First joint analysis between Gravitational Waves and High Energy Neutrinos using LIGO, Virgo and ANTARES data

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Abstract. Multi-messenger astronomy is entering an exciting period with the recent development of experimental techniques that have opened new windows of observation of the cosmic radiation in all its components. Cataclysmic cosmic events can be plausible sources of both Gravitational Waves (GWs) and High Energy Neutrinos (HENs). Such messengers could reveal new, hidden sources that are not observed by conventional astronomy. Requiring consistency between GW and HEN detection channels enables new searches and a detection would yield significant additional information about the common source. A neutrino telescope such as ANTARES can determine the time and direction of high energy neutrino events. A network of gravitational wave detectors such as LIGO and Virgo can also provide timing/directional information for gravitational wave bursts. By combining the information from these totally independent detectors, one can search for cosmic events that may arrive from common astrophysical sources. In this proceeding are presented the fundamentals of the first joint analysis between GW and HENs during the fifth LIGO science run and first Virgo science run and the 5 line configuration of ANTARES.

1. Introduction

Many astrophysical sources and cataclysmic phenomena are expected to produce gravitational waves and high-energy cosmic radiation in our Universe, in the form of photons, hadrons and presumably also neutrinos. Both gravitational waves (GW) and high-energy neutrinos (HEN) can escape very dense media and travel unabsorbed over cosmological distances, carrying information from the innermost regions of the astrophysical sources [1, 2]. While GWs originate from the dynamics of the bulk motion of the progenitor, HENs trace the interactions of accelerated protons and heavier nuclei with ambient matter and radiation in and around the source. Such messengers could also reveal new, hidden engines that have not been observed yet. Sources of joint emission include two groups of galactic sources which could be accessible to the current generation of GW interferometers and HEN telescopes [7, 6]. Microquasars are believed to be X-ray binaries involving a compact object that accretes matter from a companion star and re-emits it in relativistic jets associated with intense radio (and IR) flares [8]. Such objects could emit GWs during both accretion and ejection phases; and the latter phase could be correlated with a HEN signal as well if the jet has an hadronic component [9]. Soft Gamma Repeaters (SGRs) are X-ray pulsars with a soft γ-ray bursting activity which, according to the magnetar model, can be associated with star-quakes [8]. The deformation of the star during the outburst could produce GWs, while HENs could emerge from hadron-loaded flares. On the extragalactic scale, the most promising sources are Gamma Ray Bursts (GRBs). The commonly accepted explanation of GRBs is the so-called "fireball model" which involves a relavistic jet of plasma produced by a central source (probably compact but yet to be determined). Observed γ-rays result from the dissipation (through synchrotron or inverse Compton emission) of the jet kinetic energy. A particular kind of GRB is called choked GRB [4, 5], in which the jet does not break out of the central source, hence failing to produced a flash of γ-rays. On the contrary, high energy neutrinos can escape from very dense matter due to their weak interation. Choked GRBs are thought to be relevant sources of HENs and they are expected to produce gravitational waves, as also expected in the case of successful GRBs.

2. Network of detectors

LIGO is a network of interferometric gravitational wave detectors consisting of three interferometers in the USA [10]. Two interferometers ($4\,km$ and $2\,km$ armlength) are located in Hanford (WA), and another $4\,km$ interferometer is located in Livingston (LA). At the time of writing the $2\,km$ interferometer in Hanford is dismantled. The $3\,km$ Virgo detector is located at the site of EGO, European Gravitational Observatory, in Cascina, near Pisa (Italy) [11]. These detectors are all Michelson laser interferometers made of two orthogonal arms able to detect the quadrupolar strain in space produced by the GW. Multiple reflections between mirrors located at the end points of each arm extend the effective optical length of each arm, and enhance the sensitivity of the instrument.

The ANTARES collaboration built an underwater neutrino telescope at $2500\,m$ depth in the Mediterranean Sea [12]. The experiment aims to detect high-energy cosmic neutrinos using a 3D array of 900 photomultipliers distributed along 12 lines, spread over an area of about $0.1\,km^2$. Since the Earth acts as a shield against all particles except neutrinos, a neutrino telescope uses the detection of upward-going muons from Cherenkov light as a signature of the muon neutrino interactions with the matter below the detector.

The data collected between February 9 and September 30 2007, during the fifth LIGO science run and first Virgo science run and the 5 line configuration run of ANTARES was used for a first joint search of GWs and HENs. In the next section, we report on the analysis of this data set.

3. Analysis

One of the simplest searches that may be performed combining GW and HEN data is a triggered analysis that scans GW data around the time of the putative neutrino event by cross-correlating data from pairs of detectors. This search exploits knowledge of the time and direction to the neutrino event to improve the sensitivity. We use a coherent search technique, called X-pipeline [13], that has been utilized to perform searches for unmodelled Gravitational-Wave Bursts (GWBs) in association with GRBs [16]. It targets GWBs associated with external astrophysical triggers and performs a coherent analysis of data from arbitrary networks of gravitational wave detectors. The analysis of each external trigger is optimized independently, based on background noise characteristics and detector performance at the time of the trigger, maximizing the search sensitivity and robustness against noise-induced glitches. The pipeline also accounts for effects of uncertainties in the results such as those due to calibration amplitude and timing.

For the purpose of a search for unmodelled GWBs, a neutrino candidate is characterised by its sky position, its time of arrival (the trigger time) t_0, and by the range of possible time delays (positive and negative) Δt between the neutrino emission and the associated GW emission. The latter quantity determines the *on-source* window for the neutrino; this is the time interval which is searched for GW candidate signals. We use a symmetric *on-source* window of

$[t_0 - 500s, t_0 + 500s]$. The large *on-source* window accounts for most plausible theories of GW and HEN emission, as described in [14].

A crucial part of the procedure is the estimation of the background distributions. We set the *off-source* data to be all data within 1.5 hours of the neutrino time, excluding the *on-source* interval and estimate the background by multiple time slides of these *off-source* data. This assures that the background does not contain any signal associated with the neutrino event but has similar statistical features as the data searched in association with the neutrino. This time range is limited enough so that the detectors should be in a similar state of operation as during the neutrino on-source interval, but long enough to provide off-source segments for estimating the background.

ANTARES provided a list of 216 independent events as triggers for this analysis: 18 reconstructed with 3 lines of the detector and 198 with only 2 lines. The track is reconstructed by χ^2 fit using the time and charge of the hits on the photomultipliers. For the two-line cases the detectors are co-planar, and the reconstruction gives two solutions that are mirror images in the plane of detectors [15]. The estimated locations and their uncertainties may give rise to sky regions to be searched that are overlapping, as shown in Figure 1. In any case, the sky regions are covered by a grid of points corresponding to different arrival time delays in the GW detectors, and each of these points is searched for separately. Not all sky positions are equally probable to host the HEN source: a lognormal distribution [18] for the distance from the center of the error box describes the expected probability density for the neutrino. Such distribution is used to generate fake neutrino/GW triggers to feed in MonteCarlo simulations aimed at measuring the detection efficiency of the pipeline. Figure 2 shows an example of the HEN probability distribution as a function of opening angle for a single HEN error region.

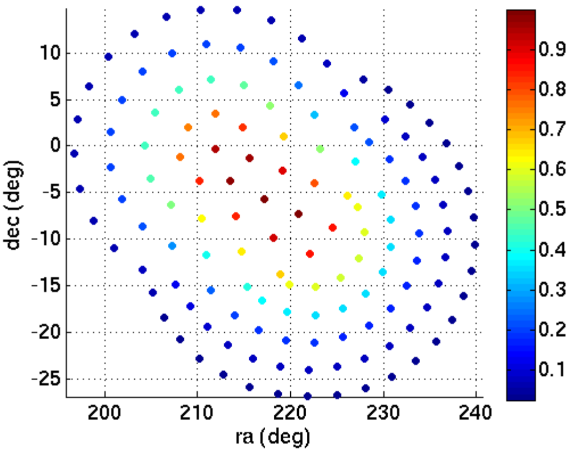

Figure 1. Searching for one point and its mirror image at once, where the color bar shows the probability distribution.

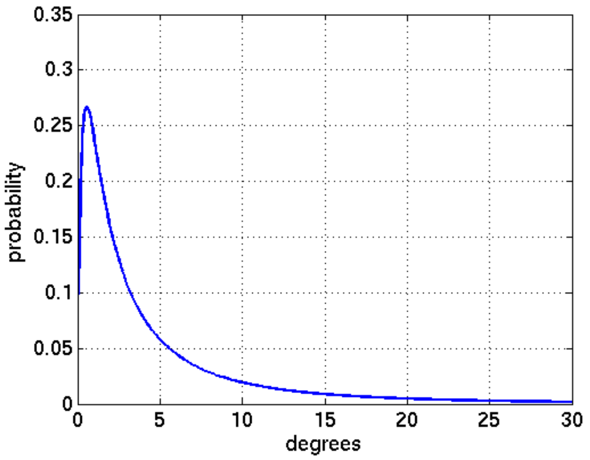

Figure 2. The plot shows the lognormal probability distribution as function of opening angle for one neutrino trigger error box.

4. Conclusions

The first requirement imposed for this triggered search for GWs is that the candidate signal be coincident in time, within an astrophysically motivated window with the external neutrino event. Hence by using a subset of the available GW data, the triggered search can be run with a lower event detection threshold than an un-triggered search (that scans all available data and looks for simultaneous jumps of energy in all detectors). For example the false alarm rate for this search is thus about ~ 100 times lower than in an untriggered search [17], allowing lower thresholds with greater sensitivity to weak GWs.

Similarly, knowledge of the source direction allows us to search only a small part of the sky and veto candidate events seen in multiple detectors at times not consistent with the expected GW arrival time difference.

This yields a higher detection probability at a fixed false alarm probability and better limits in the absence of detection. In comparison with GRBs triggered search [16] during the same period, this leads to an improvement of a factor 1.5-2 in the maximum distance at which a GW source can be detected. The search strategy described in this short paper has been implemented and results from the first joint GWs and HEN search are expected in the near future.

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