

The Analysis of ROTSE Images of Potential Counterparts to Gravitational Wave Events

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Abstract. During the most recent LIGO-GEO-Virgo science run a number of partner telescopes performed follow-up observations of gravitational wave (GW) candidates. One of these collaborators was the ROTSE project. Consisting of four optical telescopes, ROTSE responded to GW triggers and took over 700 follow-up images. Analysis of these images is currently under way using ROTSE's own image processing pipeline. We describe the analysis used to search for transients of astrophysical significance, and steps being taken to automate and optimise the analysis for rapid identification of electromagnetic (EM) counterparts to GW candidates.

1. Introduction

The most recent science run (July 2009 - October 2010) of LIGO [1] and Virgo [2] saw the first efforts to detect EM counterparts to candidate GW events. The detection of an EM counterpart to a GW signal would increase the confidence in the GW detection as well as provide complementary information about the progenitor. Several low latency pipelines were used to promptly analyse GW data, identify candidates and reconstruct their apparent sky positions. This effort is referred to as the ‘LOOC UP’ project [3]. Details on how this search was performed are documented in [4]. Several wide field-of-view optical telescopes took part in this search; including the four ROTSE-III telescopes.

2. The ROTSE-III telescope system

The Robotic Optical Transient Search Experiment (ROTSE) is dedicated to rapid follow up observations of gamma ray bursts (GRBs) as well as other fast optical transients on the time scale of seconds to days. ROTSE has consisted of two phases thus far, ROTSE-I and III. ROTSE-I consisted of a 2 x 2 array of telephoto camera lenses co-mounted on a rapid-slewing platform, located in northern New Mexico. The array was fully automated and started taking data in 1998. Observations made by ROTSE-I of GRB 990123 revealed the first detection of an optical burst occurring during the gamma-ray emission, demonstrating the value of autonomous robotic telescope systems [5]. The ROTSE-III telescope system [6] came online in 2003 and consists of four 0.45m robotic reflecting telescopes located in New South Wales, Australia (ROTSE-IIIa), Texas, USA (ROTSE-IIIb), Namibia (ROTSE-IIIc) and Turkey (ROTSE-IIId). The instruments are fully automated and make use of fast optics to give a 1.85 x 1.85 square degree field of view. ROTSE-III is capable of attaining 17th magnitude with a 5 second exposure and 18.5 magnitude with a 60 second exposure. If multiple images are stacked on top of one another or ‘coadded’ ROTSE-III can reach ~19th magnitude [7].

The LOOC UP program ran in two phases. During the latter phase, between September 2 and October 20 2010, ROTSE-III took over 700 images in response to GW triggers. The images taken span from the first night after the event occurred to one month later. Images vary in exposure length (either 20 or 60 seconds) and all four telescopes were used to gather the data. With GW detectors at the sensitivities they were at the time of the search, most or all of the triggers are unlikely to represent true astrophysical events.

3. The ROTSE image processing pipeline

The ROTSE image processing pipeline was developed and is still used by the ROTSE collaboration to search for transient objects within images taken with the ROTSE-III telescopes. The pipeline makes use of cross convolution to perform image subtraction. This relaxes the need for high quality reference images and the computational efficiency

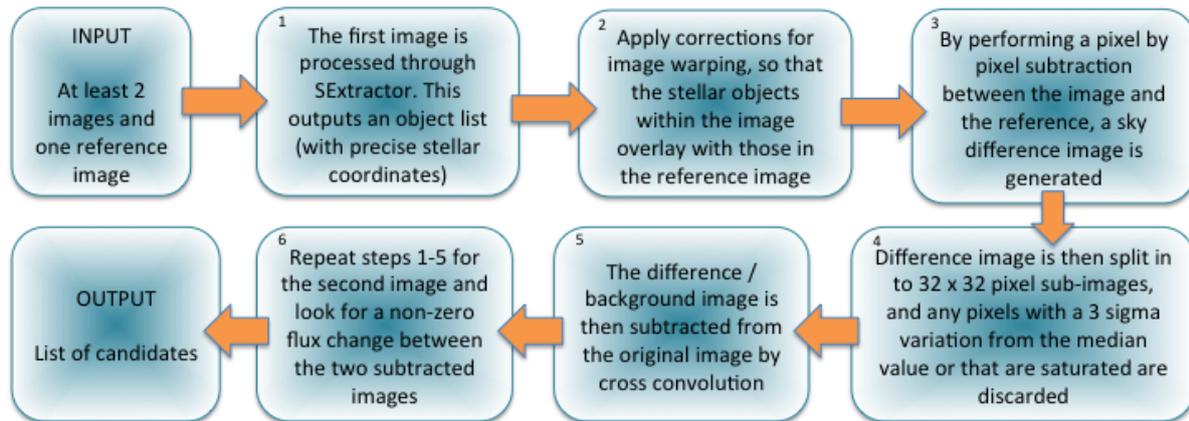


Figure 1. Flow chart describing how the ROTSE pipeline processes images to produce a list of potential candidates.

is similar to other procedures for image processing [8]. We present a brief summary of the main steps of the pipeline; for more details please see [8, 9].

When a LIGO/Virgo trigger was sent to the ROTSE telescopes, typically 30 images were taken on the first night with 8 images taken on subsequent follow-up nights, per telescope, for the first ten nights following the trigger, with additional observations around nights 15 and 30. These images were of the same part of the sky, so that images may be stacked or ‘coadded’ on top of one another. Coadding increases the limiting magnitude to which we are sensitive (i.e. to see fainter objects) without saturating the brightest objects within the image. This permits two different modes of analysis. In the coadded case, all images for a given night are combined in to two images (i.e. the first 15 (4) images are coadded to form the first image, and the second 15 (4) images are coadded to form a second image of the first night (follow-up night)), which are then compared. Image deficiency is used to pick out the transients, as described in Figure 1. This procedure is repeated separately for each night so that each night produces a separate list of candidates. The ROTSE pipeline can also perform a ‘non-coadded’ analysis, in which just the images taken from the first night are processed without coadding to see if there are any fast transients on the \sim hour time scale. The non-coadded analysis does not stack images, meaning the images would have a shallower limiting magnitude than those images which have been coadded. In the non-coadded case each consecutive pair of images produces a list of candidates.

Both analyses (coadded or non-coadded) will produce several lists of candidates identified by the pipeline. The lists from within a single analysis therefore need to be compared to produce a single list of unique candidates. The vast majority of these potential candidates will be due to poor image subtraction, with a minority due to a variable, rather than transient, source (such as a star or asteroid). We identify and remove transients,

which are not targeted, by comparing to catalogues such as SIMBAD‡ or the minor planet checker§ so that we only produce lightcurves of the most likely candidate EM counterparts.

4. Steps taken to automate the pipeline

The ROTSE image processing pipeline has been used to make some significant discoveries of optical transients. The drawbacks of the pipeline include being widget based, highly human intensive and therefore time consuming, and the limitation of only processing images from one GW candidate at a time. We have therefore taken steps to automate the pipeline and taken a slightly different approach to processing these images.

The detection of an EM counterpart to a GW event is particularly challenging in a number of respects. First, the error boxes associated with a GW candidate are large, often 100 square degrees or more. Second, the magnitude and decay timescale of an EM counterpart are unknown, necessitating observations both at early and late times, from seconds to weeks after the trigger. Both of these imply the need to process large numbers of optical images. In addition, the *a priori* unknown nature of lightcurve requires the ability to locate transients with lightcurves of different shapes. Finally, since there has not been a confirmed detection of a GW we will need to be able to assign a high statistical confidence in any putative EM counterpart, which likely will require repeating the analysis for many times not associated with GW candidates. All of these factors point to the need to automate the EM image analysis, to allow large-scale processing and quantitative characterisation of the pipeline.

The ROTSE image processing code originally took a series of commands from within IDL, as well as widget based commands to give a list of potential candidates. The automated pipeline is now able to run off one command with the end product not only being a list of unique candidates, but also all the lightcurve information for each potential candidate the pipeline identifies. In addition, multiple sets of images from multiple GW candidates are able to run simultaneously, and therefore can be submitted to condor||. We have also removed the need for an IDL licence, as the pipeline can be run through IDL Virtual Machine¶. The essence of the pipeline has not been changed at all. The original pipeline and the new automated pipeline produce the same list of candidates.

5. Future Steps

Currently in development is a post processing code. This code will run after the automated code, and makes use of the already available lightcurve information for each

‡ <http://simbad.u-strasbg.fr/simbad/>

§ <http://scully.cfa.harvard.edu/cgi-bin/checkmp.cgi>

|| <http://research.cs.wisc.edu/condor/>

¶ <http://www.exelisvis.com/language/en-us/productsservices/idl.aspx>

potential candidate the pipeline identifies. The code will apply a series of pass/fail tests to each potential candidate. At present these cuts are anticipated to test whether the candidate appears on more than one night, whether its coordinates overlap with a minor planet or known variable source (by querying the SIMBAD catalogue), as well as test to see if the lightcurve of the potential candidate has an overall negative gradient. We would also like to see if a potential candidate overlaps with a known galaxy (by making use of the gravitational wave galaxy catalogue [10]) and whether its lightcurve is similar to target theoretical lightcurves [11, 12, 13].

In addition, an injection code is being written which will inject decaying transients in to a sequence of ROTSE images. These injected transients will be modelled on objects which are already present in the image, and the code will alter its magnitude either in a random fashion or in a way which is consistent with theoretical lightcurves such as those previously suggested. With these altered images we will be able to test the efficiency of the image processing pipeline as well as obtain an independent measure of the limiting magnitude. For more details of this injection code please see the paper in these proceedings by White *et al.*.

Finally we will use images from the ROTSE archive as ‘background’ images as well as process the images the ROTSE telescopes took specifically in response to a potential GW event. This will allow us to estimate the ‘false-alarm’ rate (the rate of transients not associated with a GW candidate) to assess the statistical significance of any potential EM counterpart.

6. Concluding remarks

The automation of the ROTSE pipeline and further cuts which are being implemented will be essential to quantify the false alarm rate which in turn will be vital in adding confidence to a GW detection. In the next few months these steps will be implemented and the images analysed. These first efforts to detect EM counterparts of GW events will pave the way for the advanced detector era, where the detectors will have a ten-fold increase in sensitivity and GW detections are expected to be a regular occurrence [14].

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