بسم الله الرحمن الرحيم

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كلية الدراسات العليا

Determining the Gravitational Waves by using Spectrum Analysis

تحديد الموجات التثاقلية باستخدام تحليل الطيف

A dissertation submitted in Partial fulfillment of the requirements for a M.Sc. degree in physics sciences

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الآية

قال تعالى:

بسم الله الرحمن الرحيم

﴿اللَّهُ نُورُ السَّمَاوَاتِ وَالْأَرْضِ ۚ مَثَلُ نُورِهِ كَمِشْكَاةٍ فِيهَا مِصْبَاحٌ ۖ الْمِصْبَاحُ فِي زُجَاجَةٍ ۖ الزُّجَاجَةُ كَأَنَّهَا كَوْكَبٌ دُرِّيٌّ يُوقَدُ مِنْ شَجَرَةٍ مُبَارَكَةٍ زَيْتُونَةٍ لَا شَرْقِيَّةٍ وَلَا غَرْبِيَّةٍ يَكَادُ زَيْتُهَا يُضِيءُ وَلَوْ لَمْ تَمْسَسْهُ نَارٌ ۚ نُورٌ عَلَىٰ نُورٍ ۗ يَهْدِي اللَّهُ لِنُورِهِ مَنْ يَشَاءُ ۚ وَيَضْرِبُ اللَّهُ الْأَمْثَالَ لِلنَّاسِ ۗ وَاللَّهُ بِكُلِّ شَيْءٍ عَلِيمٌ﴾

صدق الله العظيم

سورة النور،الآية (٣٥)

DEDICATION

I dedicate this Research to:

My Mom

My Dad

Brothers and sisters

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First of all I would like to thank ALMIGTY ALLAH for offering me endowment and helped me in completing this Work.

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ABSTRACT

The presence of gravitational waves (GW) has been a matter of argument for decades, ever since their presence was predicted by Einstein's general relativity theory (GR). And because every object in the path of such a wave feels a tidal gravitational force that acts perpendicular to the wave direction of propagation, that is why their presence were investigated in terms of the presence of a very tiny strain occur in objects in their path and that is via a some certain laser interferometer devices setup, e.g. in the USA an outstanding method of detecting these waves have been established, i.e. the Laser Interferometer Gravitational Waves Observatory (LIGO). In our dissertation we've collected strain data of the observation setup of gravitational waves events from the LIGO webpage and we reproduced interpretation of the presence of gravitational waves and that is via obtaining the dynamic spectrum plots for these GW events using time series data of the strain (h) where we obtained power spectrum in the frequency- time domain through discrete Fourier time series (D- FFT) on the data. We have viewed GW in our plots where peak amplitude occur at the time: 16.53 second. Therefore, detection of GW is expected to open up a new window for observational astronomy since information carried by GW are very different from those information carried by electromagnetic waves.

المستخلص

لقد كان وجود موجات الجاذبية (GW) مسألة غامضة لعقود وذلك منذ أن تم التنبؤ بوجودها بواسطة النظرية النسبية لأينشتاين (GR) ولأن كل جسم في مسار الموجات يشعر بوجود قوة جذب تعمل عمودياً على إتجاه إنتشار هذه الموجات. لهذا تم التحقق من وجودها بواسطة أجهزة قياس التداخل الليزري (LIGO) فعلى سبيل المثال في الولايات المتحدة الأمريكية تم إنشاء هذه الطريقة المتميزة للكشف عن موجات الجاذبية.

في هذا البحث قمنا بجمع بيانات لأحداث موجات الجاذبية المرصودة بطريقة (LIGO) وحاولنا التحقق من وجود موجات الجاذبية عن طريق الحصول على مخططات الطيف الديناميكي بإستخدام السلاسل الزمنية للانفعال (h) حيث تحصلنا على طيف القدرة في مجال التردد الزمني من خلال حساب متسلسلة فورير الزمنية (D-FFT).

ومن المتوقع أن يفتح الكشف عن موجات الجاذبية (GW) نافذة جديدة لعلم الفلك المبني على الملاحظة حيث نجد أن المعلومات التي تحملها موجات الجاذبية تختلف في طبيعتها عن تلك التي تحملها الموجات الكهرومغنطيسية.

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LIST OF ABBREVIATIONS AND NOTATIONS

GW Gravitational waves.

L I G O Laser interferometer gravitational-wave observatory.

SP Special relativity.

GR General relativity.

LISA Laser interferometer space antenna.

VIRGO An Italian Michelson interferometer named after the Virgo cluster.

$\boldsymbol{M_{\odot}}$ Current mass of the sun.

CHAPTER I
INTRODUCTION

1.1. Preface

Gravitational waves (GW) have been a matter of obscurity for scientists for some time ago, although Einstein was postulated their existence since 1916, that is as a consequence of his famous theory of general relativity (GR).

Gravitational waves are emitted by coherent bulk motions of matter and coherent oscillations of space time curvature, they ripples in curvature of the space time, and spread on waves forms.

Detection of gravitational waves is important for two reasons: First, their detection is expected to open up a new window for observational astronomy, since information carried by gravitational waves are very different from those carried by electromagnetic waves; Second, detecting gravitational waves is important for our understanding of the fundamental laws of physics; the proof that gravitational waves exist will verify a fundamental 85-year-old prediction of general relativity. Also, Einstein's prediction that gravitational waves travel with same speed of light, could be checked and that is by comparing the arrival time of a gravitational wave from a source like supernovae and electromagnetic waves. Finally, if detected we could verify that these gravitational waves have the polarization predicted by general relativity.

1.2. Objectives of research

The aim of the current work is to review methods of detecting gravitational waves via some new found system setup techniques, i.e. the Laser interferometer gravitational-wave observatory (LIGO) method and the Italian Michelson interferometer named after the Virgo cluster (VIRGO) method, accordingly, we specified the following objectives:

I. To carry out a spectral analysis method on LIGO data in order to view some unconfirmed gravitational waves (GW) events.

II. To carry out a comparison between viewing results of the spectral analysis method carried out on data from VIRGO and the obtained viewing results from data of LIGO.

1.3. Research methodology

Since the main task of this dissertation is to review how to detect gravity waves and show evidences of their existence and based on a theoretical background we analyzed observational data, which were collected from the famous experiment setup of LIGO. Data represents a time series strain (h) that may reflect the passage of a gravity wave. The first step on the analysis is to collect some events from the LIGO but the presence of the gravity wave in these events were not confirmed and visualized yet in the website or in some other study, so we obtained the dynamic spectrum graphs using a MATLAB code dedicated for that purpose which is to visualize the gravity waves events.

1.4. Statement of research Problem

The theory of GR has explained many phenomena in nature; and with the great success of this theory it left many of its predictions to be questioned for evidences and proofs. One of the outstanding predictions of this general relativity theory is: gravitational waves. The existence of these waves has been a matter of debates for some long time ago. Hence, the question of how to detect gravitational waves remains a task that addressed many researches work. In this work we focused on showing the significance of some existing methods of detecting these GW.

However, detection of gravitational waves is expected to open up a new window for observational astronomy since information carried by gravitational waves are very different from those carried by electromagnetic waves. Moreover, detecting gravitational waves is important for our understanding of the fundamental laws of physics, i.e. the GR laws.

1.5. Outline of the dissertation

We organized the dissertation into four chapters. Chapter one is dedicated to introduction, and a theoretical background on gravitational waves is presented in some details in chapter two. In chapter three we present device LIGO and methodology. Finally, we presented plotting results, discussion and conclusion and final remarks in the last chapter, i.e. chapter four.

CHAPTER II

BACKGROUND: GRAVITATIONAL WAVES

2.1. General relativity and gravitational waves

Special relativity (SP) is a theory appertain to study effects of uniformed motion on both space and time, therefore there are two main rules that SP suggests: first, that all physical laws in nature are same for all frame of references; and second, that the speed of light remains constant in all references, regardless of the motion of source of light or the observer. On the other hand, the general relativity (GR) theory is dedicated to study the description of space-time curvature.

In the theory of GR the information of the varying gravitational field propagates with finite speed, the speed of light, as a ripple in the fabric of space-time. The existence of gravitational waves is an immediate consequence of any relativistic theory of gravity. However, the strength and the form of the waves depend on the details of the gravitational theory. This means that the detection of gravitational waves in the future will also serve as a test of basics of such a gravitational relativistic theory (Kokkotas ، 2002).

The fundamental geometrical framework of relativistic metric theories of gravity is space-time, which mathematically can be described as a four-dimensional manifold whose points are called events. "The choice of the coordinate system is quite arbitrary and coordinate transformations of the form $\tilde{x}^{\mu} = f^{\mu}(x^{\lambda})$ are allowed.

In GR the motion of a test particle is described by a curve in space-time. The distance ds between any two neighboring events, one with coordinates x^{μ} and the other with coordinates $x^{\mu} + dx^{\mu}$, can be expressed as a function of the coordinates via a symmetric tensor, called metric, i.e. $g_{\mu\nu}(x^{\lambda}) = g_{\nu\mu}(x^{\lambda})$, such that this curvature is given by (K.S.Thorne & S.W.Hawking ،1996) :

$$ds^2 = g_{\mu\nu} dx^{\mu} dx^{\nu} \tag{2.1}$$

In the following text, we will consider mass distributions, which we will describe by the stress-energy tensor, i.e. $T^{\mu\nu}(x^{\lambda})$. For a perfect fluid (a fluid or gas with isotropic pressure but without viscosity or shear stresses) the stress-energy tensor is given by the following expression:

$$T^{\mu v}(x^{\lambda}) = (\rho + p)u^{\mu}u^{v} + pg^{\mu v} \quad (2.2)$$

Where $p(x^{\lambda})$ is the local pressure, $\rho\ (x^{\lambda})$ is the local energy density and $u^{\mu}(x^{\lambda})$ is the four velocity of the infinitesimal fluid element characterized by the event x^{λ} (Kokkotas, 2002).

"Einstein's gravitational field equations connect the curvature tensor and the stress-energy tensor through the fundamental relation:

$$G_{\mu v} \equiv R_{\mu v} - \frac{1}{2}\, g_{\mu v}\, R = kT_{\mu v} \quad (2.3)$$

Where, $R_{\mu v}$ is the so- called Ricci tensor and comes from a contraction of the Riemann tensor ($R_{\mu v} = g^{\alpha\sigma}R_{\sigma\mu\rho v}$), R is the scalar curvature ($R = g^{\rho\sigma}R_{\rho\sigma}$), while $G_{\mu v}$ is the so-called Einstein's tensor, $k = 8\pi G/c^4$ is the coupling constant of the theory, which, unless otherwise stated will be considered equal to1, and G is the gravitational constant. This means that the gravitational field, which is directly connected to the geometry of space-time, is related to the distribution of matter and radiation in the universe.

By solving the field equations, both the gravitational field (the $g_{\mu v}$) and the motion of matter is determined. The vanishing of the Ricci tensor corresponds to a space-time free of any matter distribution. However, this does not imply that the Riemann tensor is zero. As a consequence, in the empty space far from any matter distribution, the Ricci tensor will vanish while the Riemann tensor can be nonzero; this means that the effects of a propagating gravitational wave in an empty space-time will be described via the Riemann tensor" (Kokkotas, 2002).

2.2. Energy flux carried by gravitational waves

These Gravitational waves carry energy (Instead of Einstein's theory: $E = m.c^2$) and cause a deformation of space-time. The stress-energy carried by gravitational waves cannot be localized within a wavelength. Instead, one can say that a certain amount of stress-energy is contained in a region of the space which extends over several wavelengths. "It can be proven that in the transverse–traceless (TT) gauge of linearized theory the stress-energy tensor of a gravitational wave (in analogy with the stress-energy tensor of a perfect fluid that we have defined) is given by (J-P.Lasota & J-A.Marck, 1997):

$$\mathrm{t}_{\mu\nu}^{\mathrm{Gw}} = \frac{1}{32\pi}\langle(\partial_\mu h_{ij}^{TT})(\partial_\nu h_{ij}^{TT})\rangle \tag{2.4}$$

Where the angular brackets are used to indicate averaging over several wavelengths.

For the special case of a plane wave propagating in the z direction, the stress-energy tensor has only three non-zero components, which take the simple form:

$$\mathrm{t}_{00}^{\mathrm{GW}} = \frac{t_{zz}^{GW}}{C^2} = -\frac{t_{0z}^{GW}}{c} = \frac{1}{32\pi}\frac{c^2}{G}w^2(h_+^2 + h_\mathrm{x}^2) \tag{2.5}$$

Where $\mathrm{t}_{00}^{\mathrm{GW}}$ is the energy density, t_{zz}^{GW} is the momentum flux and t_{0z}^{GW} the energy flow along the z direction per unit area and unit time (for practical reasons we have restored the normal units). The energy flux has all the properties one would anticipate by analogy with electromagnetic waves: (a) it is conserved (the amplitude dies out as: $1/r$, the flux as $1/r^2$), (b) it can be absorbed by detectors, and (c) it can generate curvature like any other energy source in Einstein's formulation of relativity. As an example, by using the above relation, we can estimate the energy flux in gravitational waves from the collapse of the core of a supernova (10 $M_\odot$), to create a black hole at a distance of 50-million-light-years ($\sim 15 Mpc$) from the earth (at the distance of the Virgo cluster of galaxies).

Accordingly, conservative estimate of the amplitude of the waves on earth is of the order of 10^{-22} (at a frequency of about 1kHz), this corresponds to a flux of about $3\ ergs/cm^2$ sec and it is an enormous amount of energy flux and is about ten orders of magnitude larger than the observed energy flux in electromagnetic waves the basic difference is the duration of the two signals; gravitational wave signal will last a few milliseconds, whereas an electromagnetic signal lasts many days. This example provides us with a useful numerical formula for the energy flux:

$$F = 3\left(\frac{f}{1kH_Z}\right)^2\left(\frac{h}{10^{-22}}\right)^2\frac{ergs}{cm^2 sec} \tag{2.6}$$

From which one can easily estimate the flux on earth, given the amplitude (on earth) and the frequency of the waves" (Kokkotas, 2002), (Saulson, 1994).

2.3. Generation of gravitational waves

Understanding the generation of gravitational waves could be grasped directly if the nature of gravitational radiation is confirmed and that is in correspondence to electromagnetic radiation, therefore, the production of electromagnetic radiation is done by slowly varying charge distribution which can be decomposed into a series of multi poles, where the amplitude of the $2^{\ell} pole$ ($\ell = 0, 1, 2, \ldots$) contains a small factor 2^{ℓ}, with equal ratio to the diameter of the source to the typical wavelength, namely, a number typically much smaller than1. From this point of view the strongest electromagnetic radiation would be expected for monopole radiation (ℓ = 0), but this is completely absent, because the electromagnetic monopole moment is proportional to the total charge, which does not change with time (it is a conserved quantity) (Saulson, 1994).

Therefore, electromagnetic radiation consists only of $\ell \geq 1$ multipoles, the strongest being the electric dipole radiation (ℓ = 1), followed by the weaker magnetic dipole and electric quadruple radiation (ℓ = 2). One could proceed with a similar analysis for gravitational waves and by following the same arguments showing that mass conservation (which is equivalent to charge conservation in electromagnetic theory) will exclude monopole radiation. Also, the rate of change of the mass dipole moment is proportional to the linear momentum of the system, which is a conserved quantity, and therefore there cannot be any mass dipole radiation in Einstein's relativity theory.

The next strongest form of electromagnetic radiation is the magnetic dipole. For the case of gravity, the change of the magnetic dipole is proportional to the angular momentum of the system, which is also a conserved quantity and thus there is no dipolar gravitational radiation of any sort. It follows that gravitational radiation is of quadruple or higher nature and is directly linked to the quadruple moment of the mass distribution (K.S.Thorne & S.W.Hawking, 1996).

Einstein derived the quadruple formula for gravitational radiation. This formula states that the wave amplitude h_{ij} is proportional to the second time derivative of the quadruple moment of the source:

$$h_{ij} = \frac{2}{r} \; \frac{G}{C^4} \ddot{Q}_{ij}^{TT} \left(t - \frac{r}{c} \right) \tag{2.7}$$

Where

$$Q_{ij}^{TT}(x) = \int \rho \left(x^i x^j - \frac{1}{3} \delta^{ij} r^2 \right) d^3 x \tag{2.8}$$

Is the quadruple moment in the TT gauge, evaluated at the retarded time $t - r/c$ and ρ is the matter density in a volume element d^3x at the positionx^i. This result is quite accurate for all sources, as long as the reduced wavelength $\tilde{\lambda} = \lambda/2\pi$ is much longer than the source size R. Using the formulae (2.4) and (2.5) for the energy carried by gravitational waves, one can derive the luminosity in gravitational waves as a function of the third-order time derivative of the quadruple moment tensor. This is the quadruple formula:

$$L_{GW} = -\frac{dE}{dt} = \frac{1}{5}\frac{G}{C^5}\langle\frac{\partial^3 Q_{ij}}{\partial t^3}\ \frac{\partial^3 Q_{ij}}{\partial t^3}\rangle \quad (2.9)$$

Based on this formula, we derive some additional formulas, which provide order of magnitude estimates for the amplitude of the gravitational waves and the corresponding power output of a source. First, the quadruple moment of a system is approximately equal to the mass M of the part of the system that moves, times the square of the size R of the system. This means that the third-order time derivative of the quadruple moment is

$$\frac{\partial^3 Qij}{\partial t^3} \sim \frac{MR^2}{T^3} \sim \frac{Mv^2}{T} \sim \frac{E_{ns}}{T} \quad (2.10)$$

where v is the mean velocity of the moving parts, E_{ns} is the kinetic energy of the component of the source's internal motion which is non-spherical, and T is the time scale for a mass to move from one side of the system to the other. The time scale (or period) is actually proportional to the inverse of the square root of the mean density of the system

$$T \sim \sqrt{R^3/GM} \quad (2.11)$$

This relation provides a rough estimate of the characteristic frequency of the system $f = 2\pi/T$. Then, the luminosity of gravitational waves of a given source is approximately (J-P.Lasota & J-A.Marck, 1997).

$$L_{GW} \sim \frac{G}{C^5}\left(\frac{M}{R}\right)^5 \sim \frac{G}{C^5}\left(\frac{M}{R}\right)^2 v^6 \sim \frac{C^5}{G}\left(\frac{R_{sch}}{R}\right)^2 \left(\frac{v}{C}\right)^6 \quad (2.12)$$

Where $R_{sch} = 2GM/c^2$ is the Schwarzschild radius of the source; It is obvious that the maximum value of the luminosity in gravitational waves can be achieved if the source's dimensions are of the order of its Schwarzschild radius and the typical velocities of the components of the system are of the order of the speed of light. This explains why we expect the best gravitational wave sources to be highly relativistic compact objects. The above formula sets also an upper limit on the power emitted by a source, which for $R \sim R_{sch}$ and $v \sim c$ is

$$L_{GW} \sim C^5/G = 3.6 \times 10^{59} ergs/\ \sec \quad (2.13)$$

This is an immense power, often called the luminosity of the universe. Using the above order-of-magnitude estimates, we can get a rough estimate of the amplitude of gravitational waves at a distance r from the source (D.G.Blair, 1991):

$$h \sim \frac{G}{C^4}\frac{E_{ns}}{r} \sim \frac{G}{C^4}\frac{\varepsilon E_{kin}}{r} \tag{2.14}$$

Where: E_{kin} $(with\ 0 \leq \varepsilon \leq 1)$ is the fraction of kinetic energy of the source that is able to produce GW. The factor ε is a measure of the asymmetry of the source and implies that only a time varying quadruple moment will emit gravitational waves. For example, even if a huge amount of kinetic energy is involved in a given explosion or implosion, if the event takes place in a spherically symmetric manner, there will be no gravitational radiation (K.P & C.Cutler, 2002).

Another formula for the amplitude of gravitational waves relation can be derived from the flux formula (2.6). If, for example, we consider an event (perhaps a supernovae explosion) at the Virgo cluster during which the energy equivalent of $10^{-4} M_{\odot}$ is released in gravitational waves at a frequency of $1\ kHz$, and with signal duration of the order of $1\ msec$, the amplitude of the gravitational waves on Earth will be: (K.S.Thorne & S.W.Hawking, 1996)

$$\text{h} \approx 10^{-22}\left(\frac{E_{GW}}{10^{-4}M_{\odot}}\right)^{\frac{1}{2}}\left(\frac{f}{1kHz}\right)^{-1}\left(\frac{\tau}{1msec}\right)^{-\frac{1}{2}}\left(\frac{r}{15Mpc}\right)^{-1} \tag{2.15}$$

For a detector with arm length of $4\ km$ we are looking for changes in the arm length of the order of :

$$\Delta\ell = h \cdot \ell = 10^{-22} \cdot 4km = 4 \times 10^{-17}\ \text{cm}$$

These numbers shows why experimenters are trying so hard to build ultra-sensitive detectors and explains why all detection efforts failed for some time ago. Finally, it is useful to know the damping time, that is, the time it takes for a source to transform a fraction $1/e$ of its energy into gravitational radiation. One can obtain a rough estimate from the following formula (K.S.Thorne & S.W.Hawking, 1996).

$$\tau = \frac{E_{kin}}{L_{GW}} \sim \frac{1}{C}R\left(\frac{R}{R_{Sch}}\right)^{3} \tag{2.16}$$

2.4. Rotating binary system

Arguably sources of gravitational waves are binaries. These consisting of black holes or neutron stars, the most promising source for the gravitational wave detectors. Binary systems are also the sources of gravitational waves whose dynamics we understand the best. If we assume that the two bodies making up the binary lie in the $x - y$ plane and their orbits are circular then the only non-vanishing components of the quadruple tensor are:

$$Q_{xx} = -Q_{yy} = \frac{1}{2}\mu a^2 cos\ 2\Omega t, \quad and \quad Q_{xy} = Q_{yx} = \frac{1}{2}\mu a^2 sin\ 2\Omega t \qquad (2.17)$$

Where Ω is the orbital angular velocity, $\mu = M_1 M_2/M$ is the reduced mass of the System and $M = M_1 + M_2$ its total mass.

According to equation (2.6) the gravitational radiation luminosity of the system is

$$L^{GW} = \frac{32}{5}\frac{G}{C^5}\mu^2 a^4 \Omega^6 = \frac{32}{5}\frac{G^4}{C^5}\frac{M^3\mu^2}{a^5} \qquad (2.18)$$

Where, in order to obtain the last part of the relation, we have used Kepler's third law, $\Omega^2 = GM/a^3$. As the gravitating system loses energy by emitting radiation, the distance between the two bodies shrinks at a rate (C. Cutler, 2002)

$$\frac{da}{dt} = -\frac{64}{5}\frac{G^3}{C^5}\frac{\mu M^2}{a^3} \qquad (2.19)$$

And the orbital frequency increases accordingly($\dot{T}/T = 1.5\dot{a}/a$). If, for example, the present separation of the two stars is a_0, then the binary system will mix after a time

$$\tau = \frac{5}{256}\frac{C^5}{G^3}\frac{a_0^4}{\mu M^4} \qquad (2.20)$$

Finally, the amplitude of the gravitational waves is:

$$h = 5 \times 10^{-22} \left(\frac{M}{2.8M_\odot}\right)^{2/3} \left(\frac{\mu}{0.7M_\odot}\right) \left(\frac{f}{100Hz}\right)^{2/3} \left(\frac{15Mpc}{r}\right) \qquad (2.21)$$

In all these formulae we have assumed that the orbits are circular. The orbits of the two bodies are approximately ellipses, but it has been shown that long before the coalescence of the two bodies, the orbits become circular, at least for long-lived binaries, due to gravitational radiation. Also, the amplitude of the emitted gravitational waves depends on the angle between the line of sight and the axis of angular momentum; formula (2.21) refers to an observer along the axis of the orbital angular momentum. The complete formula for the amplitude contains angular factors of order1. The relative strength of the two polarizations depends on that angle as well. If three or more detectors observe the same signal it is possible to reconstruct the full waveform and deduce many details of the orbit of the binary system (C.Cutler, 2002).

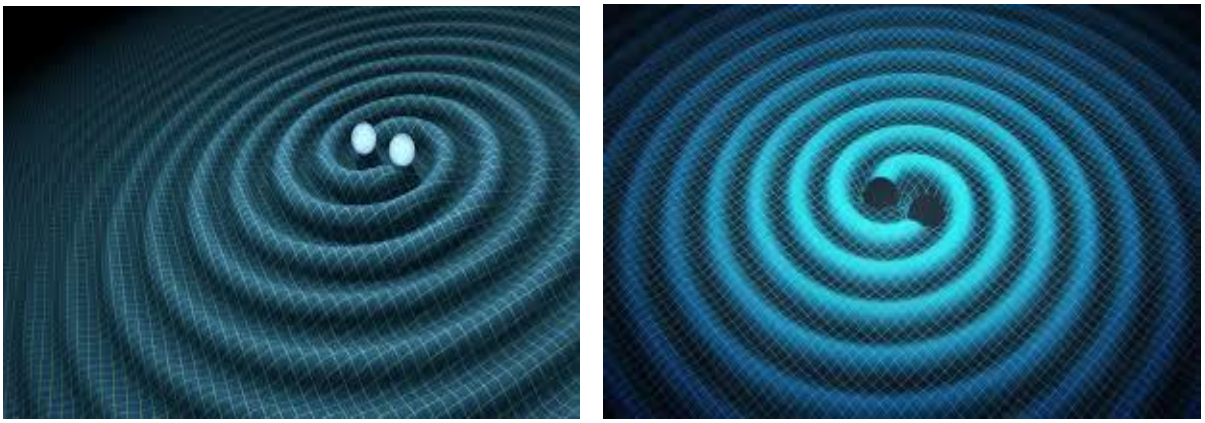

Figure (2-1): Explain the motion of Rotating binary system, (Stars, March 16, 2010).

2.5. Astronomical sources of gravitational waves

The new generation of gravitational wave detectors: Laser Interferometer Gravity-Wave Observatory (LIGO) and the Italian Michelson interferometer named after the Virgo cluster (VIRGO) have very good chances of detecting gravitational waves, we can only make educated guesses as to the possible astronomical sources of gravitational waves. The detectability of these sources depends on three parameters: their intrinsic gravitational wave luminosity, their event rate, and their distance from the Earth. The luminosity can be approximately estimated via the quadruple formula that we discussed earlier. Even though there are certain restrictions in its applicability (weak field, slow motion), it provides a very good order-of-magnitude estimate for the expected gravitational wave flux on Earth. The rate, at which various events with high luminosity in gravitational waves take place is extrapolated from astronomical observations in the electromagnetic spectrum. Still, there might be a number of gravitationally luminous sources, for example binary black holes, for which we have no direct observations in the electromagnetic spectrum. Finally, the amplitude of gravitational wave signals decreases as one over the distance to the source. Thus, a signal from a supernova explosion might be clearly detectable if the event takes place in our galaxy (2-3 events per century), but it is highly unlikely to be detected if the supernova explosion occurs at far greater distances, of order $100\ Mpc$, where the event rate is high and at least a few events per day take place. All three factors have to be taken into account when discussing sources of gravitational waves (J-P.Lasota & J-A.Marck, 1997), (K.S.Thorne & S.W.Hawking, 1996).

It was mentioned earlier that the frequency of gravitational waves is proportional to the square root of the mean density of the emitting system; this is approximately true for any gravitating system. For example, neutron stars usually have masses around $1.4M_{\odot}$ and radii in the order of 10 km; thus if we use these numbers in the relation $f \sim \sqrt{GM/R^3}$ we find that an oscillating neutron star will emit gravitational waves primarily at frequencies of $2-3\ kHz$. By analogy, a black-hole with a mass$\sim 100M_{\odot}$, will have a radius of ~ 300 km and the natural oscillation frequency will be$\sim 100\ Hz$. Finally, for a binary system Kepler's law provides a direct and accurate estimation of the frequency of the emitted gravitational waves. For two $1.4M_{\odot}$ neutron stars orbiting around each other at a distance of 160 Km, Kepler's law predicts an orbital frequency of 50 Hz, which leads to an observed gravitational wave frequency of $100\ Hz$ (K.D.KOKKOTAS, 2002).

2.6. Radiation from gravitational collapse

Type II supernovae are associated with the core collapse of a massive star together with a shock-driven expansion of a luminous shell which leaves behind a rapidly rotating neutron star or a black hole, if the core has mass of$>\ 2-3M_{\odot}$. The typical signal from such an explosion is broadband and peaked at around 1 kHz. Detection of such a signal was the goal of detector development over the last three decades.

However, we still know little about the efficiency with which this process produces gravitational waves. For example, an exactly spherical collapse will not produce any gravitational radiation at all. The key question is what is the kinetic energy of the non-spherical motions since the gravitational wave amplitude is proportional?

After 30 years of theoretical and numerical attempts to simulate gravitational collapse, there is still no great progress in understanding the efficiency of this process in producing gravitational waves. For a conservative estimate of the energy in non-spherical motions during the collapse, leads to events of an amplitude detectable in our galaxy, even by bar detectors. The next generation of laser interferometers would be able to detect such signals from Virgo cluster at a rate of a few events per month (K.D.KOKKOTAS, 2002).

The main source for deviations from spherical or axial symmetry during the collapse is the angular momentum. During the contraction phase, the angular momentum is conserved, and the star spins up to rotational periods of the order of 1 msec. In this case, consequent processes with large luminosity might take place in this newly born neutron star. A number of instabilities, such as the so-called bar mode instability and the r-mode instability, may occur which radiate copious amounts of gravitational radiation immediately after the initial burst. Gravitational wave signals from these rotationally induced stellar instabilities are detectable from sources in our galaxy and are marginally detectable if the event takes place in the nearby cluster of about 2500 galaxies, the Virgo cluster, $15\ Mpc$ away from the Earth. Additionally, there will be weaker but extremely useful signals due to subsequent oscillations of the neutron star; f, p and w modes are some of the main patterns of oscillations (normal modes) of the neutron star that observers might search for these modes have been studied in detail and once detected in the signal, they would provide a sensitive probe of the neutron star structure and its supra nuclear equation of state. Detectors with high sensitivity in the kHz band will be needed in order to fully develop this so-called gravitational wave aster seismology.

If the collapsing central core is unable to drive off its surrounding envelope, then the collapse continues and finally a black hole forms. In this case the instabilities and oscillations that we discussed above are absent and the newly formed black hole radiates away, within a few milliseconds, any deviations from axisymmetric and ends up as a rotating or Kerr black hole. The characteristic oscillations of black holes (normal modes) are well studied, and this unique ringing down of a black hole could be used as a direct probe of their existence. The frequency of the signal is inversely proportional to the black hole mass. For example, it has been stated earlier that a $100M_{\odot}$ black hole will oscillate at a frequency of $\sim 100\ Hz$ (an ideal source for LIGO), while a supermassive one with mass $10^7 M_{\odot}$, which might be excited by an in falling star, will ring down at a frequency of $10^{-3}\ Hz$ (an ideal source for Laser Interferometer Space Antenna (LISA)). The analysis of such a signal should reveal directly the two parameters that characterize any (uncharged) black hole; namely its mass and angular momentum (K.D.KOKKOTAS, 2002).

2.7. Radiation from binary systems

Binary systems are the best sources of gravitational waves because they emit copious amounts or gravitational radiation, and for a given system we know exactly what is the amplitude and frequency of the gravitational waves in terms of the masses of the two bodies and their separation. If a binary system emits detectable gravitational radiation in the bandwidth of our detectors, we can easily identify the parameters of the system. According, the observed frequency change will be

$$\dot{f} \sim f^{11/3} M^{5/3} \tag{2.22}$$

and the corresponding amplitude will be

$$h \sim \frac{M^{5/3} f^{2/3}}{r} = \frac{\dot{f}}{r f^3} \tag{2.23}$$

Where $M^{5/3} = \mu M^{2/3}$ is a combination of the total and reduced mass of the system, called chirp mass. Since both frequency f and its rate of change $\dot{f}$ are measurable quantities, we can immediately compute the chirp mass (from the first relation), thus obtaining a measure of the masses involved. The second relation provides a direct estimate of the distance of the source. These relations have been derived using the Newtonian theory to describe the orbit of the system and the quadruple formula for the emission of gravitational waves. Post-Newtonian theory inclusion of the most important relativistic corrections in the description of the orbit can provide more accurate estimates of the individual masses of the components of the binary system.

When analyzing the data of periodic signals the effective amplitude is not the amplitude of the signal alone but $h_c = \sqrt{n}\,.h$, where n is the number of cycles of the signal within the frequency range where the detector is sensitive. A system consisting of two typical neutron stars will be detectable by LIGO when the frequency of the gravitational waves is $\sim 10Hz$ until the final coalescence around 1000Hz. This process will last for about 15 min and the total number of observed cycles will be of the order of 10^4, which leads to an enhancement of the detectability by a factor 100. Binary neutron star systems and binary black hole systems with masses of the order of $50M_{\odot}$are the primary sources for LIGO. Given the anticipated sensitivity of LIGO, binary black hole systems are the most promising sources and could be detected as far as 200 Mpc away. The event rate with the present estimated sensitivity of LIGO is probably a few events per year, but future improvement of detector sensitivity (the LIGO II phase) could lead to the detection of at least one event per month. Supermassive black hole systems of a few million solar masses are the primary source for LISA (J-P.Lasota & J-A.Marck, 1997).

These binary systems are rare, but due to the huge amount of energy released, they should be detectable from as far as the boundaries of the observable universe (K.D.KOKKOTAS, 2002).

2.8. Radiation from spinning neutron stars

A perfectly axisymmetric rotating body does not emit any gravitational radiation. Neutron stars are axisymmetric configurations, but small deviations cannot be ruled out. Irregularities in the crust (perhaps imprinted at the time of crust formation), strains that have built up as the stars have spun down, off-axis magnetic fields, and/or accretion could distort the axisymmetric. A bump that might be created at the surface of a neutron star spinning with frequency f will produce gravitational waves at a frequency of $2f$ and such a neutron star will be a weak but continuous and almost monochromatic source of gravitational waves. The radiated energy comes at the expense of the rotational energy of the star, which leads to a spin down of the star.

If gravitational wave emission contributes considerably to the observed spin down of pulsars, then we can estimate the amount of the emitted energy. The corresponding amplitude of gravitational waves from nearby pulsars (a few kpc away) is of the order of $h \sim 10^{-25} - 10^{-26}$, which is extremely small. If we accumulate data for sufficiently long time, e.g., 1 month, then the effective amplitude, which increases as the square root of the number of cycles, could easily go up to the order of $h_c \sim 10^{-22}$. We must admit that at present we are extremely ignorant of the degree of asymmetry in rotating neutron stars, and these estimates are probably very optimistic. On the other hand, if we do not observe gravitational radiation from a given pulsar we can place a constraint on the amount of non-asymmetry of the star (K.S.Thorne & S.W.Hawking, 1996).

2.9. Cosmological gravitational waves

One of the strongest pieces of evidence in favor of the Big Bang scenario is the (2.7) $°K$ cosmic microwave background radiation. This thermal radiation first bathed the universe around 380,000 years after the Big Bang. By contrast, the gravitational radiation background anticipated by theorists was produced at Planck times, i.e. at 10^{-32} sec or earlier after the Big Bang. Such gravitational waves have travelled almost unimpeded through the universe since they were generated. The observation of cosmological gravitational waves will be one of the most important contributions of gravitational wave astronomy. These primordial gravitational waves will be, in a sense, another source of noise for our detectors and so they will have to be much stronger than any other internal detector noise in order to be detected. Otherwise, confidence in detecting such primordial gravitational waves could be gained by using a system of two detectors and cross-correlating their outputs. The two LIGO detectors are well placed for such a correlation (K.S.Thorne & S.W.Hawking, 1996).

2.10. Properties of gravitational waves

The most prominence change that gravitational waves undergo as they propagate is the decrease in amplitude while they travel away from their source, and the redshift they feel (cosmological, gravitational or Doppler), as is the case for electromagnetic waves.

There are other effects that marginally influence the gravitational waveforms, for instance, absorption by interstellar or intergalactic matter intervening between the observer and the source, which is extremely weak (actually, the extremely weak coupling of gravitational waves with matter is the main reason that gravitational waves have not been observed). Scattering and dispersion of gravitational waves are also practically unimportant, although they may have been important during the early phases of the universe (this is also true for the absorption). Gravitational waves can be focused by strong gravitational fields and also can be diffracted, exactly as it happens with the electromagnetic waves (K.S.Thorne & S.W.Hawking, 1996).

There are also a number of “exotic” effects that gravitational waves can experience, that are due to the nonlinear nature of Einstein’s equations (purely general relativistic effects) properties mentioned above there is a correspondence with electromagnetic waves. Gravitational waves are fundamentally different, however, even though they share similar wave properties away from the source. Gravitational waves are emitted by coherent bulk motions of matter (for example, by the implosion of the core of a star during a supernova explosion) or by coherent oscillations of space-time curvature, and thus they serve as a probe of such phenomena. By contrast, cosmic electromagnetic waves are mainly the result of incoherent radiation by individual atoms or charged particles as a consequence, from the cosmic electromagnetic radiation. We mainly learn about the form of matter in various regions of the universe, especially about its temperature and density, or about the existence of magnetic fields. Strong gravitational waves, are emitted from regions of space time where gravity is very strong and the velocities of the bulk motions of matter are near the speed of light. Since most of the time these areas are either surrounded by thick layers of matter that absorb electromagnetic radiation or they do not emit any electromagnetic radiation at all (black holes), the only way to study these regions of the universe is via gravitational waves (Kokkotas, 2002), (D.G.Blair, 1991).

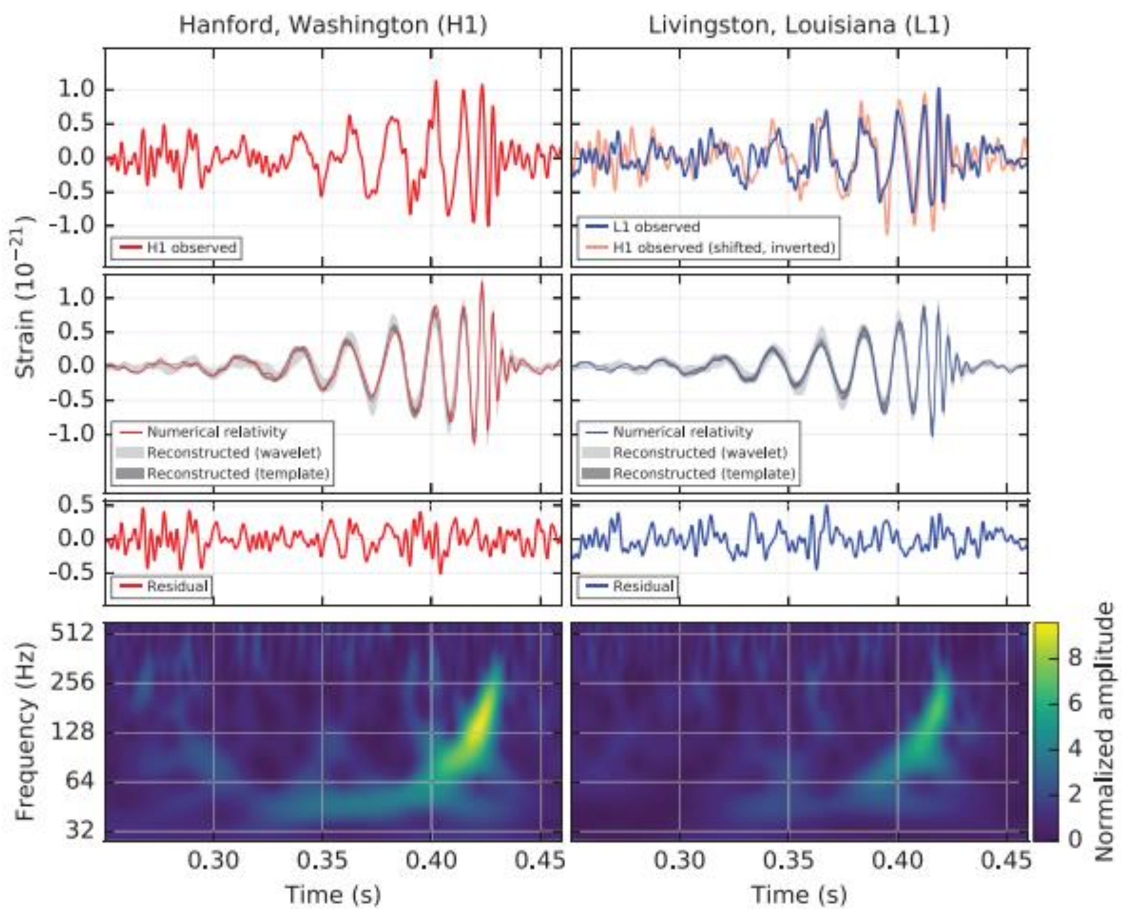

Figure (2-2): The gravitational-wave event GW150914 observed by the LIGO Hanford (H1, left column panels) and Livingston (L1, right column panels) detectors. Times are shown relative to September 14, 2015 at 09:50:45 UTC. For visualization, all-time series are filtered with a 35–350 Hz band pass filter to suppress large fluctuations outside the detectors' most sensitive frequency band, and band-reject filters to remove the strong instrumental spectral lines seen in the Fig. 3 spectra. Top row, left: H1 strain. Top row, right: L1 strain. GW150914 arrived first at L1 and $6.9^{+0.5}_{-0.4}$ ms later at H1; for a visual comparison, the H1 data are also shown, shifted in time by this amount and inverted (to account for the detectors' relative orientations). Second row: Gravitational-wave strain projected onto each detector in the 35–350 Hz band. Solid lines show a numerical relativity waveform for a system with parameters consistent with those recovered from GW150914 confirmed to 99.9% by an independent calculation carried out by another author. Shaded areas show 90% credible regions for two independent waveform reconstructions. One (dark gray) models the signal using binary black hole template waveform .The other (light gray) does not use an astrophysical model, but instead calculates the strain signal as a linear combination of sine-Gaussian wavelets. These reconstructions have a 94% overlap. Third row: Residuals after subtracting the filtered numerical relativity waveform from the filtered detector time series. Bottom row: A time-frequency representation of the strain data, showing the signal frequency increasing over time. (B.P.Abbott & R.Abbott, 2016) and the references there in.

CHAPTER III

DATA AND METHODOLOGY

3.1. The device LIGO

Before presenting the LIGO detector for gravitational waves we note that: Holes-Taylor mentioned the existence of gravitational waves, and they provide evidence through binary systems, accordingly, the received gravitational waves signal depend on the change in the shape of the detector LIGO, i.e. L shape. Anybody in the path of the wave will feel an oscillating tidal gravitational force that acts in a plane perpendicular to the wave's direction of propagation. This means that a group of freely moving masses, placed on a plane perpendicular to the direction of propagation of the wave, will oscillate as long as the wave passes through them, and the distance between them will vary as a function of time. Thus, the detection of gravitational waves can be accomplished by monitoring the tiny changes in the distance between freely moving test masses. these changes are extremely small; for example, when the Holes-Taylor binary system finally merges, the strong gravitational wave signal that will be emitted will induce changes in the distance of two particles on earth, that are ($1\ km$) apart much smaller than the diameter of the atomic nucleus. To measure such motions of macroscopic objects is a tremendous challenge for experimentalists; as early as the mid-1960s, Joseph Weber designed and constructed heavy metal bars, seismically isolated, to which a set of piezoelectric strain transducers were bonded in such a way that could detect vibrations of the bar if it had been excited by a gravitational wave. Today, there are a number of such apparatuses operating around the world which have achieved unprecedented sensitivities, but they still are not sensitive enough to detect gravitational waves. Another form of gravitational wave detector that is more promising uses laser beams to measure the distance between two well-separated masses. Such devices are basically kilometer sized laser interferometers consisting of three masses placed in an L-shaped configuration. The laser beams are reflected back and forth between the mirrors attached to the three masses, the mirrors lying several kilometers away from each other (D.G.Blair, 1991).

A gravitational wave passing by will cause the lengths of the two arms to oscillate with time and when one arm contracts, the other expands, and this pattern alternates. The result is that the interference pattern of the two laser beams changes with time. With this technique, higher sensitivities could be achieved than are possible with the bar detectors.

It is expected that laser interferometry detectors are the ones that will provide us with the first direct detection of gravitational waves. A pair of masses joined by a spring can be viewed as the simplest conceivable detector. In practice, a cylindrical massive metal bar or even a massive sphere is used instead of this simple system. When a gravitational wave hits such a device, it causes the bar to vibrate. By monitoring this vibration, we can reconstruct the true waveform. The next step, following the idea of resonant mass detectors, was the replacement of the spring by pendulums. In this new detector the motions induced by a passing-by gravitational wave would be detected by monitoring, via laser interferometry, the relative change in the distance of two freely suspended bodies (J-P.Lasota & J-A.Marck, 1997).

The use of interferometry is probably the most decisive step in our attempt to detect gravitational wave signals. In what follows, we will discuss both resonant bars and laser interferometry detectors. Although the basic principle of such detectors is very simple, the sensitivity of detectors is limited by various sources of noise. The internal noise of the detectors can be Gaussian or non-Gaussian. The non-Gaussian noise may occur several times per day such as strain releases in the suspension systems which isolate the detector from any environmental mechanical source of noise, and the only way to remove this type of noise is via comparisons of the data streams from various detectors. The so-called Gaussian noise obeys the probability distribution of Gaussian statistics and can be characterized by a spectral density$S_n(f)$. The observed signal at the output of a detector consists of the true gravitational wave strain h and Gaussian noise (K.P & C.Cutler, 2002).

The optimal method to detect a gravitational wave signal leads to the following signal-to-noise ratio (D.G.Blair, 1991).

$$\left(\frac{S}{N}\right)^2_{opt} = 2\int_0^\infty \frac{\left|\tilde{h}(f)\right|^2}{S_n(f)}df \qquad (3.1)$$

Where, $\tilde{h}(f)$ is the Fourier transform of the signal waveform; it is clear from this expression that the sensitivity of gravitational wave detectors is limited by noise (J-P.Lasota & J-A.Marck, 1997).

3. 2. Beam detectors

3.2.1. Laser interferometers

Idea these device work the relative change in the distance of two well-separated masses by monitoring their separation via a laser beam that continuously bounces back and forth between them; (This technique is actually used in searching for gravitational waves by using the so-called Doppler tracking technique, where a distant interplanetary spacecraft is monitored from earth through a microwave tracking link; the earth and spacecraft act as free particles) soon, it was realized that it is much easier to use laser light to measure relative changes in the lengths of two perpendicular arms. Gravitational waves that are propagating perpendicular to the plane of the interferometer will increase the length of one arm of the interferometer, and at the same time will shorten the other arm, and vice versa. This technique of monitoring the waves is based on Michelson interferometry. $\mathrm{L-shaped}$ Interferometers are particularly suited to the detection of gravitational waves due to their quadruple nature (Saulson, 1994).

Figure (3-1): Explain device LIGO (Laser Interferometer Gravitational Observatory). (Orwig, 10/03/2014)

Contain a schematic design of a Michelson interferometer; the three massesM_0, M_1 and M_2 are freely suspended. Note that the resonant frequencies of these pendulums should be much smaller than the frequencies of the waves that we are supposed to detect since the pendulums are supposed to behave like free masses (D.G.Blair, 1991).

Mirrors are attached to M_1 and M_2 and the mirror attached on mass M_0 splits the light (beam splitter) into two perpendicular directions. The light is reflected on the two corner mirrors and returns back to the beam splitter. The splitter now half transmits and half-reflects each one of the beams. One part of each beam goes back to the laser, while the other parts are combined to reach the photo detector where the fringe pattern is monitored. If a gravitational wave slightly changes the lengths of the two arms, the fringe pattern will change, and so by monitoring the changes of the fringe pattern one can measure the changes in the arm lengths and consequently monitor the incoming gravitational radiation (K.P & C.Cutler, 2002).

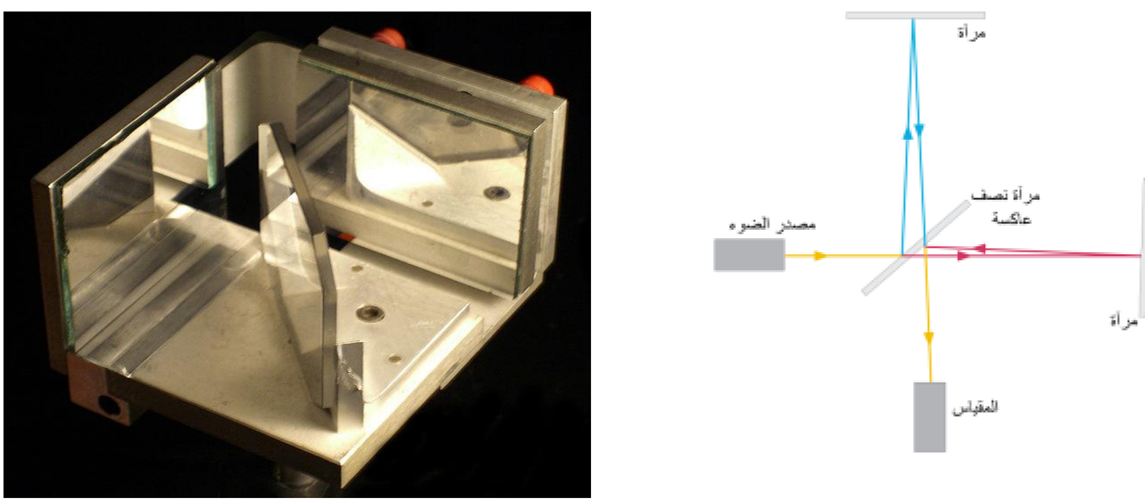

Figure (3-2): Explain Michelson device and its components (Leywon, 21 April 2017).

Consider an impinging gravitational wave with amplitude h and $(+)$ polarization, propagating perpendicular to the plane of the detector. We will further assume that the frequency is much higher than the resonant frequency of the pendulums and the wavelength is much longer than the arm length of our detector. Such a wave will generate a change of $\Delta L \sim hL/2$ in the arm length along the x- direction and an opposite change in the arm length along the y- direction. The total difference in length between the two arms will be:

$$\frac{\Delta L}{L} \sim h \tag{3.2}$$

And for a gravitational wave with amplitude $h \sim 10^{-21}$ and detector arm- length 4 km (such as LIGO), this will induce a change in the arm-length of about: $\Delta L \sim 10^{-16}$.

In the general case, when a gravitational wave with arbitrary polarization impinges on the detector from a random direction, the above formula will be modified by some angular coefficients of order 1 (D.G.Blair, 1991).

In practice, things are arranged so that when there is no actual change in the arms, all light that returns on the beam splitter from the corner mirrors is sent back into the laser, and only if there is some motion of the masses there is an output at the photo detector. If the light bounces a few times between the mirrors before it is collected in the photodiode, the effective arm length of the detector is increased considerably, and the measured variations of the arm lengths will be increased accordingly. This is a quite efficient procedure for making the arm length longer. For example, a gravitational wave at a frequency of 100 Hz has a wavelength of 3000 Km, and if we assume 100 bounces of the laser beam in the arms of the detector, the effective arm-length of the detector is 100 times larger than the actual arm-length, but still this is 10 times smaller than the wavelength of the incoming wave. The optical cavity that is created between the mirrors of the detector is known as a Fabry-Perot cavity and is used in modern interferometers.

In the remainder of this paragraph we will focus on the Gaussian sources of noise and their expected influence on the sensitivity of laser interferometers (K.P & C.Cutler, 2002).

A. Photon shot noise: When a gravitational wave produces a change ΔL in the arm-length, the phase difference between the two light beams changes by an amount $\Delta\phi = 2b\Delta L/\lambda\!\!\!^{-}$, where $\lambda\!\!\!^{-}$ is the reduced wavelength of the laser light ($\sim 10^{-8} cm$) and b is the number of bounces of the light in each arm. It is expected that a detectable gravitational wave will produce a phase shift of the order of 10^{-9}rad.

The precision of the measurements, though, is ultimately restricted by fluctuations in the fringe pattern due to fluctuations in the number of detected photons. The number of photons that reach the detector is proportional to the intensity of the laser beam and can be estimated via the relation $N = N_0 \sin^2(\Delta\phi/2)$, where N_0 is the number of photons that the laser supplies and N is the number of detected photons. Inversion of this equation leads to an estimation of the relative change of the arm lengths ΔL by measuring the number of the emerging photons N. However, there are statistical fluctuations in the population of photons, which are proportional to the square root of the number of photons. This implies an uncertainty in the measurement of the arm length:

$$\delta(\Delta L) \sim \frac{\tilde{\lambda}}{2b\sqrt{N_0}} \tag{3.3}$$

Thus, the minimum gravitational wave amplitude that we can measure is

$$h_{min} = \frac{\delta(\Delta L)}{L} = \frac{\Delta L}{L} \sim \frac{\tilde{\lambda}}{bLN_0^{1/2}} \sim \frac{1}{bL}\left(\frac{\hbar c\,\tilde{\lambda}}{\tau I_0}\right)^{1/2} \tag{3.4}$$

WhereI_0: the intensity of the laser light $(\sim 5 - 10\,W)$ and τ is the duration of the measurement. This limitation in the detector's sensitivity due to the photon counting uncertainty is known as photon shot noise. For a typical laser interferometer the photon shot noise is the dominant source of noise for frequencies above 200 Hz, while its power spectral density $S_n(f)$ for frequencies 100-200Hz is of the order of $\sim 3 \times 10^{-23}\sqrt{Hz}$ (C.Cutler, 2002).

B. Radiation pressure noise: According to formula (2.27), the sensitivity of a detector can be increased by increasing the intensity of the laser. However, a very powerful laser produces a large radiation pressure on the mirrors. Then an uncertainty in the measurement of the momentum deposited on the mirrors leads to a proportional uncertainty in the position of the mirrors or, equivalently, in the measured change in the arm-lengths. Then, the minimum detectable strain is limited by

$$h_{min} \sim \frac{\tau}{m}\frac{b}{L}\left(\frac{\tau\hbar I_0}{c\tilde{\lambda}}\right)^{1/2} \tag{3.5}$$

Where m is the mass of the mirrors.

As we have seen, the photon shot noise decreases as the laser power increases, while the inverse is true for the noise due to radiation pressure fluctuations. If we try to minimize these two types of noise with respect to the laser power, we get a minimum detectable strain for the optimal power via the very simple relation:

$$h_{\min} \sim \frac{1}{L}\left(\frac{\tau\hbar}{m}\right)^{1/2} \tag{3.6}$$

Which for the LIGO detector (where the mass of the mirrors is ≈100 kg and the arm length is 4 km), for observation time of (1) ms , gives $h_{\min} \approx 10^{-23}$.

C. Quantum limit. An additional source of uncertainty in the measurements is set by Heisenberg's principle, which says that the knowledge of the position and the momentum of a body is restricted from the relation$\Delta x \cdot \Delta p \geq \hbar$. For an observation that lasts some time τ, the smallest measurable displacement of a mirror of mass m isΔL; assuming that the momentum uncertainty is$\Delta p \approx m \cdot \Delta L/\tau$, we get a minimum detectable strain due to quantum uncertainties

$$h_{\min} = \frac{\Delta L}{L} \sim \frac{1}{L}\left(\frac{\tau\hbar}{m}\right)^{1/2} \tag{3.7}$$

Surprisingly, this is identical to the optimal limit that we calculated earlier for the other two types of noise. The standard quantum limit does set a fundamental limit on the sensitivity of beam detectors. An interesting feature of the quantum limit is that it depends only on a single parameter, the mass of the mirrors (K.S.Thorne & S.W.Hawking, 1996).

D. Seismic noise. At frequencies below 60 Hz, the noise in the interferometers is dominated by seismic noise. This noise is due to geological activity of the earth, and human sources, e.g., traffic and explosions. The vibrations of the ground couple to the mirrors via the wire suspensions which support them. This effect is strongly suppressed by properly designed suspension systems. Still, seismic noise is very difficult to eliminate at frequencies below 10^{-5} Hz (J-P.Lasota & J-A.Marck, 1997).

E. Residual gas-phase noise. The statistical fluctuations of the residual gas density induce a fluctuation of the refraction index and consequently of the monitored phase shift. Hence, the residual gas pressure through which the laser beams travel should be extremely low. For this reason the laser beams are enclosed in pipes over their entire length. Inside the pipes a high vacuum of the order of 10^{-9} Torr guarantees elimination of this type of noise.

Prototype laser interferometry detectors have been already constructed in the USA, Germany and UK. These detectors have an arm length of a few tens of meters and they have achieved sensitivities of the order of $h \sim 10^{-19}$.The construction of the new generation of laser interferometry detectors is near completion and some of them have already collected data. It is expected that will be in full operation (Saulson, 1994). The US project named LIGO consists of two detectors with arm length of 4 Km, one in Hanford, Washington, and one in Livingston, Louisiana.

The detector in Hanford includes, in the same vacuum system, a second detector with arm length of 2 km. The detectors are already in operation and they have recently achieved the designed sensitivity (D.G.Blair, 1991).

3.2.2. Space detectors

Both bars and laser interferometers are high-frequency detectors, but there are a number of interesting gravitational waves sources which emit signals at lower frequencies.

The seismic noise provides an insurmountable obstacle in any earth-based experiment and the only way to surpass this barrier is to fly a laser interferometer in space.

LISA will consist of three identical drag-free spacecraft's forming an equilateral triangle with one spacecrafts at each vertex. The distance between the two vertices (the arm length) is 5×10^6 km. The spacecrafts will be placed into the same heliocentric orbit as earth, but about 20^o behind earth. The equilateral triangle will be inclined at an angle of 60^o with respect to Earth's orbital plane. The three spacecraft would track each other optically by using laser beams. Because of the diffraction losses it is not feasible to reflect the beams back and forth as is done with LIGO. Instead, each spacecraft will have its own laser. The lasers will be phase locked to each other, achieving the same kind of phase coherence as LIGO does with mirrors. The configuration will function as three, partially independent and partially redundant, gravitational wave interferometers.

At frequencies$f \geq 10^{-3}$, LISA's noise is mainly due to photon shot noise. The sensitivity curve steepens at $f \sim 3 \times 10^{-2}\, Hz$ because at larger frequencies the gravitational waves period is shorter than the round-trip light travel time in each arm. For$f \leq 1 \times 10^{-2}\, Hz$, the noise is due to buffeting-induced random motions of the spacecraft, and cannot be removed by the drag- compensation system. LISA's sensitivity is roughly the same as that of LIGO, but at 10^5 times lower frequency.

Since th-e gravitational waves energy flux scales as $F \sim f^2 h^2$, this corresponds to 10^{10} times better energy sensitivity than LIGO (K.D.KOKKOTAS, 2002).

3.3. MATLAB

MATLAB is known as a multi-paradigm numerical computing environment and proprietary programming language developed by Math Works.

MATLAB allows matrix manipulations plotting of function and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages, including C, C++, C#, Java, Fortran and Python.

3.3.1. The MATLAB environment

The MATLAB environment (on most computer systems) consists of menus, buttons and a writing area similar to an ordinary word processor. There are plenty of help functions that you encouraged you to use it. The writing area that you will see when you start MATLAB, is called the command window. In this window you give the commands to MATLAB. For example, when you want to run a program you have written for MATLAB you start the program in the command window by typing its name at the prompt. The command window is also useful if you just want to use MATLAB as a scientific calculator or as a graphing tool. If you write longer programs, you will find it more convenient to write the program code in a separate window, and then run it in the command window.

3.3.2. Useful functions and operations in MATLAB

Using MATLAB as a calculator is easy: Example:

Compute 5 sin (2.53-pi) +1/75. In MATLAB this is done by simply typing

5*sin (2.5^ (3-pi)) +1/75

At the prompt. Be careful with parentheses and don't forget to type * whenever you multiply!

Note that MATLAB is case sensitive. This means that MATLAB knows a difference between letters written as lower and upper case letters. For example, MATLAB will understand sin (2) but will not understand Sin (2).

3.4. Fourier transform (FT)

The Fourier transform (FT) decomposes a function of time (a signal) into the frequencies that make it up, in a way similar to how a musical chord can be expressed as the frequencies (or pitches) of its constituent notes. The Fourier transform of a function of time is itself a complex-valued function of frequency, whose absolute value represents the amount of that frequency present in the original function, and whose complex argument is the phase offset of the basic sinusoid in that frequency.

The Fourier transform is important in mathematics, engineering, and the physical sciences. Its discrete counterpart, the Discrete Fourier Transform (DFT), which is normally computed using the so-called Fast Fourier Transform (FFT), has revolutionized modern society, as it is ubiquitous in digital electronics and signal processing. Radio astronomers are particularly avid users of Fourier transforms because Fourier transforms are key components in data processing (e. g, periodicity searches) and instruments (e.g, antennas, receivers, spectrometers), and they are the corner stores of interferometry and aperture synthesis.

3.5. The spectral analysis carried on

The analysis should be carried on is to calculate the normalized amplitude of the strain time series data on frequency- time domain and to plot results, a MATLAB code is written to achieve this. The algorithm is simple: read the data from a text file, calculate the power of the discrete fast Fourier on the time series data (D- FFT), and plot the result on frequency- time domain. For this we used the following MATLAB library main functions: dlmread, spectrogram, and surf. Here, is the code in two versions for two different frequencies:

1- The Code for GPS (1186741861) at (4096) Hz

```
sp=1;
%% Read data from a text file
N = dlmread('V-V1_LOSC_4_V2-1186741845-32.txt','\t',4);
JJJ=N;

%% Calculate the power of the discrete fast Fourier time
series data D- FFT on a frequency time domain
[P,F,T] = spectrogram(JJJ,1024,1/sp);

%% Plotting the normalized amplitude
surf(T/1000,F*10,10*log10(abs(P)),'EdgeColor','none')
axis xy;
axis tight;
colormap(jet);
shading flat;
view(0,90);
xlabel('Time');
ylabel('Frequency  (Hz)');
```

2- The Code for GPS (1186741861) at (16384) Hz

```
sp=1;
%% Read data from a text file
N = dlmread('V-V1_LOSC_16_V2-1186741845-32.txt','\t',4);
JJJ=N;*

%% Calculate the power of the discrete fast Fourier time
series data D- FFT on a frequency time domain
[P,F,T] = spectrogram(JJJ,1024,1/sp);

%% Plotting the normalized amplitude
surf(T/4000,F*10,10*log10(abs(P)),'EdgeColor','none')
axis xy;
axis tight;
colormap(jet);
shading flat;
view(0,90);
xlabel('Time');
ylabel('Frequency  (Hz)');
```

CHAPTER IV

RESULTS OF GW DETECTION METHOD, DISCUSSION AND CONCLUSIONS

4.1. Result of the dynamic spectrum plots

Here, we present results of the dynamic spectrum plots of strain data; note that all strain data used here after noise subtraction. The following figures show dynamic spectrum plots obtained from data collected on the date of: August, 14 2017, and collected from different devices. (M Vallisneri, 2014). The time series data of the strain were transformed using Fast Fourier Transforms and the spectral density of the data were obtained and plotted with frequency and time to get these dynamical spectrum plots, see next plots and captions of plots for more details.

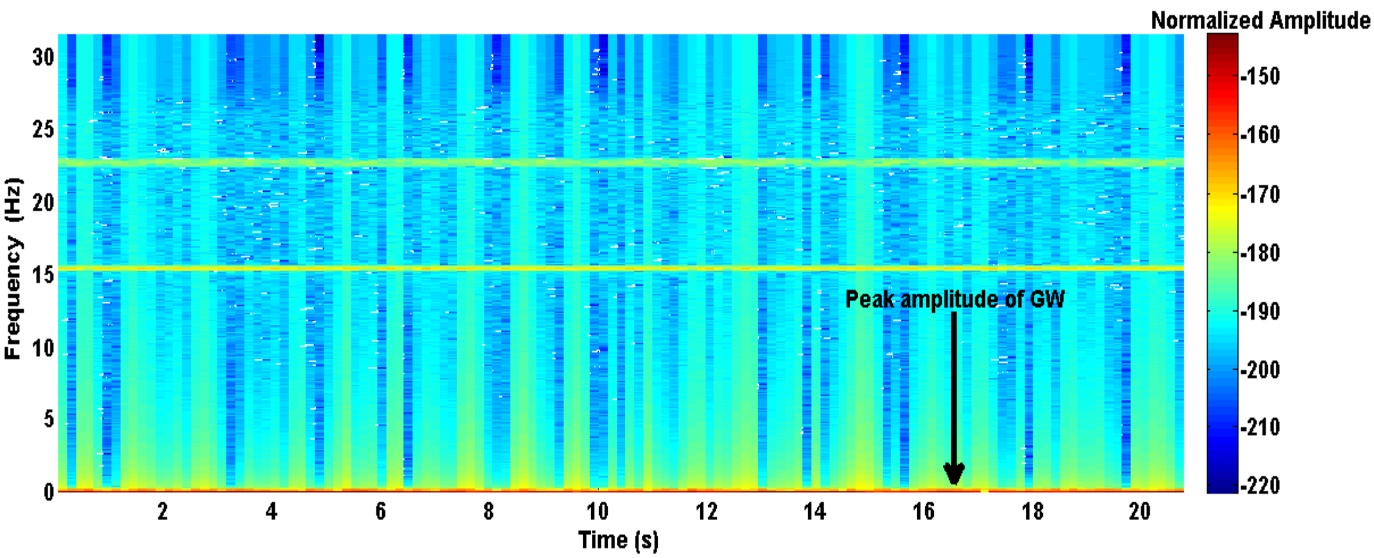

Figure (4-1): Show dynamic spectrum of data from the device on **Hanford** GPS (1186741861) at (4096) Hz at 32 second (event signal reaches peak amplitude 16.53 second ±30 msec from start, see the arrow position in the figure). (M Vallisneri, 2014)

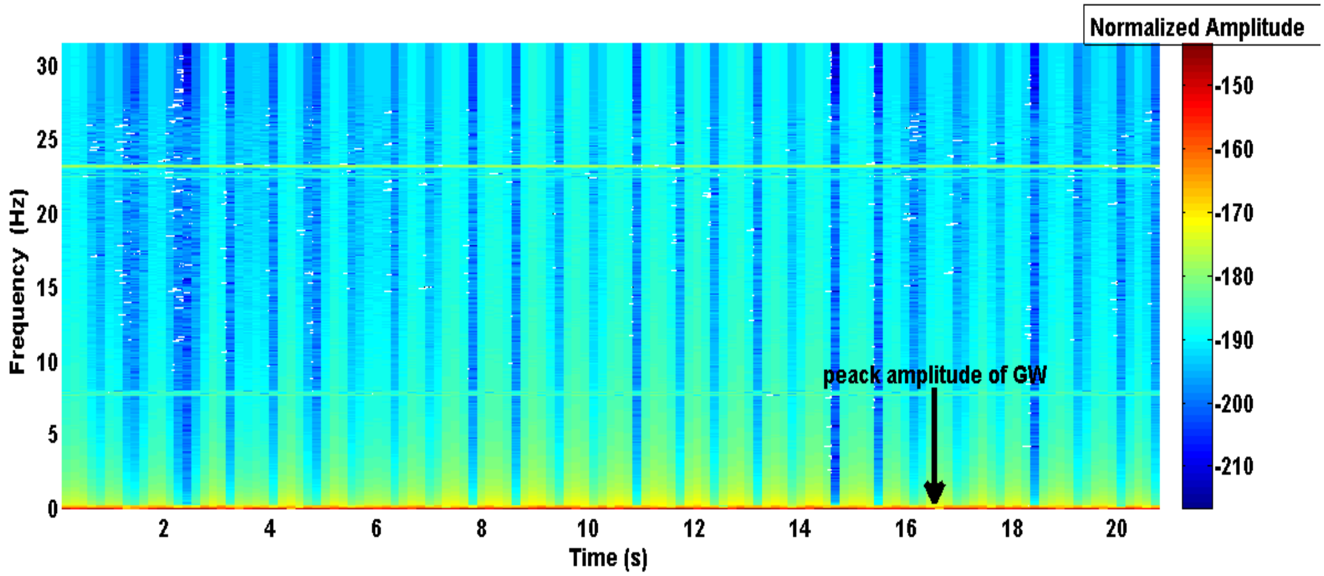

Figure (4-2): Show dynamic spectrum of data from the device on **Livingston** GPS (1186741861) at (4096) Hz at 32 second (event signal reaches peak amplitude 16.53 second ±30 msec from start, see the arrow position in the figure). (M Vallisneri, 2014)

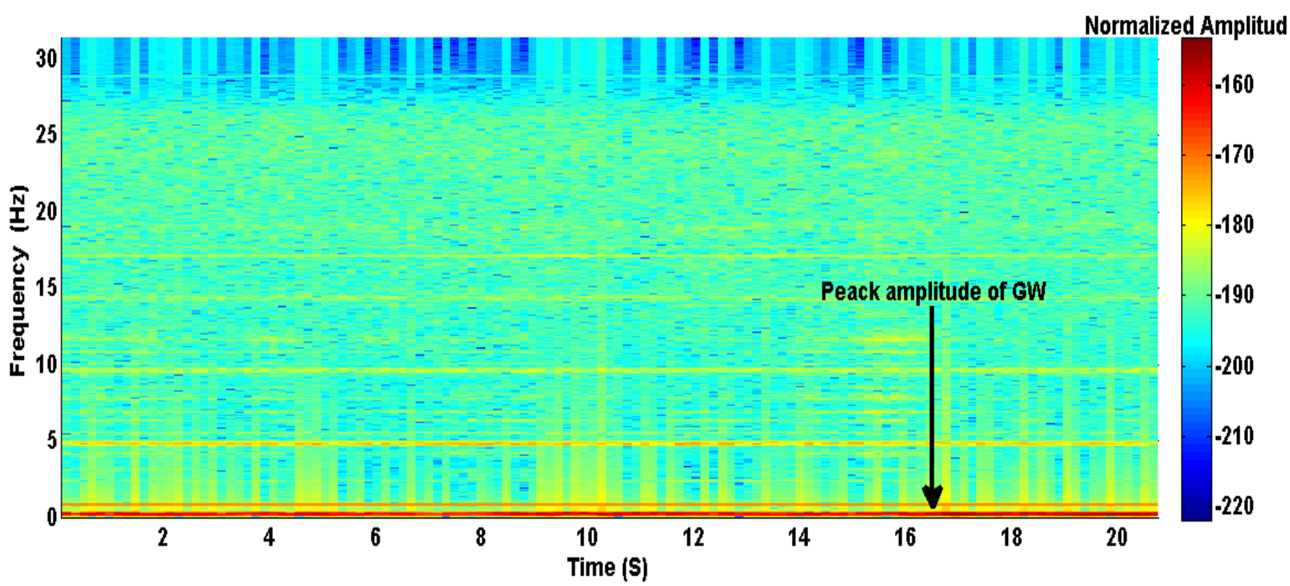

Figure (4-3): Show dynamic spectrum of data from the device on **Virgo** GPS (1186741861) at (4096) Hz at 32 second (event signal reaches peak amplitude 16.53 second ±30 msec from start, see the arrow position in the figure). (M Vallisneri, 2014)

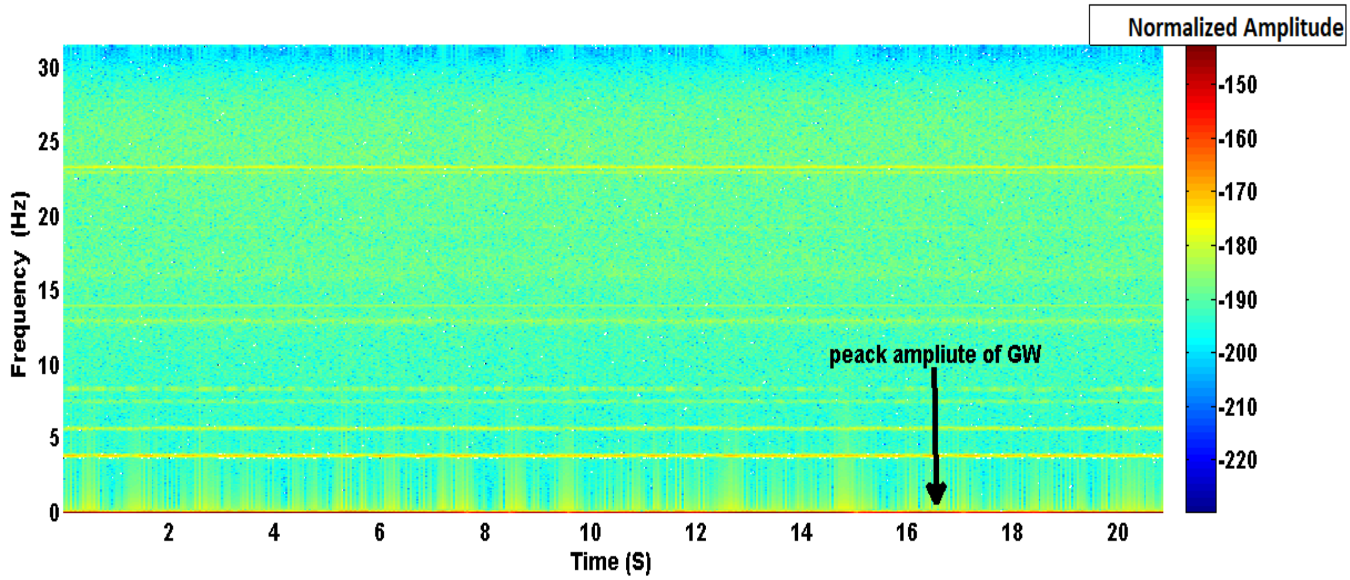

Figure (4-4): Show dynamic spectrum of data from the device on **Hanford** GPS (1186741861) at (16384) Hz at 32 second (event signal reaches peak amplitude 16.53 second ±30 m sec from start, see the arrow position in the figure). (M Vallisneri, 2014)

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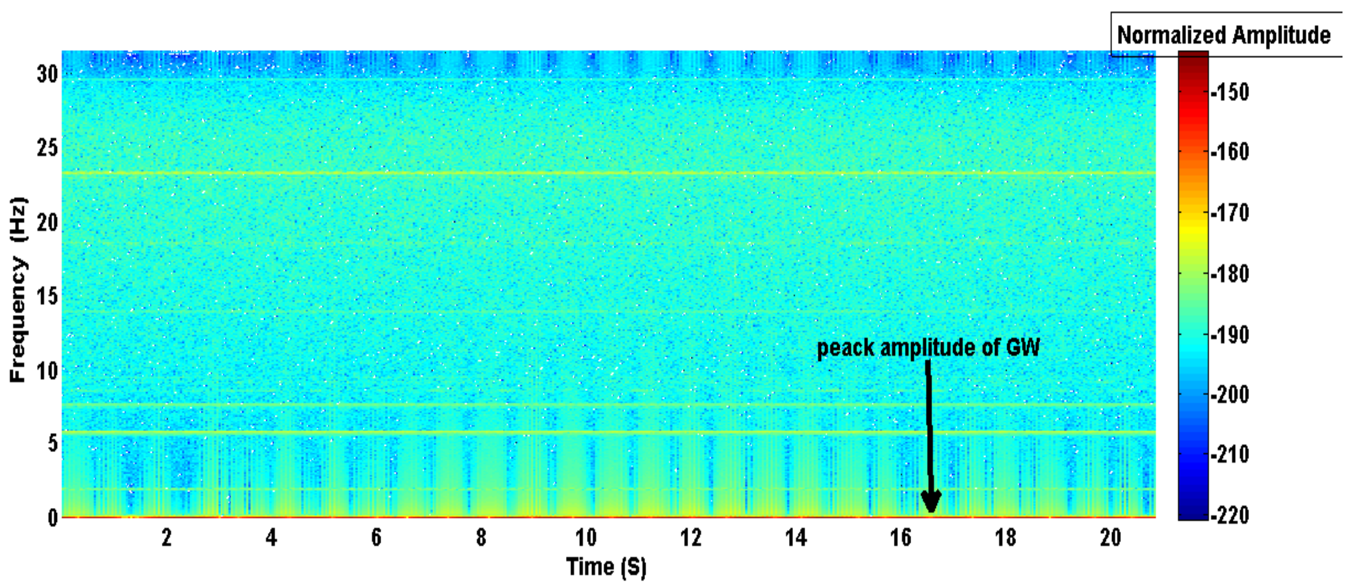

Figure (4-5): Show dynamic spectrum of data from the device on **Livingston** GPS (1186741861) at (16384) Hz at 32 second (event signal reaches peak amplitude 16.53 second ±30 m sec from start, see the arrow position in the figure). (M Vallisneri, 2014)

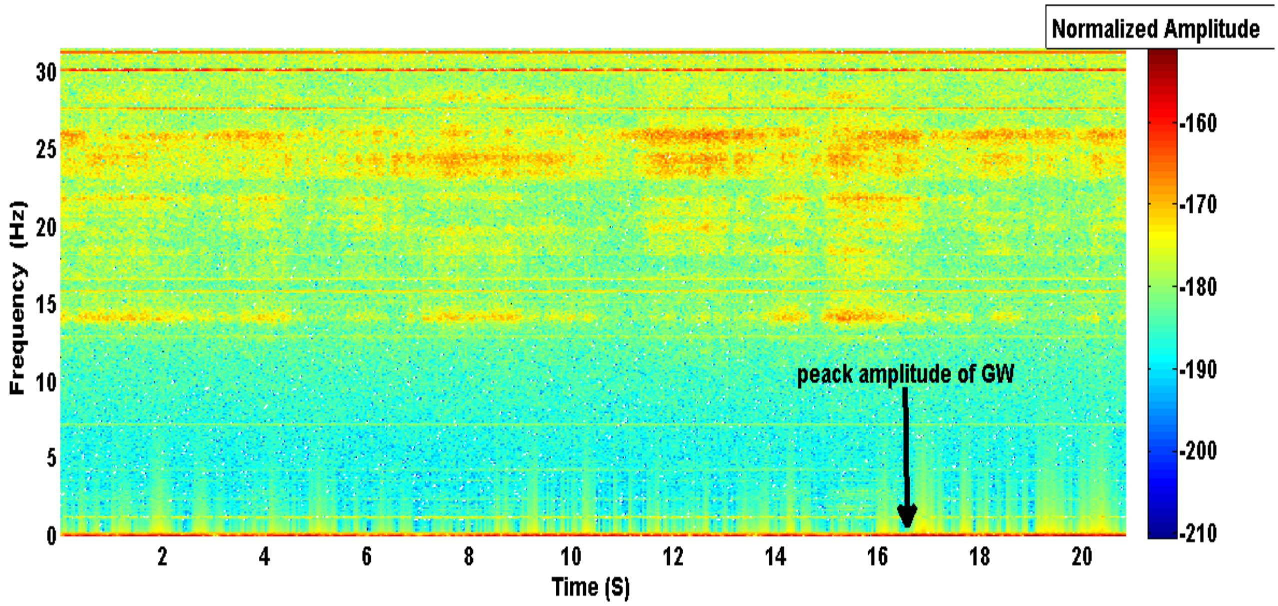

Figure (4-6) : Show dynamic spectrum of data from the device on **Virgo** GPS (1186741861) at (16384) Hz at 32 second (event signal reaches peak, amplitude 16.53 second ±30 m sec from start, see the arrow position in the figure). (M Vallisneri, 2014)

4.2. Discussion

Gravitational waves affect any mass object located on its passage through a transverse strain, therefore the strain data obtained from the LIGO devices at each observation side and also the data from the VIRGO device are expected to view the GW. Looking at the resulting dynamic spectral graphs (Figures: 3.1, 3.2, 3.3, 3.4, 3.5, and 3.6) the location of the peak amplitude of the GW were determined according to data provider, but on the above graphs these peaks not so much obvious in particular to data from LIGO device the reason is the dominating noise sources as well as the events are localized within a narrow time span about few parts of 100 divisions of the second (0.10 – 0.60) to some extend the GW peak is clear on the plots of data collected from VIRGO. In all cases the GW event amplitude is peak at 16.53 seconds. Therefore, in comparing between viewing GW from data of LIGO device and VIRGO device it is obvious that VIRGO device data show the GW more clearly, and this can be explained because of the absence of seismic noise sources in the VIRGO data.

4.3. Conclusions

This review showed the value of observing GW via devices like: LIGO and VIRGO, and as long as more events to be recorded in the future that will open up a gate to a new era in understanding the universe surrounding us. We believe that these methods of detecting GW are of value and also convincing in terms of observation methodology for the GW.

4.4. Recommendations

As a concluding remark we recommend to carry out more analysis in order to view well the peak amplitude of the GW, e.g. to truncate data in the narrow time span of the peak amplitude of the GW and to zoom out.

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