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Harmonic analysis of tide gauge data 2013-2014 in Bulgaria

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In last few years a subject of many scientific researches is the variation mean sea level, which is sure indicator occurring climate change. At Bulgarian Black Sea coast is situated tide gauges in harbor area of cities Varna and Burgas. The measurements were started at 1928. The measured data may present as sum of mean sea level, tidal influence and storm surges. Computed trend from tide gauge data clearly indicates increase of MSL (1.4 mm/y. for Varna and 2.00 mm/y for Burgas).

The subject of research is analyzing of short term tidal components. The analysis determines order of influence of short term tides at mean monthly values of MSL. For purpose of research one year of radar gauges data is used.

New radar gauges are installed in 2013. For processing of data it was used method of harmonic analysis, based on theory that the data of research could be represented as sum of harmonic functions with a amplitudes and phases.

Key words: sea level, harmonic analysis, tidal constituents

INTRODUCTION

Main cause of variation of sea level is tidal and non-tidal influence. Non-tidal variation is caused by changing in atmospheric pressure, temperature, and influence of wind.

The variation of gravity field of Earth is caused by gravity forces of Moon and Sun is the main force for occurring tides. Tides are result of periodical influences acting at previously known frequencies and amplitudes.

These influences are known as tidal constituents. The period of observations from 365.25 days is enough for analyzing diurnal and semi-diurnal tidal constituents. It is required period of observations of several years to examine influence long period tidal constituents.

The radar gauges provide systematic base of observations independent of human support. This high quality data ensure opportunity to analyze importance of short-term variations and its contributions for calculating MSL.

Least-squares based harmonic analysis was used for solve tidal constituents. This method is based on theory that observed data series can be presented by sum of components whit previously known frequencies stable in time.

The purpose of research is to analyze tidal constituents and their influence to mean sea level variation. The least squares technique has many advantages over other methods: no restrictions of equally spaced continues data with no gaps, does not have to stick strictly to synodic periods for tidal constituents, easily compute variance between the data time series and the predicted time series.

USED DATA

Tide gauges at Bulgarian Black sea coast is situated in cities Burgas and Varna. The measurements started in 1928. At this site tide gauges is mechanical type - stilling well gauges “A.Ott” (Kempten).

It is necessary the maintenance of the system to be observed regularly by operator, who takes control measurements. In past decade new tide gauge systems had been improved which could operate independently. These are acoustic, pressure and radar gages [1].

The radar gauges emits microwave impulses by antenna of system, reflected signal is received back again by antenna. Time from emission to reception of signals is proportional to level of measured sea surface. The main advantages of radar gauges to other systems are easy maintenance, and independency of emitted signal from temperature and pressure change.

In 2013 new radar gauges VegaPuls s60 were installed above high water level in draw well of tide gauges in Varna (lat./long. – 43.1926°/27.9114°) and Burgas (lat./long. – 42.4887°/27.4795°). Observations of sea surface are registered in every 15 seconds at these sites.

For the purpose of this research hourly data for period 01.05.2013-01.05.2014 for station Varna and 27.05.2013-27.05.2014 for station Burgas was analyzed.

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For station Varna 8072 from 8760 hourly values, for station Burgas registered data is 7260 from 8760 hourly values.

SEPARATION OF TIDAL CONSTITUENTS

The frequencies of tidal constituent is related to astronomical parameters of celestial bodies which have major influence at gravity field of Earth- the Sun and the Moon. Important periods are: mean solar day (24.00 hours), mean lunar day (24.84 hours), period of tropical month 27days, tropical year-365.25days, period of lunar perigee 8.847 years, period of lunar node 18.61 years.

Tidal constituents are divided into groups according their frequencies to: astronomical half daily, astronomical daily and long period. Most important of them are written in Table 1.

Table 1. Important tidal constituents

Tides	**Period** (days)	**Frequency** (^{o}/hours)	**Origin**
Astronomical half daily			
K_2	0.499	30.0821^{o}	Sun/Moon
R_2	0.499	30.0411^{o}	Sun
S_2	0.500	30.0000^{o}	Sun
T_2	0.501	29.9589^{o}	Sun
L_2	0.508	29.5378^{o}	Moon
M_2	0.518	28.9841^{o}	Moon
N_2	0.527	28.4397^{o}	Moon
Astronomical daily			
K_1	0.997	15.0411^{o}	Sun / Moon
P_1	1.000	14.9589^{o}	Sun
M_1	1.035	14.4967^{o}	Moon
O_1	1.076	13.9430^{o}	Moon
Q_1	1.120	13.3987^{o}	Moon
Long period			
M_F	13.66	0.0027^{o}	Moon
M_M	27.55	0.0055^{o}	Moon
S_{SA}	182.70	0.0363^{o}	Sun
S_A	364.96	0.0732^{o}	Sun

The harmonic analysis presents observed data as sum of harmonic functions sine and cosines at previously known frequencies with amplitude and phase. The selection of tidal constituents included in the model, was based to length of time series and quality of data.

According to [3] for period of one year of observations its necessary to use 60 to 100 tidal constituents, for 19 years of observations, analysis would include 300 constituents. The frequencies of some tidal constituents are very close.

The separation of tidal constituent was made according to synodic period. The minimum period of time required to separate two nearby tidal constituents is synodic period. It is defined as interval between two consecutive conjunctions of phase of two constituents. For the analysis is important to separate not only two tidal constituent, but correctly separate many pairs of constituents with different synodic period. We should use the longest synodic period.

According to [4] separation of two tidal constituent we need for diurnal: O1 from M1 (27.55 days), P1 from M1 (32.5 days); P1 from K1 (182.6 days); K1 from S1 and K1 from P1 (365.25 days); for semidiurnal K2 from S2 (182.6 days), T2 from S2 (365.25 days).

The period of observations from 365 days sufficient for performing least squares harmonic analysis and to separate key constituents. It is necessary to use data from several years of observations to solve Sa and semiannual -Ssa constituent.

To define the influence of nodal tide should be analyzed data of 19 years observations. Data was corrected for nodal tide. For harmonic analysis with error estimates has been used MatLab program T_Tide.m [2].

Used function of harmonic analysis is

$$x(t) = b_0 + b_1 t + \sum_{k=1...M} A_k \cos(\sigma_k t) + B_k \sin(\sigma_k t) \quad (1)$$

Here $x(t)$ is hourly sea level for time moment t, b_0 is mean sea level at epoch of measurement b_1 is annual mean sea level trend, σ_k – frequency of tidal constituent, A_k, B_k – components of tidal constituents amplitude. M – number of tide constituents used in model

$$H_t = \sqrt{A_k^2 + B_k^2} \quad (2)$$

$$g_t = \arctan \frac{B_k}{A_k} \quad (3)$$

(2) is amplitude of tidal constituent, (3) is phase of tidal constituent.

The significant constituents have been separated with respect to Signal to Noise Ratio (SNR). Tidal constituents with SNR greater than 2 are significant. SNR is set as a proportional of signal power to noise power. According to [2] SNR greater than 2 is significant and should been used for calculating predicted value.

RESULTS

The analysis determinates that significant tidal constituents are some diurnal O1, P1, K1, PHI1, THE1, semi diurnal N2, M2, S2, K2, third diurnal MK3, M3 and quarter diurnal – SK4. Major influence has constituents K1 and M2 with amplitudes of 1.8 cm and 1.9 cm.

The significant tidal constituents solved from harmonic analysis from tide gauge Varna are presented in Table 2.

Table 2. Significant parameters solved from harmonic analysis for station Varna – frequencies of tidal constituents, amplitudes, phases, estimated errors and SNR values

Tide Varna	**freq**	**Amp (cm)**	**amp_err (cm)**	**Phase (°)**	**Phase_err**	**SNR**
O1	0.0387307	0.81	0.3	52.15	23.25	8.1
P1	0.0415526	0.97	0.3	67.46	16.69	12
K1	0.0417807	1.84	0.3	63.37	9.7	42
PHI1	0.0420089	0.59	0.3	333.87	27.91	4.3
THE1	0.0430905	0.41	0.3	351.76	42.88	2.1
N2	0.0789992	0.4	0.1	5.41	20.43	7.4
M2	0.0805114	1.9	0.1	9.69	4.27	170
MKS2	0.0807396	0.7	0.1	314.72	14.57	23
S2	0.0833333	1.02	0.1	10.65	8.23	49
K2	0.0835615	0.53	0.1	335.58	19.65	13
M3	0.1207671	0.05	0.01	330.03	30.12	3.3
MK3	0.1222921	0.05	0.01	117.1	38.94	2.5
SK4	0.1668948	0.04	0.01	252.26	45.55	2.5
3MK7	0.2833149	0.03	0.01	239.98	39.77	2.1

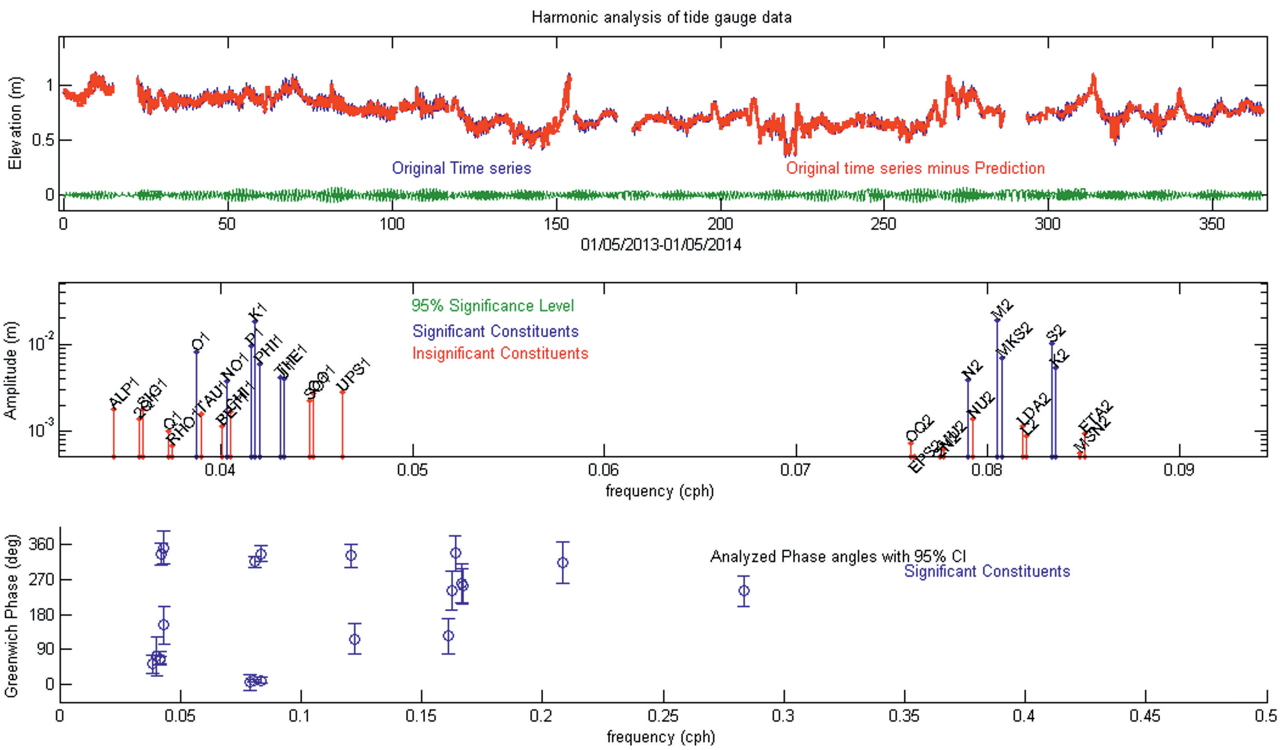

Fig. 1. Station Varna: (a) – whit blue line is shown observed data, green line – prediction according to significant constituents, red line – residual series - prediction; (b) – amplitudes of significant constituents(SNR>2) – blue line; red line – insignificant amplitudes (c) – phases whit error of significant tidal constituents to Greenwich meridian.

Table 3. Significant parameters solved from harmonic analysis for station Burgas – frequencies of tidal constituents, amplitudes, phases, estimated errors and SNR values

Tide Burgas	freq	amp (cm)	amp_err (cm)	Phase (º)	Phase_err (º)	SNR
ALP1	0.034397	0.24	0.2	184.8	48.24	2.1
Q1	0.037219	0.25	0.2	67.64	45.83	2.2
O1	0.038731	0.82	0.2	65.47	13.73	24
BET1	0.04004	0.33	0.2	166.19	35.34	3.8
NO1	0.040269	0.3	0.2	123.16	36.7	3.1
P1	0.041553	0.72	0.2	89.63	13.35	18
K1	0.041781	1.56	0.2	77.17	6.82	85
PHI1	0.042009	0.56	0.2	17.24	17.65	11
OO1	0.044831	0.25	0.2	53.32	73.78	2.1
N2	0.078999	0.4	0.1	20.24	16.35	11
M2	0.080511	2.13	0.1	27.76	3.07	330
MKS2	0.08074	0.75	0.1	8.75	10.97	41
S2	0.083333	1.08	0.1	29.87	6.24	85
K2	0.083562	0.69	0.1	11.34	12.3	34
M3	0.120767	0.06	0.01	0.76	23.44	5.5
SO3	0.122064	0.06	0.01	115.75	28.75	5.4
MK4	0.164073	0.05	0.01	318.16	33.11	4.4
2SK5	0.208447	0.08	0.01	19.52	24.49	6.6

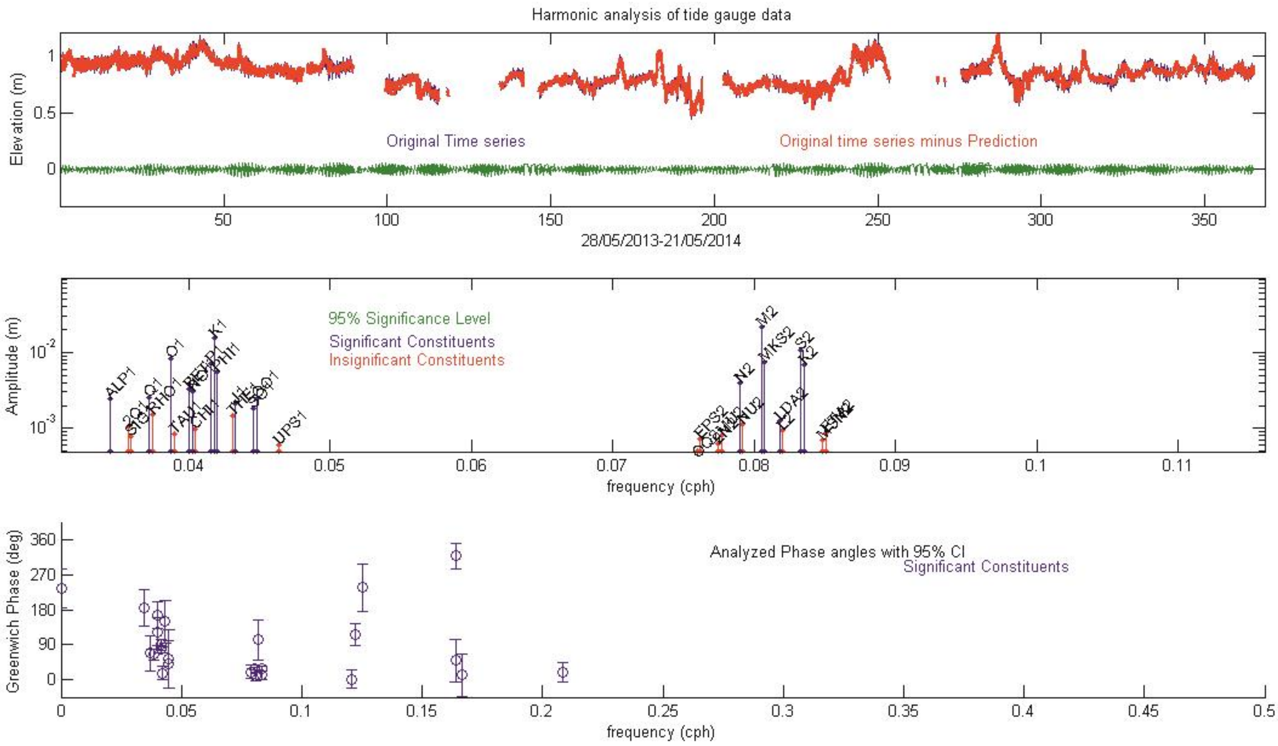

Fig. 2. Station Burgas: a – with blue line is shown observed data, green line – prediction according to significant constituents, red line – residual series – prediction; b – amplitudes of significant constituents(SNR>2) – blue line; red line – insignificant amplitudes; c – phases whit error of significant tidal constituents to Greenwich meridian.

Table 4. Calculated amplitudes for tidal constituents: a) from this research b) from [5]

	VARNA Amplitudes (cm)			**BURGAS Amplitudes (cm)**	
Tidal constituent	**a)**	**b)**	**Tidal constituent**	**a)**	**b)**
O1	0.81	0.7	O1	0.82	0.9
P1	0.97	0.6	P1	0.72	0.8
K1	1.84	1.8	K1	1.56	2.3
PHI1	0.59	—	PHI1	0.56	—
THE1	0.41	—	OO1	0.25	—
N2	0.4	0.4	N2	0.4	0.4
M2	1.9	2.2	M2	2.13	2.4
MKS2	0.7	—	MKS2	0.75	—
S2	1.02	1.2	S2	1.08	1.4
K2	0.53	0.3	K2	0.69	0.4
M3	0.05	—	M3	0.06	—
MK3	0.05	—	SO3	0.06	—
SK4	0.04	—	MK4	0.05	—
3MK7	0.03	—	2SK5	0.08	—

Calculated significant tidal constituents for station Burgas are presented in Table 3. From data we can establish diurnal Q1, O1, P1,K1, PHI1 semidiurnal N2, M2, S2, K2, MKS2 third diurnal – M3, SO3, quarter diurnal – MK4 tidal constituents.

CONCLUSION

The harmonic analysis determinates significant short term tidal constituents at tide gauge station Varna and Burgas. In Table 4 were compared the amplitudes calculated from analysis and amplitudes determinate in [5], they are in a good agreement. Because of longer period of investigation in this research more constituents were estimated. To fill data gaps we should use overall impact of short and long term tidal constituents.

The long period tidal constituent wasn't calculated because of the insufficient data period. The analysis of several years of observations will improve calculated results, and allow opportunity to compare annual changes in tides, and mean sea level.

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ХАРМОНИЧЕН АНАЛИЗ НА МАРЕОГРАФНИ ДАННИ 2013–2014 г.

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(Резюме)

През последните години обект на много научни изследвания е глобалното изменение на морското ниво, което е сигурен индикатор за настъпващите климатични промени.

На българското черноморско крайбрежие са разположени мареографни станции в пристанищата на градовете Варна и Бургас. Регистрациите започват от 1928 г. Регистрираните данни могат да се разглеждат като сума от средната стойност на морското ниво, приливни влияния и щормови влияния.

Получените от обработка на мареографни измервания резултати показват положителен тренд на изменението на средното морско ниво на Черно море (1.4 mm/y за Варна, 2.00 mm/y за Бургас), който е съпоставим със средните стойности в глобален мащаб.

Обект на изследванията са късопериодичните приливни компоненти. Проведеният анализ установява степента на влиянието им върху изчислените средно месечни стойности на морското ниво.

Използвани са данни от аналоговите мареографни апарати, както и от новите радарни мареографи, инсталирани през 2013 г. За целта се използва период на наблюдения от една година от радарните мареографи.

За обработването на данните е използван метода на хармоничния анализ, основаващ се на тезата, че регистрираните стойности на морското ниво могат да се представят като определен брой хармонични функции, амплитуда и фазова честота