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INDIRECT OBSERVING OF THE LOW-FREQUENCY GRAVITATIONAL WAVES ASSOCIATED WITH THE GAMMA- RAY BURST GRB 051103 BY ANALYSIS OF LIGO DATA

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The results of comparative analysis of gravitation-wave observatory LIGO data associated with gamma-ray burst GRB 051103 at maximum sensitivity frequency domain (100-200 Hz) are presented. The non-stationarity of the L1 detector's signal in time-frequency domain with the exact binding its manifestations at GRB 051103 was observed. Based on known astrophysical models and data an interpretation of results is offered. The interpretation supposes the indirect registration via detector L1 LIGO of gravitational waves which are associated with GRB 051103.

Keywords: time-frequency analysis, gravitational waves, gamma-ray bursts, binary systems, black holes.

A registration of gravitational waves which was predicted the general relativity theory (GRT) will be important experimental result for confirmation of the Universe's modern physical picture, because in this case the space-time continuum will be not only mathematical model, but will acquire the physical object's properties [1.2]. Therefore, today some famous projects to find gravitational waves there are. The projects which were based on the use of ground-based laser interferometers: American project LIGO (Laser Gravitational-wave Observatory) and the European project Virgo were most successful.

A measure of the magnitude of gravity waves at interferometry is a dimensionless relative interferometer base's deformation h (strain) under the influence of gravitational wave. However, at estimation of the interferometer's noise level a dimensions amplitude h_c measured in $\mathrm{Hz}^{-1/2}$. The noise of the four kilometers detectors L1 and H1 into the maximum sensitivity frequency band (100-200) Hz at final series of measurements was not greater than $3 \cdot 10^{-23} \mathrm{Hz}^{-1/2}$, which corresponds to the project's target settings. Noise levels of the two kilometers detectors H2 and L2 are 8dB greater than the noise levels of the four kilometers detectors. Interferometer currently decommissioned and rebuilt on an improved version (Advanced LIGO) which must provide noise reduction to $3 \cdot 10^{-24} Hz^{-1/2}$ after 2017-2018 years [3].

Amplitude-frequency characteristics of the expected sources of gravitational waves are well known [4,5]. LIGO project was focused on registration of gravitational waves from merging neutron stars and the collapse of supernovas' external shells in the frequency range $10 - 10^3$ Hz. The project was designed to direct registration of gravitational waves. An estimation of waves polarization can be made by pairwise perpendicularly arrangement of detectors, and recognizing of directions to sources can be made by presence of significant distance between similar detectors (L1, L2 detectors are located in Louisiana; H1, H2, detectors are located in Washington State). The methods of analysis are mainly aimed at the identification of statistically significant relationships between the signals of the detectors. But until now on this way at achieved noise's level the useful signals are not registered.

July 11, 2012 the comprehensive report based on the results of the study of the relationship between the short gamma-ray burst GRB051103 and synchronous measurements of the gravitational wave magnitude by LIGO's L1 and H2 detectors was published on the LIGO's Document Control Center website [6]. A statistically significant correlation between gamma-ray burst and interferometric data have been not identified [7]. The report was accompanied with publication of the measurements' data: strain registration by detector H2 (H2-STRAIN_16384Hz-815043278-2190 and H2-STRAIN_4096Hz-815045078-256), strain registration by detector L1 (L1-STRAIN_16384Hz-815043278-2190 and L1-STRAIN_4096Hz-815045078-256) and noise spectrum for the detectors, related to the same point in time. According to file name data sampling rate were 16384S/s (samples per second) or 4095S/s, the recording duration 256s or 2190s and sampling beginning time GPS815043278 (03.11.05 08:54:25 GMT) or GPS815045878 (03.11.05 09:24:25 GMT). GRB051103 beginning GMT is 09:25:43, 03.11.05 785, and its total duration 17 ms (time of maximum glow is about 2ms) [8].

Additionally, in the description of the report [6], it was reported that the data with sampling frequencies 16384Hz and 4095Hz are the result of high-pass filtering source data with cut-off frequencies 20 Hz and 30 Hz, respectively, in order to reduce the influence of the dominant seismic noise.

Figure 1 presents the results of the spectral analysis of sensors' (L1 and H2) signals in frequency band where interferometers have maximum sensitivity. Despite high-frequency filtering of signals L1-STRAIN_16384Hz-815043278-2190 and H2-STRAIN_4096Hz-815045078-256 their spectrum in frequency band 100-200 Hz is the negative-going branch of the dominant noise. Seismic noise masks these signals. Signal spectrum L1-STRAIN_4096Hz-815045078-256 in the same frequency band has a manifest local minimum which indicates adequate rejection of dominant noise only for L1 detector by using regimes of registration and preprocessing. Therefore a comparative analysis of signals in the greatest sensitivity's domain is meaningless, so further analysis was done only for the signal L1-STRAIN_4096Hz-815045078-256.

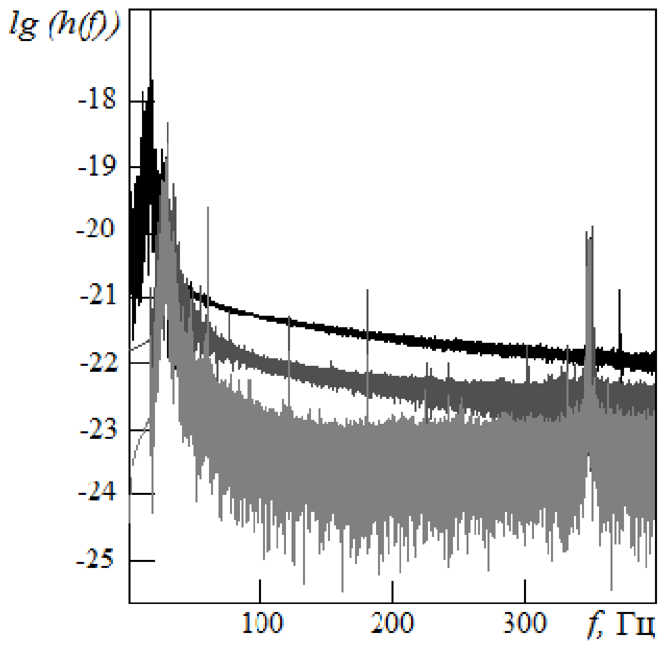

Fig.1

In the papers [9,10] we have proposed and approbated high-sensitivity method of analysis for detection of harmonic and quasiharmonic signals amid the random noise. The method is based on a comparison between signal's waveform and sine wave with analyzed frequency, regardless of signal's amplitude. Proposed method was called form-analysis. The result of analysis for digital signals is a two-dimensional matrix $\boldsymbol{I_f}$ (m, n), each element of which is form-index $I_f\,(m, n)$, where m,n is analyzed period and time in samples. The form-index is a non-dimensional measure of similarity between signal's waveform at time n and sine wave with period m. The form-index has maximum value 3 for pure harmonics with period m and minimum value -1 (background) for signals with non-harmonic waveforms.

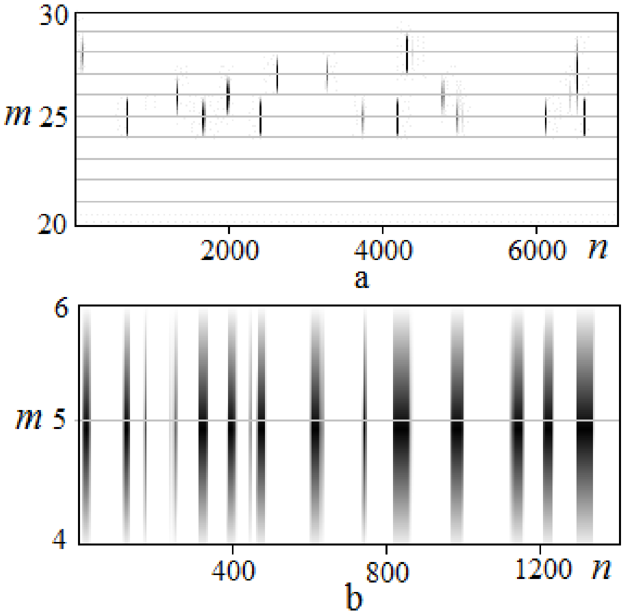

Fig.2

Figure 2a presents the results of analysis for arbitrary part of signal L1-STRAIN_4096Hz-815045078-256 with duration in 7500 samples (~ 1, 83s') and with periods from interval 20-30 samples (4,9-7,3ms). The form-factor exceeded over the background value only in periods' interval m = 24-29 (5,9-7,0ms), which corresponds to the frequency range of 140-170Hz.

Taking into account the properties of the form-analysis the registration significant form-factor in the frequency band 140-170Hz can be bound up with presence in the band the physically implemented vibrations which are independent from detector's seismic noise. These vibrations can be considered as a useful signal only in terms of its differences from the nature of detector's basic noise. The observed vibrations by type of manifestations can be attributed as detector's thermal noise which determines the interferometer's sensitivity at frequency ~ 100 Hz [11].

For bringing information about useful signal's properties to only one non-dimensional parameter resampling of signal L1-STRAIN_4096Hz-815045078-256 with sampling rate 820S/s was fulfilled after the procedure of low-pass digital filtration. As a result the resolution of analysis was reduced fivefold. In Figure 2b presents that after resampling all information about the useful signal gone in band m=5 (period 6, 1ms, frequency about 160Hz). The dynamics of form-index of useful signal in that band corresponds to stationary random process.

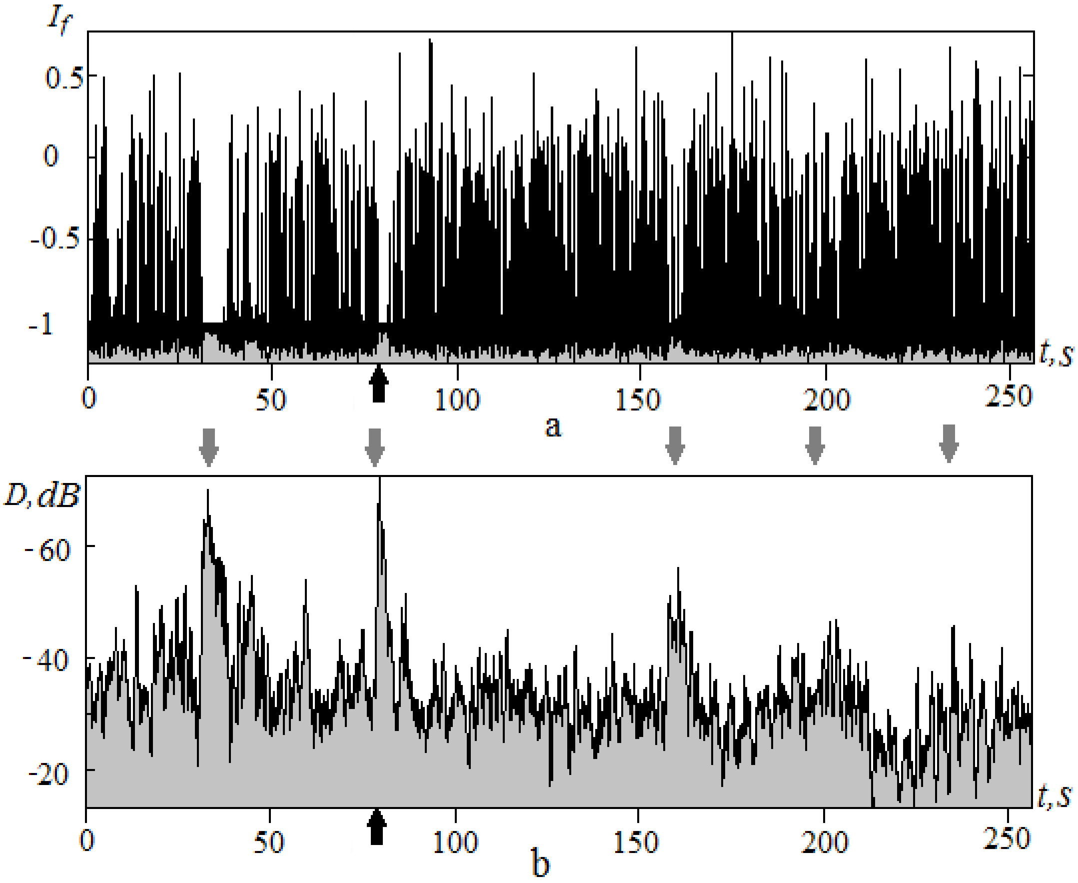

Fig.3

In Figure 3a presents the results of analysis of signal L1-STRAIN_4096Hz-815045078-256 after resampling on full time interval 256s. On long time intervals the form-index remains stationary, but on relatively short time intervals (windows-like) the form-index is reduced until background values (-1) that corresponds to a rapid decrease in useful signal-to-seismic noise ratio. Comparison of signal start time with time short gamma-ray burst GRB 051103 indicates that the gamma-ray burst occurred 79s after the start of the recording (in Figure 3 the time gamma ray burst is marked as a black arrow on the timeline). Gamma-ray burst is exactly concurring with front border of second window. This coincidence may be not accidental, since the gamma-ray burst was very short (17ms) and throughout the signal (256s) only two windows with explicit front border is observed.

Interrelation between short gamma-ray bursts and gravitational waves derives from some physical models of GRB's origin which are based on coalescence of compact objects in binary systems [12]. If the speed of gravity waves equal to the speed of light in vacuum, a synchrony between gamma-ray bursts' and gravitation waves' registration must be observe. By analogy, we can assume that non-stationarity in the process (fig. 3a) associates with relatively slow changing of detector's dynamic properties which is caused changing space-time properties (metric) as result of incoming gravitational waves associated with a process of gamma-ray burst generating. Since seismic noise detector is the monochromatic signal with random amplitude we can assume as first approximation that with the arrival of gravitational waves a Q-factor of the seismic noise is reduced.

At lower values of form-index in the windows a decrease of form-index dispersion there is too. The Figure 3b presents the form-index dispersion's value during observation time in decibels relative to the maximum value. The lowest dispersion values occur in area of the windows' bottoms, but the dispersion axis on the Figure 3a was turned to traditional format, in which the gravitational wave magnitude increase corresponds to the visual increase of estimation parameter (dispersion).

The gamma-ray burst GRB 051103 belongs to the gamma-ray bursts with known direction to the source. The most likely source of the burst was in a group of actively interacting galaxies M81/M82/NGC3077, located at a distance of 3.6 Mps (12 million light years) from Earth [13]. Interest to GRB 051103 as a potential source of gravitational waves was connected, firstly, with the relative proximity of galaxies groups M81/M82/NGC3077 to Earth and, secondly, with the ability to generate large-amplitude gravitational waves in the course of astrophysical processes (coalescence) by generating of short gamma-ray bursts.

The Fig. 4 presents a qualitative scheme of gravitational waves generation during the process of compact binary objects' coalescence by K. Thorne [14]. The coalescence is begun by a lengthy stage of inspiral (1) that ends with the last stable circular orbit. In some papers [15,16] the final stage of the inspiral is called plunge. After passing the event horizon there comes a merger stage (2) that ends with the formation of a rotating Kerr black hole. At ringdown stage (3) a magnitude gravity waves of Kerr black hole rapidly decreases without frequency changing.

The coparison Fig.3b and Fig.4 shows a quality similarity between waveforms. Similar parts of waveforms in figures was marked by vertical arrows, which allow to mark of coalescence stages. The first two high waves in Figure 3b belong to inspiral stage and the last three waves belong to ringdown stage.

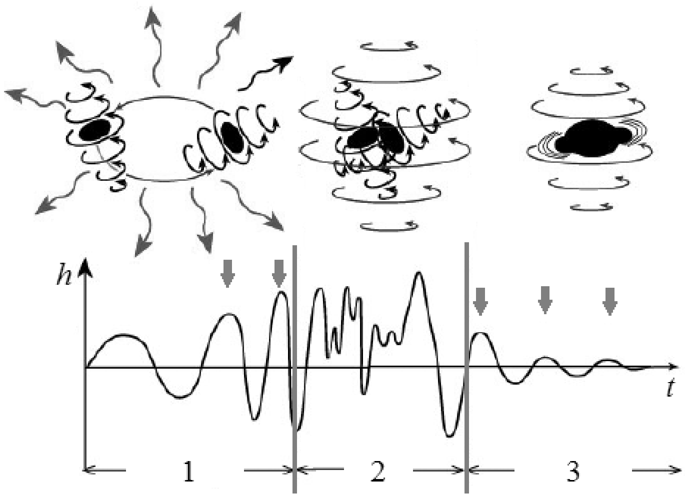

Fig.4

Waiting the project LISA (Laser Lisa Space Antenna) realization the binary objects as sources of low-frequency gravitational waves have been the subject of a lot theoretical studies [15, 16, 17, 18], based on the numerical simulation of the coalescence dynamics. The quantitative estimations of gravitational wave's parameters for different types of compact objects at inspiral stage and at ringdown stage were received. At merger stage the coalescence's processes are chaotic, so the parameter of gravitational waves and duration of the stage are not known [14].

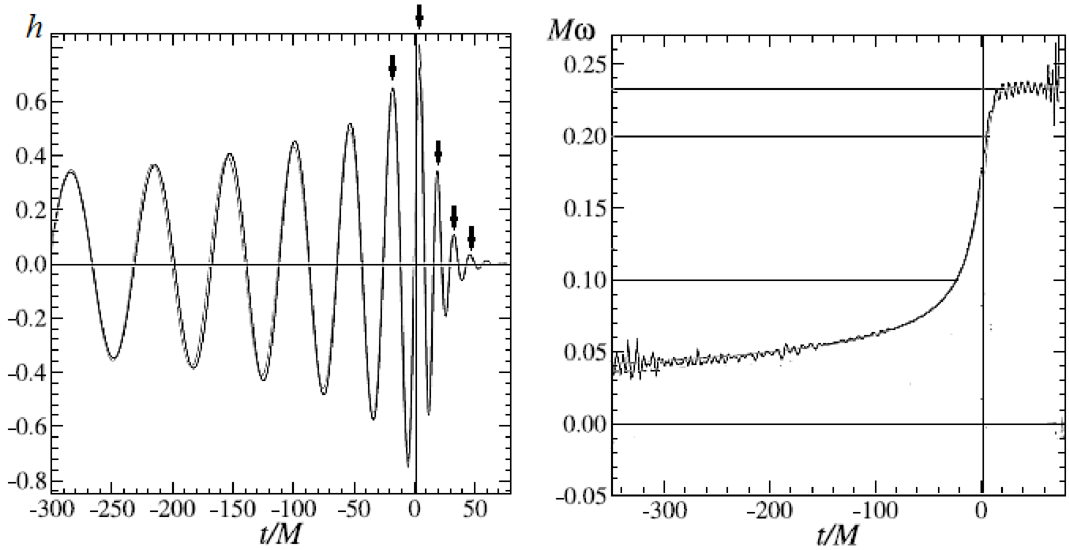

Fig.5

The Figure 5 presents the results of a simulation of the coalescence of two compact rotating objects with mass ratio 1: 4 [17]. The legs of theoretical waveform corresponded to results of analysis (fig. 4b) are shown by vertical arrows. At merger stage the theoretical waveform is absent by reason of both theoretical and computational complexities of modeling. In the system G = c = 1 time is measured in $M = 5 \cdot 10^{-5}$ (M/M_{Sun}) c, where M is the total mass of coalesced objects; M_{Sun} is the mass of the Sun. Time scale's zero corresponds to the transition of a smaller object through the event horizon.

By comparing figures 3b and 5 an estimate of the total mass of the coalesced objects may be made. At ringdown stage $M\omega$ = 0.23, where ω is the angular frequency of objects' rotation which is two times less than gravitational waves' frequency. In Fig. 3b wave's period at ringdown stage T_{ring} = 40 c, so the total mass of objects:

$$M = (M\omega) \cdot 2T_{ring} \cdot (2\pi)^{-1} = 0{,}23 \cdot 80/6{,}28 = 3\text{c} = 6 \cdot 10^4\ M_{Sun}.$$

According to the estimation and by the model presented in Figure 5 the mass of small object is 12000 M_{Sun}, and the mass of large object 48000 M_{Sun}. The objects of such mass can be the black holes only, but their mass is less than the mass of the supermassive black holes (10^5 M_{Sun}) and much more than the mass of stellar-like black holes. The estimated mass is not typical for black holes, but compact objects with middle mass were observed in X-ray range by telescope Chandra. The compact objects in the Galaxy M82 have masses in range from 12000 M_{Sun} to 43000 M_{Sun} [19]. It is an important discovery in astrophysics for the last time. The close convergence the estimated mass with results of direct X-ray observations in most likely source's area confirms an interpretation truth.

Additionally an estimation of angular velocity increase for the last stable circular orbit can be received on Fig.5. On the time interval about $20M$ the angular velocity increases about twice from $0.1/M$ to $0.2/M$. On Fig. 3a width of first window is 8, 25c, and width of second window 4,5c, that corresponds to approximately doubling the angular velocity on the last stable circular orbit too.

The existing level of knowledge about generation of powerful gravitational waves dynamics allows searching and primary identification based on analysis of signal only one detector with a maximum sensitivity.

The comparative analysis of the potential gravitational waves' sources leads to conclusion that waves with greatest amplitudes can be obtained in the low frequency range from coalescence of black holes with total mass in range from $10^4 M_{Sun}$ to $10^6 M_{Sun}$. The results of direct observation of sky in the X-ray range evince that such events can to occur in nearby galaxies and that further increases the estimate of the expected gravity waves' magnitude. However, ground-based laser interferometers have maximum sensitivity in the middle frequency range and do not allow the direct registration of low-frequency waves.

The analysis LIGO detectors' signals shows that the seismic noise at frequencies 20-30 Hz mainly determines their waveform. The method of analysis, which allows registering in frequency domain of detector's higher sensitivity the weak useful signals not related to formation of the seismic noise waveform, is presented.

The analysis of available LIGO's data associated with GRB 051103 led to conclusion that only the data of L1 detector sampled with rate 4096S/s can be appropriate for investigation in frequency domain of interferometer's greatest sensitivity. Other data in the domain are masked by the seismic noise.

As result of the investigation the stationary random useful signal was received. Some windows-like stretches where signal's stationarity was broke were registered.

The GRB 051103 is exactly concurring with front border of one of the stretches. From assumptions about an exposure of low-frequency gravitational waves with large magnitude on the ratio “useful signal / seismic noise” a possible of gravitational waves’ indirect observation associated with GRB 051103 was proclaimed. As other appropriate signals for comparative analysis was have not, a dynamic interpretation of the results is the only one way to the hypothesis’ confirmation.

In accordance with available results of theoretical modeling of gravitational waves for binary systems the total mass ($6 \cdot 10^4$ M_{Sun}) of the compact objects was estimated. At first time the appropriate waveform from compact objects’ coalescence was observed experimentally. Moreover our estimation of binary system’s mass corresponds to the independent estimation of the black holes’ masses in the galaxies group M81/M82 /NGC3077 associated with gamma-ray burst GRB 051103 from direct observations in the X-ray range.

Simultaneous registration of gamma ray burst GRB 051103 and reception of gravitational waves directly confirms that the speed of gravity waves’ propagation is equal to the light speed in vacuum and coalescence of intermediate-mass black holes can be considered as a sort of “central engine” for generation of short gamma-ray bursts.

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