Estimating transient detection efficiency in electromagnetic follow up searches

Darren J. White\textsuperscript{1} for the LIGO Scientific Collaboration and the Virgo Collaboration

\textsuperscript{1}Department of Physics and Astronomy, University of Sheffield, Sheffield, UK S3 7RH

E-mail: d.white@sheffield.ac.uk

Abstract. During the most recent LIGO-Virgo science run (Dec 17 2009 to Jan 8 2010 and Sep 2 to Oct 20 2010) multi-messenger searches were performed using several partner telescopes. This resulted in large data sets with images covering several square degrees of the sky. Analysis of these images is currently underway using a variety of different tools. We present an overview of these efforts, in particular the development of new tools which enable us to establish the efficiency for transient images in the fields. This is critical in establishing the sensitivity of gravitational wave and electromagnetic multi-messenger searches to the astrophysical signals we expect to be associated with gravitational waves.

1. Introduction

During the summer of 2010, a joint science run between LIGO and Virgo allowed us to attempt an electromagnetic (EM) follow up campaign in order to image sky locations of possible gravitational wave (GW) sources in the hope of detecting any EM counterparts \cite{1}. Low latency pipelines analysed GW data and produced triggers for human verification. Following data quality checks the most likely sky positions any viable triggers were sent to partner telescopes across the globe. Images taken for these triggers are currently being analysed using a variety of methods. In particular, images taken using the ROTSE telescopes and the Liverpool Telescope will be analysed using image subtraction \cite{2}, which allows us to detect down to faint magnitudes. In order to quantify the efficiency of our analysis method, it is necessary to inject transients into the images.

2. Follow-up images taken with ROTSE and the Liverpool Telescope

The ROTSE system \cite{3} consists of 4 robotic telescopes situated at Los Alamos, New Mexico, USA, Coonabarabran, Australia, Mt. Gamsberg, Namibia and Bakirlitepe, Turkey, each with a 0.45 m aperture. This provides a 3.5 square degree Field of View (FoV). These telescopes imaged (using a ‘clear’ filter) areas of the sky relating to 5 triggers produced by the low latency pipelines. The strategy used was to image the region 30 times in one night as soon after the trigger as possible, followed by 8 images for as many nights as possible for up to approximately one month after the trigger. This produced a total of 782 images for analysis, with limiting magnitudes of around 17\textsuperscript{th} magnitude. The Liverpool Telescope \cite{4} is a 2 m robotic telescope with a 4.6’ FoV situated at the Observatorio del Roque de los Muchachos, La Palma, Spain. Images were taken with the main telescope using the SDSS r’ band filter. We followed up a
single trigger, in which we took eleven images of the galaxy that is the most likely host of the GW source, each with a 300 second exposure time (with overheads). This allowed us to reach an image depth of $\sim 21^{\text{st}}$ magnitude as soon after the trigger as possible, with a further 11 images taken approximately one month later. In addition, we were able to obtain images from two secondary finder scopes having 1 and 20 degree FoV centered on the same field which can reach $18^{\text{th}}$ and $12^{\text{th}}$ magnitude respectively. This produced a total of 22 narrow field images with a further 172 images from the secondary scopes.

3. Estimating efficiency

As described above, the follow-up campaign resulted in hundreds of images, all of which need to be analysed and characterised in order to provide a quantitative statement on any detection or limits on any non-detection. By injecting transients we can quantify several important parameters in our follow-up search, such as the efficiency with which we can detect specific afterglow models (see below), the distance ranges our searches are sensitive to given these models and the magnitude limit of the image subtraction method.

3.1. Afterglow models

In order to test the efficiency of our analysis, it is useful to test how well the pipelines detect the EM transients expected as counterparts. The most promising sources of GW signals are the mergers of compact objects (neutron stars and black holes) and core collapse supernovae. The EM sources believed to be associated with these events are long Gamma Ray Bursts (GRBs) [5], short GRBs [6] and the radioactive decay of neutron rich matter (known as the Kilonova model [7]). For the injections, we used the observed afterglows of on-axis GRBs and the decay model expected for kilonovae (see Fig. 1). The transient flux depends on both the distance to the source, and the difference in time between the original event and the time the image was taken.

![Figure 1](image.png)

**Figure 1.** Examples of the light curves we used as models for transient injections. On the left is the radioactive afterglow model from [7]. On the right, an example of measured Long GRB light curves taken from [5].
Figure 2. Examples of injected transients in a single image. The top images show a region of an image before (left) and after (right) injection of a bright object. The bottom image shows a different injection comparing the process with (left) and without (right) scaling in the manner described below.

3.2. Injection method

The method described here is originally only designed to work on the telescopes mentioned above, as other telescopes are being analysed with different methods and therefore have different requirements, but it has been created to be as robust as possible for future analyses. For our work in particular, the image subtraction method is sensitive to any variances in background around a transient, so a simple “cut-and-paste” of a model star into the image (either real or a 2 dimensional gaussian, with no care taken regarding the background noise or the varying PSF across the image) may not be sufficient.

The injection pipeline relies on the selection of bright, isolated stars in the field. This ensures that the object flux is dominated by Poissonian noise from the source, rather than sky or instrument noise, allowing a smooth, scaled injection which has a realistic point spread function (PSF), and with no nearby stars erroneously copied into the injection location. A position close to the source star in the field is chosen at random as the injection position, along with a randomly chosen model and associated distance to the source. In each image identified, the background subtracted flux of the original star is scaled according to the magnitude required for
the image calculated using the time difference between the first image and the current image. The scaled flux, $F_{\text{starscaled}}$, is calculated using:

$$F_{\text{starscaled}} = \frac{F_{\text{star}}}{10^{\frac{\text{mag}_\text{image} - \text{mag}_\text{inj}}{2.5}}}.$$  \hspace{1cm} (1)

where $F_{\text{star}}$ is the flux of the original star, $\text{mag}_\text{image}$ is the magnitude of the original star in the image and $\text{mag}_\text{inj}$ is the required magnitude of the injected transient. In order to obtain realistic backgrounds it is necessary to scale the injection region by a factor $f$. Without scaling the injection region, the background noise added in quadrature, post-injection, will be:

$$\sigma(\text{postinj})^2 = \sigma(\text{preinj})^2 + \sigma(\text{star})^2$$ \hspace{1cm} (2)

where $\sigma(\text{star})$ is the standard deviation of the background around the source star, and $\sigma(\text{preinj})$ and $\sigma(\text{postinj})$ are the standard deviations of the background of the injection region before and after injection respectively. The background noise, post injection, is therefore obviously larger than the original background noise. This can result in image subtractions in which this excess noise is clearly visible, possibly producing a higher than expected likelihood of detecting injections and increasing the error in photometry, depending on the methods used. In order to account for this, the injection region must be scaled so that the background before and after injection remains the same:

$$\sigma(\text{preinj})^2 = f^2 \times \sigma(\text{preinj})^2 + \sigma(\text{star})^2$$ \hspace{1cm} (3)

which rearranges to:

$$f = \sqrt{1 - \frac{\sigma(\text{star})^2}{\sigma(\text{preinj})^2}}.$$ \hspace{1cm} (4)

By scaling the injection region before injecting the transient we reduce the background noise in the injection region, but also the mean of the injection region, so we therefore add a constant value across all pixels such that the mean of the background and the noise in the background remains the same post-injection. This constant is calculated by comparing the mean before and after scaling, and the difference is simply added to each pixel in the injection region. After adding our transient object, we have a smooth injection in which both the mean and standard deviations of the background are the same as before the injection. Two example injections, both with and without scaling, can be found in Fig. 2.

4. Conclusion
The most recent joint science run allowed us to take hundreds of images of the sky. This presents a huge challenge to not only develop efficient methods of analysing these images, but also to be able to provide quantitative results. Calculating the efficiencies and limits of our analysis pipelines is extremely important for both detection and non-detection. Using injected transients across a series of images allows us to provide the efficiencies and limits of both the images and our analysis methods, and also allows us to fully understand the significance of the results we obtain.

References
[1] The LIGO Scientific Collaboration and Virgo Collaboration: J Abadie et al 2012 A&A 539 A124 (Preprint 1109.3498)
[2] Alard, C 2000 A&AS 144 363–370
[3] Akerlof, C W et al 2003 PASP 115 132–140 (Preprint arXiv:astro-ph/0210238)
[4] Steele, I A 2001 NAR 45 45–47
[5] Kann, D A et al 2010 *ApJ* 720 1513–1558 (*Preprint* 0712.2186)
[6] Kann, D A et al 2011 *ApJ* 734 96 (*Preprint* 0804.1959)
[7] Metzger, B D et al 2010 *MNRAS* 406 2650–2662 (*Preprint* 1001.5029)