Why an indirect observation of low-frequency gravitational waves by dint of the ground-based laser interferometers is possible?

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Abstract. The noise sources of gravitational wave detectors for ground-based laser interferometers by example of LIGO were analyzed. As shown the low-frequency gravitational waves (GW) cause to changes in the detectors' dynamic properties, which manifested as the Q-factor's changes of low-frequency seismic component in a detectors' integral noise that leads to the possibility of indirect GW's observation in the frequency range (~ 100 Hz) of a detectors' extreme sensitivity. The experimental estimation of GW's properties by results of indirect observation is presented.

Keywords: laser interferometers, gravitational waves, observation of gravitational waves.

Introduction

A registration of the GWs which were predicted in the framework of general theory of relativity (GTR) is significant for the confirmation of the universe's modern physical picture, since the space-time of GTR will cease to be a mathematical model, and will accept the property of the physical object. In addition, the GW observations will provide a lot of additional information about the early stages of the universe's evolution, a development of galaxies and the high-energy processes close to relativistic compact objects [1,2]. Therefore some projects for GW searching were realized. The most successful were projects based on using of ground-based laser interferometers: American project LIGO (Laser Interferometer Gravitational-wave Observatory) and the Franco-Italian project Virgo (the Virgin).

The GW amplitude's measure at laser interferometry is the dimensionless relative deformation *h* of interferometer's base which was formed between mirrors on the free suspension under the influence of GW. So the laser interferometers can be considered as devices for extremely precise measurements of deformations.

The highest detector's sensitivity was achieved for first phase of the project LIGO (LIGO Initial). But at the target level of detectors' noise the useful signals were not observed.

Noise of interferometers' detectors by LIGO example

For estimating of interferometer's noise the dimensional amplitude $h(f)$ (in $Hz^{-1/2}$) is used. The noise of LIGO four-kilometer detectors L1 and H1 in frequency band of higher sensitivity (100-200)Hz at the final series of measurements was not greater than $3\cdot10^{-23}Hz^{-1/2}$, that corresponds to the target parameters of the project. The noise of two-kilometer detectors L2 and H2 is about 8Db higher. Now the LIGO interferometers are rebuilt on an improved version (Advanced LIGO) which must provide noise reduction to $3\cdot10^{-24}Hz^{-1/2}$ [3].

The seismic noise (mechanical vibration), thermal noise of mirrors (test masses) and mirrors' suspension, shot noise and radiation pressure are the main sources of detectors ground-based laser interferometers' noise. The amplitude-frequency characteristics of main sources of LIGO detectors' noise are presented in fig.1. The goal characteristic of integral noise for initial LIGO is presented in same figure as a dedicated polyline. The seismic noise determines the low-frequency part of integral noise. The shot noise determines high-frequency noise of detectors. The integral noise within the maximum sensitivity's domain (100-1000 Hz) is defined by thermal noise of the mirrors' suspension.

The LIGO detectors noise characteristics are unique because the amplitude of mechanical movements of macroscopic objects such as mirrors (mirrors weight ~ 10 kg) is comparable with amplitude of thermal motion of molecules and atoms.

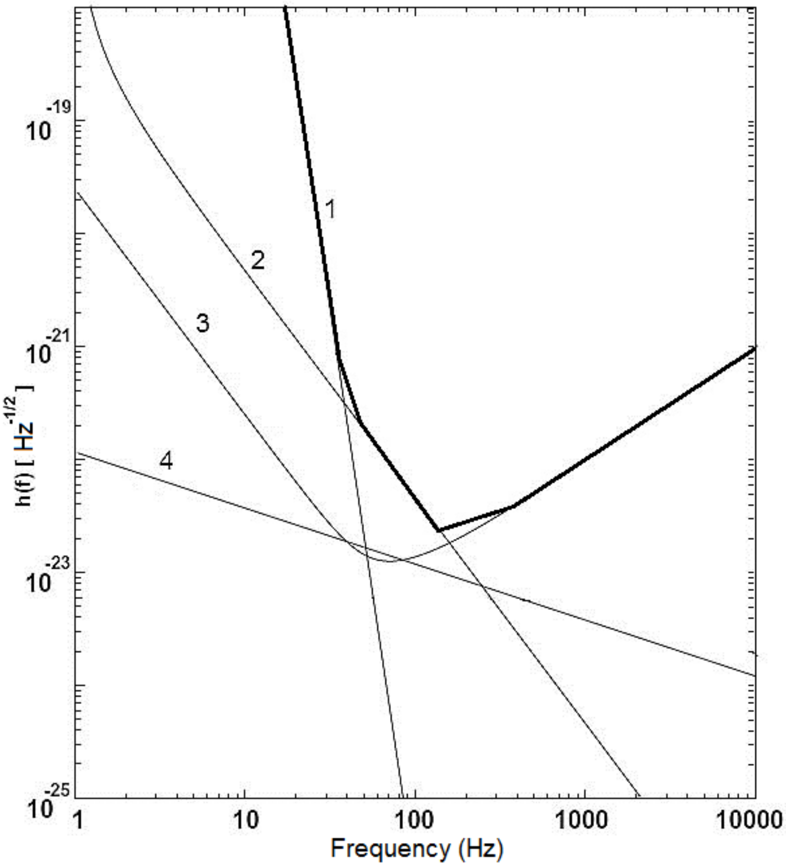

Fig.1. The goal characteristics of the main sources of detectors' noise for Initial LIGO [4]: 1 – seismic noise; 2 – suspension thermal noise; 3 – radiation pressure & shot noise; 4 – test mass thermal noise.

Analysis of the interferometers' signals by LIGO data

In view of the well-known amplitude-frequency characteristics of the potential sources of GW [5.6], the frequency band of LIGO detectors' most sensitive (fig. 1) corresponds to the GW's frequency for the mergers of star-like binary systems with mass $M \sim M_{Sun}$, where M_{Sun} is the mass of the Sun, and for the collapse of Supernovas' external shells. The LIGO detectors are designed for direct registration of GW, with the ability to estimation their polarization (L-shaped configuration of Michelson interferometers) and directions to the source due to distance 3030km between detectors (detectors L1, L2 are in Louisiana, H1, H2 are in Washington State).

Thus the usual strategy of direct primary registration GW is based on some principles:

1. The frequency of potential sources of GW should be in frequency band of detectors' maximum sensitivity 100Hz-1kHz;
2. The signals which were received from different detectors simultaneously should be handled by spectral-correlational methods for comparative analysis;
3. The key criterion of GW registration is a statistically significant relationship between the results of the comparative analysis.

The first condition leads to reducing the number of important potential GW sources available for registration, because the sources with greatest magnitudes of GW such as mergers of intermediate black holes with masses $(10^2 - 10^4)M_{Sun}$ and supermassive black holes with masses $(10^5 - 10^7)M_{Sun}$ have the GW frequencies $(10^{-2}–1)$Hz and $(10^{-5}–10^{-3})$Hz, respectively.

An efficiency of spectral-correlational methods at comparative analysis under the stipulation that the unstable useful signal has a slight excess above the noise is connected with a need of analysis on long time periods (day, week even month and year). Therefore, these methods are suitable for siren-like sources (pulsars, binary systems far off merge), but not for the flashes (mergers of binary systems, collapses). Application of traditional methods of time-frequency analysis which are based on the power estimations to flashes is problematic because useful signal's excess above the background can be observed only on two-three periods of GW.

Comparison of signals of similar detectors at the stage of primary exceedances of the useful signal above the background is problematic too because the detectors' dynamic characteristics on the level of noise are not quite similar.

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 [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 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 09:24:25GMT). 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. Thus we had possible to analyze the real signals of LIGO detectors after standard prehandling.

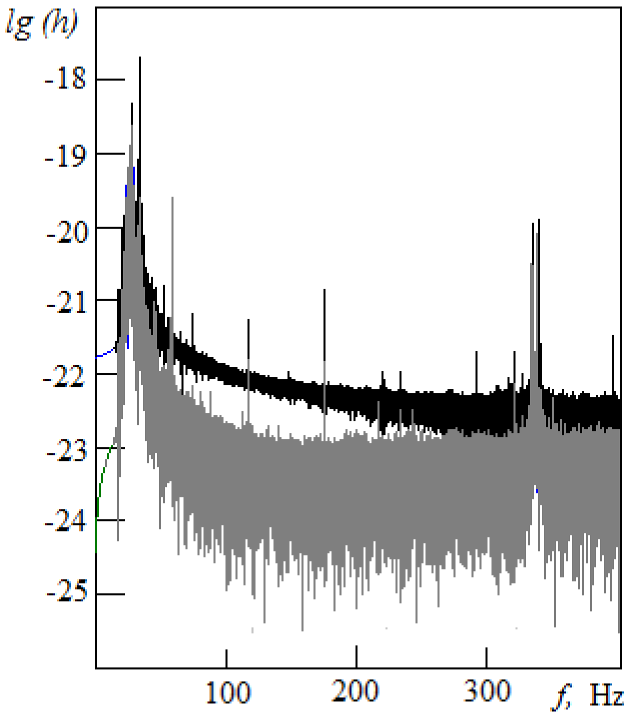

Fig.2. Spectrums of signals H2-STRAIN_4096Hz-815045078-256 (black) и L1-STRAIN_4096Hz-815045078-256 (gray).

We had compared the two signals obtained with different LIGO detectors which were handled by similar modes of digitization and filtering: H2-STRAIN_4096Hz-815045078-

256 and L1-STRAIN_4096Hz-815045078-256. Figure 2 presents the spectrums of the signals received during all time of observing (256s). Signals' spectrums correspond to the spectrum of seismic noise which contains the dominant harmonic with frequency about 30Hz and with random amplitude.

In the frequency band of greatest sensitivity (100-200 Hz) the largest difference between spectrums there is. The spectrum of detector L1 is close to integrated target characteristic of the noise (fig. 1) with a local minimum in the band of greatest sensitivity, where spectrum is formed by the suspension's thermal noise. In the spectrum of detector H2 the suspension's thermal noise is suppressed by dominant harmonic of seismic noise. That is connected not only with greater amplitude of the harmonic, but with lesser Q-factor (quality factor) of seismic noise for the detector H2.

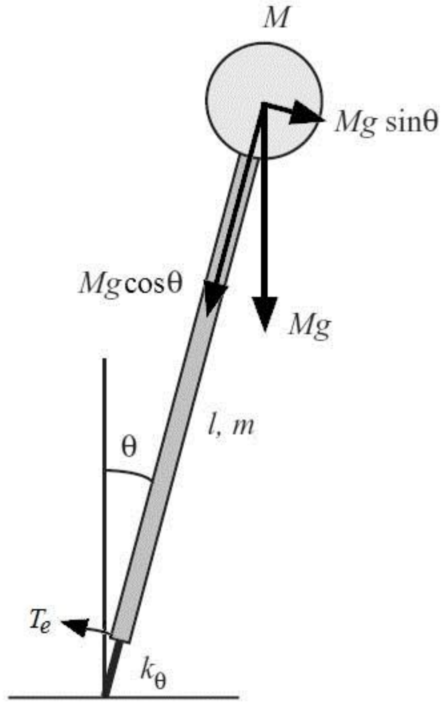

Fig.3. Dynamic scheme of the invert pendulum: k_θ – torsion rigidity of absorbers; T_e - elastic moment; M,m,l – lumped mass, distributed mass and length of pendulum respectively.

Source of the LIGO detectors' seismic noise at frequency ≈ 30 Hz is the multistage suspension of test masses (mirrors) under an influence of random seismic movements (grounds, atmosphere, ocean, industrial activity and other) [4]. Mirrors are suspended on the frame using steel wire. The frame is mounted on elastic shock absorbers. The dynamic scheme of the frame on the elastic shock absorbers can be presented as invert pendulum (Figure 3). Q-factor of the pendulum can be written as

$$Q=l^2(k_{eff}/k_\theta)Q_{int}, \qquad (1)$$

where $k_{eff} = (k_\theta /l^2) - (m/2 + M)g/l$ – effective rigidity of pendulum taking into account the gravitational force; Q_{int} – intrinsic pendulums' Q-factor which are determined by damping properties of absorbers and environment's damping influence [8].

The equation (1) shows that the Q-factors of the same type pendulums which have the different locations can be different, because the local values of the gravitational acceleration can be different too. In addition, the elastic-dissipative properties of structurally similar shock absorbers can be various and unstable. The first registration of useful signal at the level of the utmost sensitivity can be achieved on detector with the least level of noise therefore the statistical and dynamical criteria of a registration's verification which are based on a large number of theoretical works [9,10,11,12,13] aimed at establishing the GW forms take on special significance.

In papers [14,15] we have shown that the analysis of the signal L1-STRAIN_4096Hz-815045078-256 in the band of detector's greatest sensitivity 140-170 Hz the stationary random thermal noise was observed mainly. But the noise on relative long time intervals (~ 10s) was suppressed by seismic noise which had the main frequency ≈ 40 Hz. Taking into account the random magnitude of seismic noise on time intervals of ~ 10 c and remoteness of main frequency from range of the analysis the most likely cause of the suppression of thermal noise can be reducing of seismic noise's Q-factor. Spectrum of detector H2 (fig. 2) is evidence of the suppression of thermal noise in the band of greatest sensitivity due to the higher magnitude and smaller Q-factor of seismic noise in the detector.

In papers [14.15] a correlation between the suppression of L1 detector's thermal noise and short gamma-ray burst GRB 051103 [16] were recovered. The sequence and duration of suppression's time intervals correspond to the results of GW's modeling for the merge's process binary system (black holes) with total mass $6{\cdot}10^4$ M_{Sun} [12]. The part of received GW's waveform which is simultaneous with the gamma-ray burst is presented in fig. 4. The image can be considered as analogue of GW's magnitude (energy) in logarithmic scale. The GW has a steep leading edge such as in shock waves.

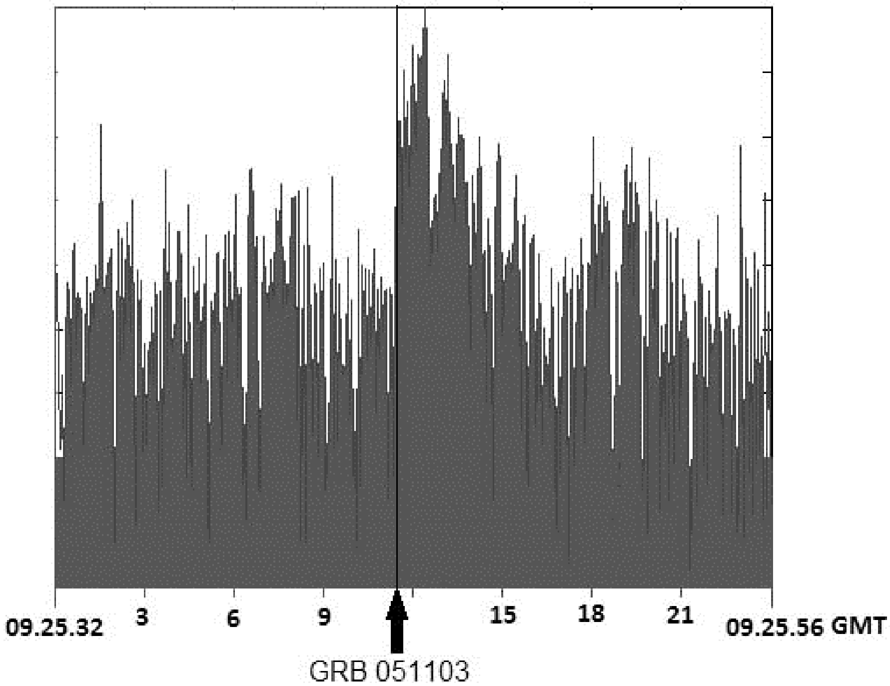

Fig.4. The image of GW's waveform. Time is in second on GMT scale.

In GTR the GW are considered as waves of space-time continuum [1.2]. The space-time of GTR is a magnificent mathematical model of gravitational field but space-time cannot be considered a physical substance for transmission of GW. The substance transmitting the GW is the space vacuum [17]. The equality speed of GW with speed of light (fig. 4) corresponds to a "quintessence" (a sort of dark matter) as the model of space vacuum [18]. As noted R. Cardwell in paper [19], "the vacuum is not rigid, but instead is susceptible to fluctuations driven by gravity". Therefore GW can be considered as the waves of pressure in accordance with state equation $p = w\rho$, where ρ is the density of vacuum energy; $w = -1$ for the standard quintessence model.

Analysis of the expression (1) shows that at the expected values of GW's magnitudes the effective stiffness and torsion stiffness of inverse pendulum remain constant and Q-factor can be changed only by changing the pendulum's intrinsic Q-factor (Q_{int}), which depends on the influence of an environment. The test masses of interferometers are constructively in high vacuum therefore the environment for mirrors in adopted model is the quintessence. The damping properties of quintessence will increase with increasing of vacuum energy under influence of GW in accordance with state equation. Then the Q-factor of seismic noise under influence of GW will decrease. The effect must appear primarily on the steep leading edge of shock waves from mergers of massive binary systems, as observed in the experiment.

Conclusion

The most perspective sources for detection of GW are mergers of black holes in binary systems with a total mass exceeding 10^4 M_{Sun} . The frequency of such events is less than 10^{-2}Hz that is outside the work frequency band of the existing ground-based interferometers (100-1000) Hz.

Change of the environment's properties under influence of GW can manifest itself in changing of the dynamic properties of the detectors. In particular, with the change of damping environment's properties as a result of changing the vacuum energy's density under action of GW the Q-factor of the detector's seismic noise can be changed too. Taking into account the combined nature of detectors' noise the registration of GW can be based on an analysis of the relationship between mechanical and thermal noise of the detectors. The low-frequency GW will manifest itself as low-frequency changes of dynamic properties of detectors.

For use of such approach the seismic noise of interferometer's sensor must has high initial Q-factor and the main frequency of seismic noise f_S must be many larger than the frequency of GW f_{GW} ($f_S >> f_{GW}$). In connection with these conditions the investigation of the high-level quality nanomechanical systems [20] to identify slow systematic changes Q-factor has interest.

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