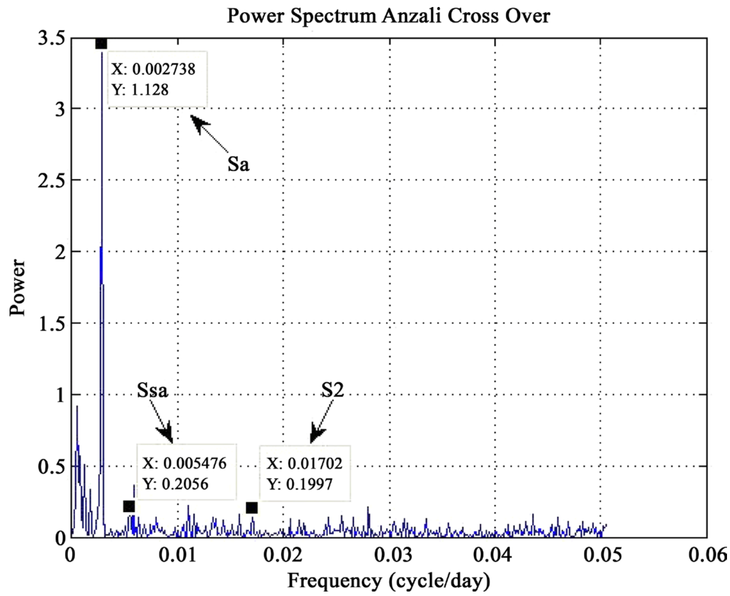

Figure 2. Alias frequency of S2 component, semi-annual (Ssa) and annual (Sa) frequencies.

Statistical Tests

The significance of the spectral values can be statistically tested that is the most important advantages to the least square spectral analysis method [12].

It is possible to define the approving or rejecting criterion for primary hypothesis $H_o : S(\omega_i) = o$ as follow:

$$S(\omega_i) = \begin{cases} \leq \left(1+\dfrac{\gamma}{2}F_{\gamma,2,\alpha}\right)^{-1} \longrightarrow H_o \quad \text{Acceptance} \\ > \left(1+\dfrac{\gamma}{2}F_{\gamma,2,\alpha}\right)^{-1} \longrightarrow H_o \quad \text{Rejection} \end{cases} \tag{12}$$

Here, $F_{\gamma,2,\alpha}$ the equation of Fisher distribution with 2 degrees of freedom and confidence level $(1-\alpha)$ that in this part the confidence level is 95% $(\alpha = 0.05)$.

Spectral analysis with approach LSSA on time series of altimeter cross over points and tide gauge stations was done. As show spectral analysis on time series of altimeter cross over near tide gauge station of Anzali (**Figure 3**) and spectral analysis of time series Anzali tide gauge (**Figure 4**) completely correspond. Power spectrum of both time series analysis reveal Ssa is most affected frequency. However, spectral analysis on Anzali tide gauge shows frequency of once per day but not be seen on altimeter analysis. This analysis was performed for other tide gauge stations and altimeter cross over points that the results are well consistent with each other (**Figures 5-8**). Some significant periods observed in time series are shown in **Table 4**.

5. Tide Modeling

To analyze and predict the tide the following equation was used [13] [14]

$$h(t) = Z_o + \sum\left[f_n(t)H_n\cos\left(\delta_n t - g_n + V_n(t_o) + u_n(t)\right)\right]. \tag{13}$$

Tide components $n = 1, 2, \cdots, N$.

Here:

Z_o is the average Sea level, N is the number of tide components, δ_n is angular frequency, $\left(\dfrac{\text{degree}}{\text{hour}}\right)$, $V_n(t_o)$, astronomical argument, $f_n(t)$ nodal factor, $u_n(t)$ nodal phase, H_n component amplitude, g_n delay phase.

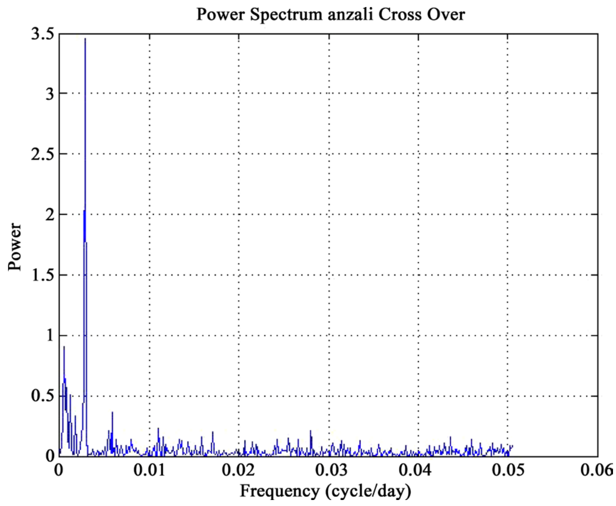

Figure 3. Power spectrum of time series near tide gauge satellite station of Anzali from crossover of passes 16 to 209.

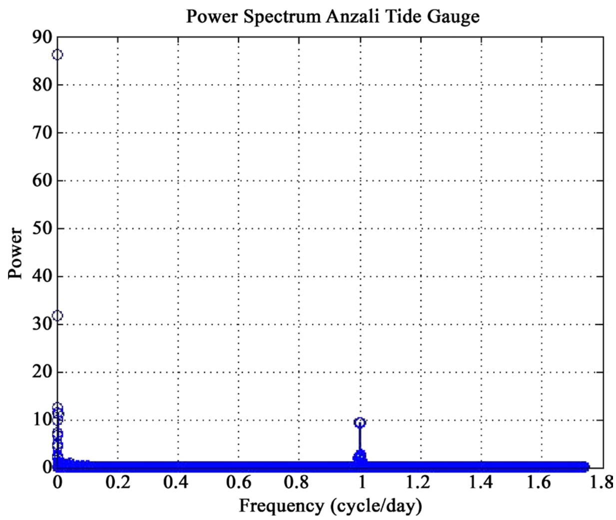

Figure 4. Power spectrum of time series of Anzali tide gauge station.

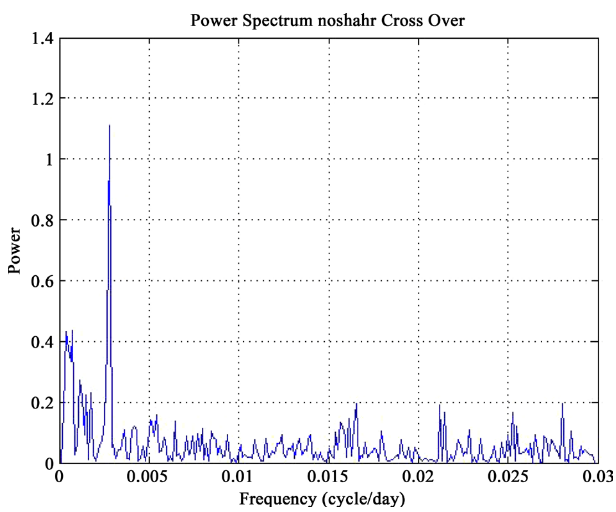

Figure 5. Power spectrum of time series near tide gauge satellite station of Noshahr from crossover of passes 16 to 31.

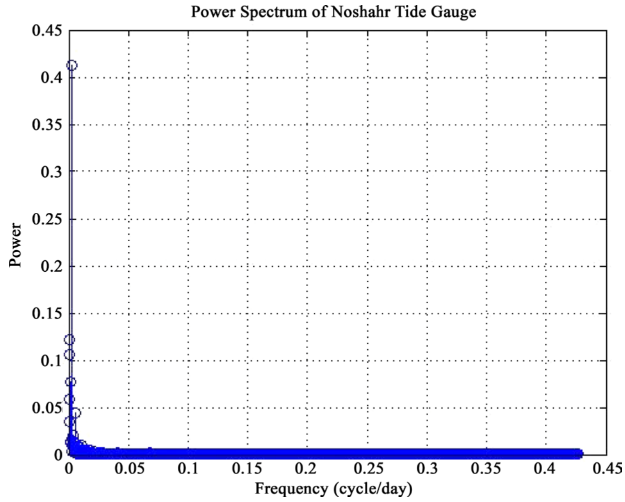

Figure 6. Power spectrum of time series of Noshahr tide gauge station.

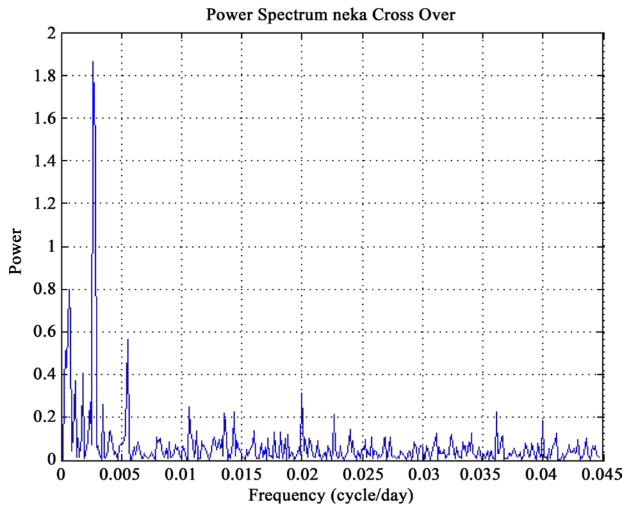

Figure 7. Power spectrum of time series near tide gauge satellite station of Neka from crossover of passes 107 to 92.

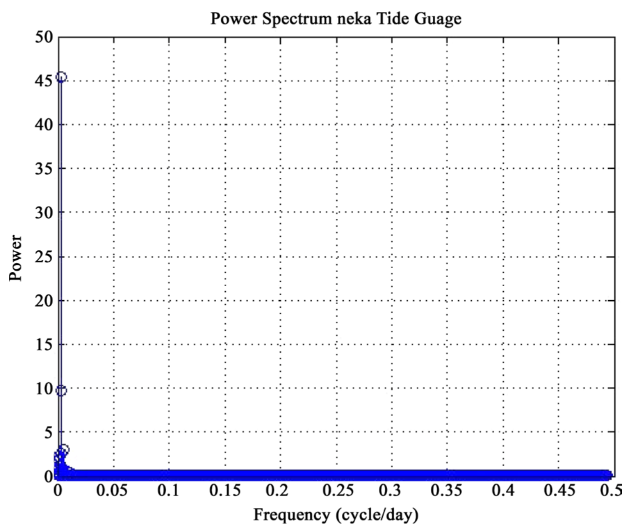

Figure 8. Power spectrum of time series of Neka tide gauge station.

Table 4. Some significant periods observed in the time series stations.

Name of station	(Cycle per day) frequency	Period
Anzali-Cross Over	0.00028	9.7 years
	0.00075	3.6 years
	0.00050	5.4 years
	0.0011	2.4 years
	0.0017	1.6 years
	0.0027	1 years
	0.0054	6 month
	0.0058	5.7 month
	0.011	3 month
	0.017	1.9 month
	0.028	1.1 month
Anzali-Tide Gauge	0.00091	3 years
	0.0018	1.5 years
	0.0027	1 years
	0.0036	9.1 month
	0.0054	6 month
	0.0074	4.5 month
	0.0082	4 month
	0.017	1.9 month
Noshahr-Cross Over	0.00028	9.7 years
	0.00075	3.6 years
	0.00050	5.4 years
	0.0011	2.4 years
	0.0017	1.6 years
	0.0027	1 years
	0.0077	4.3 month
	0.013	2.5 month
	0.024	1.3 month
	0.028	1.1 month
Noshahr-Tide Gauge	0.00068	4 years
	0.0010	2.6 years
	0.0013	2 years
	0.0027	1 years
	0.0037	9 month
	0.0054	6 month
	0.011	3 month
Neka-Cross Over	0.00028	9.7 years
	0.00064	4.2 years
	0.0027	1 years
	0.0055	6 month
	0.010	3.2 month
	0.014	2.3 month
	0.019	1.7 month
	0.023	1.4 month
Neka-Tide Gauge	0.00064	4.2 years
	0.0010	2.5 years
	0.0021	1.2 years
	0.0027	1 years
	0.0032	10.2 month
	0.0054	6 month
	0.0082	4 month
	0.01	3.2 month

After spectral analysis for extraction effective frequency, modeling of time series was performed with using Equation (13). The amplitude and phase of each frequency were determined and In the following with calculated variables of equation thirteen modeling was done. **Figures 9-14** show time series modeling and residuals.

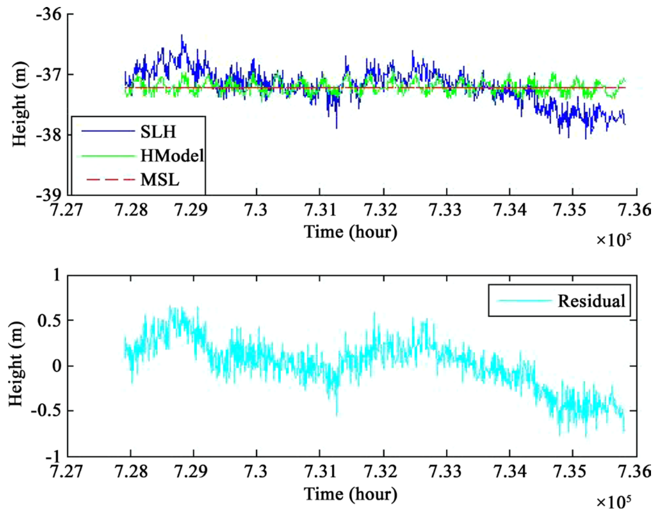

Figure 9. Time series along with tide modeling and residualsin station Anzali-cross over.

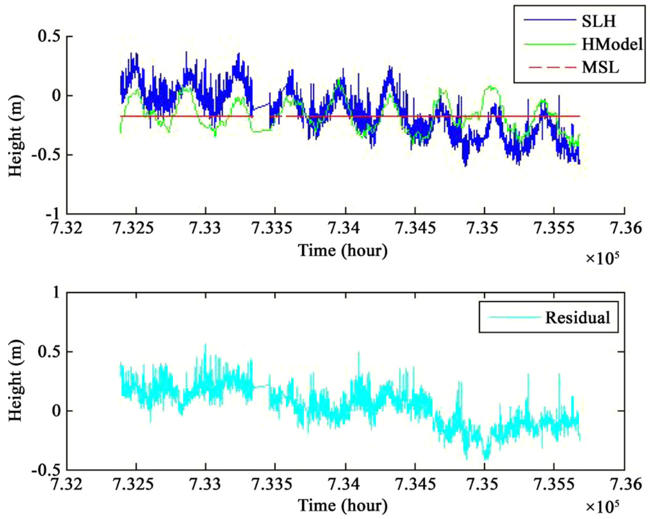

Figure 10. Time series along with tide model and residual in Anzali tide gauge station.

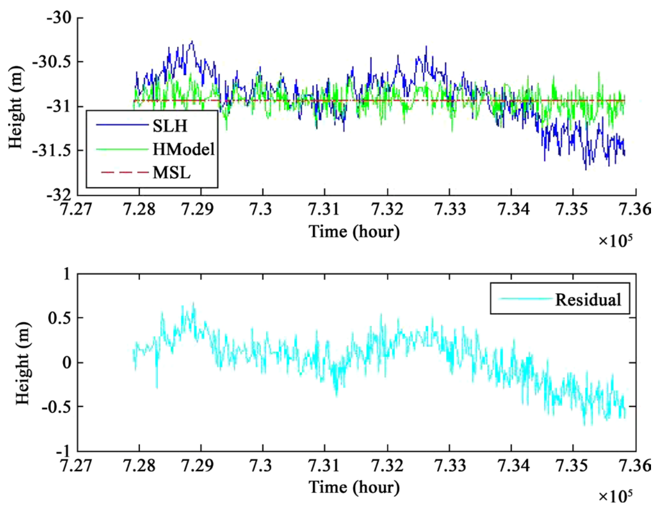

Figure 11. Time series along with tide model and residual in Noshahr cross over station.

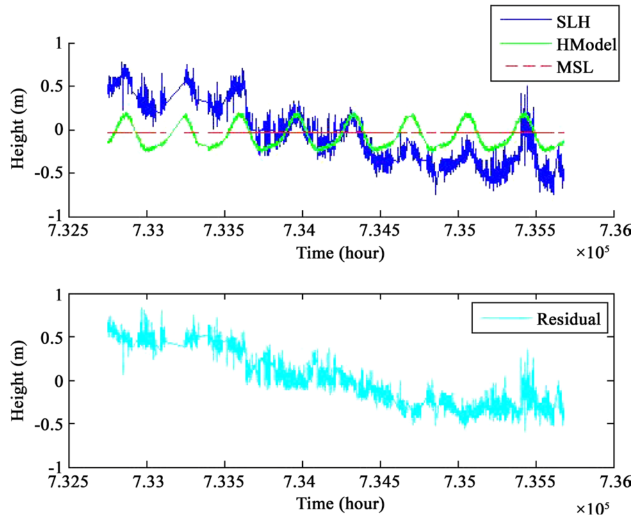

Figure 12. Time series along with tide model and residual in Noshahr tide gauge station.

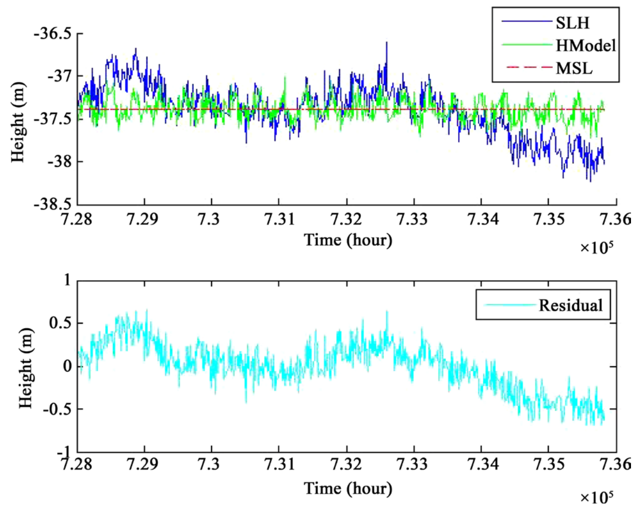

Figure 13. Time series along with tide model and residual in Neka-cross over station.

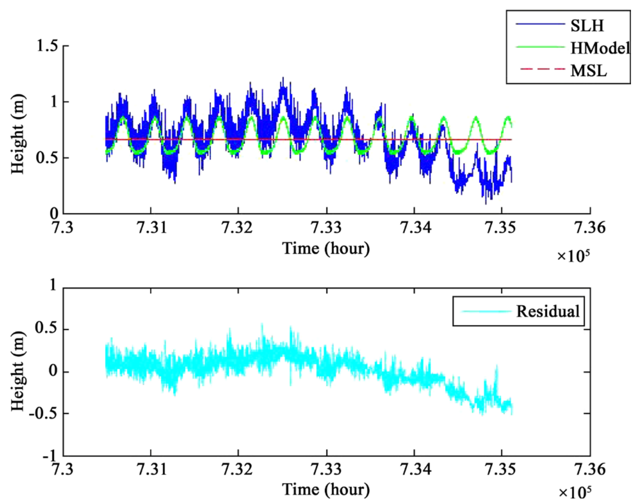

Figure 14. Time series along with tide model and residual in Nekatide gauge station.

6. Conclusions

Using the least square spectral analysis on time series the tide gauge stations and time series by observing satellite altimetry of annual periods, biannual and monthly in the Caspian Sea were discovered and spectral analyses of time series for tide gauge observations and altimetry observations are corresponding. But, it was totally clear that because tide gauge data existed in a lower tide gauge interval don't show several years' periods and a series of periods are seen in spectral analyses observed via time series of satellite altimetry that are not seen in the spectral analyses of time series of tide gauges.

By least square spectral analysis on time series observations for tide gauge stations and time series by observations of satellite altimetry annual periods, biannual and monthly periods were discovered in Caspian Sea which showed several local influential tide components via global model of tide achieved by satellite, like global models of Got and… that existed in corrections of SSH which are not able to be elicited well.

The tide analysis of 40 components of time series by altimetry observations is approximately corresponding but, their gratitude scale is different and influence of each component was similar in comparison to tide analyses of tide gauge stations in the annual components and biannual that were corresponding but, the effect of the entire components was not similar. After comparing tide analysis of the time series of observations for satellite altimetry observation with tide gauge stations, the tide analysis of tide gauge stations showed lack of influence of tide gauge components except annual and biannual component showed controversy to time series altimetry observations, but in tide analysis of time gauge stations there were several components with small values that in this way, the tide analysis of altimetry observation of time series showed that other components existed in addition to annual, biannual and monthly components. The prominent problem of tide gauge data for the coast of the north of Caspian Sea was lack of collecting and appropriate gathering remaining still with many gaps. Also, sampling distances of Anzali tide gauge daily and tide gauge of Noshahr once every three hours have influences on tide modeling and decrease calculating precision.

The results shows that the annual (Sa) and semi-annual Solar (Ssa) constituents on all of the ports listed have the highest amplitude in comparison with the other constituents which are respectively 16 cm, 18 cm and 15 cm for annual constituent and 2.8 cm, 5.4 cm and 3.7 cm for semi-annual constituent.

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