Electromagnetic follow-up of gravitational wave transient signal candidates

Marica Branchesi\textsuperscript{1,2} on behalf of LIGO Scientific Collaboration and Virgo Collaboration

\footnotesize{\textsuperscript{1} DiSBeF, Università degli Studi di Urbino “Carlo Bo”, 61029 Urbino, Italy
\textsuperscript{2} INFN, Sezione di Firenze, 50019 Sesto Fiorentino, Italy

E-mail: marica.branchesi@uniurb.it

Abstract. Pioneering efforts aiming at the development of multi-messenger gravitational wave (GW) and electromagnetic (EM) astronomy have been made. An EM observation follow-up program of candidate GW events has been performed (Dec 17 2009 to Jan 8 2010 and Sep 4 to Oct 20 2010) during the recent runs of the LIGO and Virgo GW detectors. It involved ground-based and space EM facilities observing the sky at optical, X-ray and radio wavelengths. The joint GW/EM observation study requires the development of specific image analysis procedures able to discriminate the possible EM counterpart of GW triggers from contaminant/background events. The paper presents an overview of the EM follow-up program and the image analysis procedures.

1. Introduction

The GW detectors, LIGO \cite{1} and Virgo \cite{2}, aim at the first direct detection of gravitational waves from very energetic astrophysical events. The most promising sources are mergers of neutron stars (NS) and/or stellar mass black holes (BH), and the core collapse of massive stars. These events are also believed to produce the most electromagnetically luminous objects in the Universe. Gamma-Ray Bursts (GRBs) are thought to be associated with the coalescence of NS-NS or NS-BH binaries or the collapse of very massive stars (see \cite{3} and references therein). Another scenario associated with compact object mergers is the prediction \cite{4} of isotropic optical transients, called kilonova, powered by the radioactive decay of heavy elements synthesized in the merger ejecta.

In this respect, multi-messenger GW and EM astronomy is a very promising field of research. An electromagnetic counterpart discovered through a follow-up of a gravitational wave candidate event would considerably increase the confidence in the astrophysical origin of the GW signal. The detection of an EM counterpart would give a precise localization and potentially lead to the identification of the host galaxy and the redshift. GW and EM observations provide complementary insights into the progenitor and environment physics. In the long term, combined measurements of the source distance and redshift through GW and EM radiation, respectively, may allow a new way of estimating cosmological parameters.

The development of a low-latency GW data analysis pipeline has permitted the use of gravitational wave candidate signals to conduct the first EM follow-up program \cite{5} (Dec 17 2009 to Jan 8 2010 and Sep 4 to Oct 20 2010) during the last LIGO/Virgo observation periods. The
present paper summarizes the GW-data analysis followed to obtain the prompt EM observation, the EM-observation strategy and the image analysis procedures used to search for the EM-counterparts.

2. Low latency GW data analysis
One of the challenges of successfully obtaining prompt EM observations is to identify the GW candidates quickly: the data from the three operating detectors (the two LIGOs and Virgo) must be transferred and analyzed in near-real time.

The LIGO Scientific Collaboration (LSC) and the Virgo Collaboration developed a low latency GW-data analysis. Search algorithms [6, 7, 8] run over the data coming from the detectors, generate a list of triggers and estimate the potential sky position of the source on the basis of the differences in the signal arrival time and amplitude at each detector. Automated procedures are then designed to select statistically significant triggers suitable for the EM observation and to determine the telescope pointing positions. This process, that typically takes $\sim 10$ minutes, is followed by a manual event validation. A team of trained experts is on duty and evaluate the detector performances. The entire procedure, from data acquisition to the alert sent to telescopes, is typically completed within 30 minutes.

The triggers selected as candidates for EM follow-up are the ones occurring in simultaneous observations of all three detectors and with a power above a threshold estimated from the distribution of background events. A full description of the GW trigger selection and the entire EM follow-up process is detailed in [5].

3. EM observation strategy and observatories involved in the EM follow-up
The uncertainty in the source direction reconstruction scales inversely with the signal-to-noise ratio [9]. GW events near the detection threshold are localized into regions of tens, or in some cases even hundreds, of square degrees. Follow-up EM-telescopes with a wide Field Of View (FOV) are thus required. However, the majority of EM telescopes have a FOV which is much smaller than the GW angular error box and additional priors are necessary to improve the location accuracy and increase the chance that the actual source be EM observed.

Taking into account the GW detector sensitivity to the signals coming from NS binaries [10], the EM observable Universe is limited to an horizon of 50 Mpc. The observation is restricted [11] to the regions occupied by Globular Clusters and Galaxies (listed in the Gravitational Wave Galaxy Catalog [12]) within 50 Mpc. To determine the telescope pointing position, the probability sky map based on GW data is “weighted” taking into account the luminosity and the distance of these nearby galaxies [13] and globular clusters. Tens of thousands of galaxies are included within the 50 Mpc horizon and the GW observable sources will be mainly extragalactic.

The cadence of EM observations is guided by the expected extragalactic EM counterpart. The optical afterglow of an on-axis GRB peaks few minutes after the EM/GW prompt emission. The kilonova model predicts an optical light curve that peaks a day after the GW event, due to the time that the out-flowing material takes to become optically thin. The agreement with the EM facilities allowed several epoch observations: the first one as soon as possible, the day after and observations over longer time-lags to cover the transient light curve dimming.

The follow-up program involved ground-based and space EM facilities observing the sky in different EM bands: the Liverpool Telescope, the Palomar Transient Factory (PTF), Pi of the Sky, QUEST, ROTSE III, SkyMapper, TAROT and the Zadko Telescope observing the sky in the optical band, the Swift satellite with X–ray and UV/Optical telescopes, and the interferometers LOFAR and EVLA in the radio band.
4. EM image analysis procedures to search for the EM counterpart
The EM image analysis aims to detect the transient object counterpart of the GW signal by analyzing a series of images taken in consecutive epochs after the GW event. The analysis method is conceptually similar to the one used to study GRB afterglows with one main difference: the arc minute localization of the current generation gamma-ray observatories allows a significant reduction of the search area with respect to the GW observations. In the case of a GW event, the image area to analyze is the one occupied by nearby galaxies and globular clusters in the telescope FOV taking also into account the possible offset between host center and the transients (observed up to tens of kpc [14] and predicted by simulations up to few Mpc [15]). Searching for transients in a large sky area requires the development and use of specific image analysis procedures able to discriminate the EM counterpart from background/contaminant events.

Several analysis pipelines are actually being developed and tested by the LSC and the Virgo Collaboration in partnership with astronomers. The image analysis procedure depends on the EM observation band, however, the main steps in common are: i) the identification of all transient objects in the images, ii) the removal of contaminating events (astrophysical background/foreground events and possible fake transient events linked to the procedure itself).

4.1. Optical transient search in the wide-field telescope observations
A total of 14 alerts have been sent out to the telescopes and 9 of them led to images being taken by at least one optical telescope. The image analysis procedures able to identify the transients in wide field optical images are based on two different approaches: the “image subtraction” and the “catalog cross check” methods.

An example of a pipeline based on “cross-correlation of object catalogs” is the one designed and tested with the images collected by the two TAROT [16] and the Zadko [17] telescopes. The main steps of the fully automated analysis pipeline are as follows:

(i) extraction of the catalog of objects visible in the images using SExtractor [18];
(ii) removal of “known objects” listed in a star reference catalog (USNO-A2.0) by using a positional cross-correlation tool match [19]. A magnitude check is then used to identify from the list of “known objects” the ones that show a flux variation with respect to the reference catalog and recover the possible transients overlapping these objects.
(iii) trace objects in common to several image catalogs by using a cross-positional check. This results in a light curve for each traced object;
(iv) rejection of “rapid contaminating transients” (like cosmic rays, asteroids or noise) by requiring the presence in a number of consecutive images;
(v) rejection of “background transients” by selecting objects lying in the image regions associated with the galaxies and globular clusters within 50 Mpc. Each galaxy region takes into account the possible offset between the host galaxy center and the optical transients;
(vi) rejection of “contaminating events” like galaxies, variable stars or false transients by analyzing the light curves. The code selects the objects that show a luminosity dimming with time. Assuming that the dimming is described by a single power-law \( L \propto t^{-\beta} \), corresponding to a linear variation in terms of magnitude equal to \( m = 2.5\beta \log_{10}(t) + C \), a “slope index” \( 2.5\beta \) is defined and evaluated for each objects. The expected “slope index” for GRB afterglows and kilonova-like light curves is around 2.5-3. In practice, a conservative cut is applied by selecting as the possible EM counterparts the objects with the “slope index” larger than 0.5. This value has been checked using Monte Carlo simulations.

For a survey red limiting magnitude of 15.5 and using images assumed to be observed 1,2 3 days after the GW events, the preliminary results on the pipeline sensitivity indicate that the majority of GRB afterglows can be detected further away the GW horizon distance of 50 Mpc,
while the kilonova objects can be detected up to a distance of 15 Mpc. These results are obtained by repeatedly running the pipeline over sets of TAROT and Zadko images where fake on-axis GRB and kilonova optical transients were injected.

4.2. X–ray/UV-Optical transient search using the Swift satellite

The Swift satellite [20] gives the possibility to follow-up in the X–ray and Ultraviolet/optical bands a transient event detected by a ground-based observatory. Two candidate GW trigger alerts were sent. Each alert was observed by Swift twice with a time latency of few months between the two epoch observations.

The main steps of the X–ray image analysis are: i) the detection of the source visible in the FOV; ii) the comparison with the number of serendipitous sources expected in the FOV, statistically estimated using the 2XMM catalog source counts; iii) the analysis of the light curve to identify objects that show a flux dimming in the two time observation images. The following UV/Optical analysis consists of: i) searching for the counterparts of the X–ray sources detected; ii) cross-checking with the DSS catalog to identify unknown objects or objects that show a flux variations; iii) analysis of the light curve to investigate UV-Optical source variability.

4.3. Radio Transient Search using LOFAR and EVLA

The radio observations, in addition to providing information on the radio emission of the EM counterpart, possibly allow observation of events not detected at higher frequencies due to obscurcation of dust and daylight that limit the optical sensitivity. Moreover, upcoming radio arrays and nowadays LOFAR [21] give the opportunity to cover multiple sky patches of few tens of sq. degrees (similar to GW error box) in a single observation.

Five candidate GW-trigger alerts were sent and observed by LOFAR. LOFAR started recently to explore the low-frequency sky (30-80/110-240 MHz) never explored before. An automated analysis procedure to detect transients is still under development. Challenges to radio transient searches are linked to the noise contaminating sources from the atmosphere and the time/space varying ionosphere that complicate the image calibration.

The EVLA [22] started to participate to the low-latency follow-up project after October 14th when no science GW-trigger were sent to the telescope. Since the radio afterglow is expected to peak later and evolve more gradually with respect to the optical and X–ray afterglow as observed in the GRBs, a high-latency follow-up consisting in three epochs observations (3 weeks, 5 weeks and 8 months after the GW trigger) has been performed for two GW trigger alerts. For each of them the 3 most likely host galaxies were observed. The data analysis consists of: i) detection of the radio sources in the FOV; ii) light curve analysis for variability study; iii) identification for contaminating radio sources, (e.g. the variability of the Radio Active Galactic Nucleii emission caused by the scintillation of our Galaxy’s interstellar medium).

5. Concluding remarks

The present paper reports on the first EM follow-up program to GW candidates performed by the LIGO/Virgo collaborations together with partner observatories. Different procedures to detect the EM counterpart are under test and development for the different EM-bands. Evaluation of the rate of EM false detections (unrelated to the GW event and observed by chance in the field) due to astrophysical or technical contaminants is under study for each analysis procedure and EM-band. The follow-up program is a milestone toward the advanced detector era. With a ten-fold improvement of sensitivity [23], the number of detectable sources increases by a factor of $10^3$. According to these predictions the advanced detectors will either make the first detection, or place strict constrains on astrophysically interesting quantities. The observation of an EM counterpart could be a crucial ingredient in deciding the astrophysical nature of the first event and start GW/EM multi-messenger astronomy.
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