IDENTYFYING ELECTROMAGNETIC TRANSIENTS USING IMAGE SUBTRACTION

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ABSTRACT

Over the past several years the LIGO, Virgo and GEO600 gravitational-wave detectors have operated together as a worldwide network. The combined data from these detectors allows sky localization of astrophysical gravitational-wave sources. By running searches for transient gravitational waves shortly after the data is taken, sky locations can be communicated to electromagnetic observers early enough to allow measurement of any electromagnetic emission in the aftermath of a strong gravitational-wave signal. By measuring both the gravitational and the electromagnetic radiation we can learn a significant amount about their source.

Over the past year, electromagnetic images of sky locations corresponding to low-threshold gravitational-wave triggers have been acquired. These are now being analyzed for optical transients. Challenges include unrelated disturbances such as asteroids, satellites, clouds and other objects in space. I will describe the procedure for identifying electromagnetic transients with a pipeline based on image subtraction.

1. INTRODUCTION

Newton described gravity as a force that acts instantaneously over long distances and causes falling objects to accelerate independent of their mass or composition. Einstein's theory of general relativity says that gravity can be thought of the distortion of space where the acceleration by distortion is independent of the mass or composition of the falling body. When trying to picture the distortion-space theory of gravity, it is easiest to think of the sky as a space-time fabric that bends around massive objects and that GW's are basically fluctuations in the geometry of space-time produced when massive objects change their shape and orientation rapidly. Einstein's theory of also says that GW's propagate outward at the speed of light.

There are some astrophysical systems such as binary neutron star mergers and supernovae that are predicted to emit both gravitational waves and electromagnetic radiation. EM radiation also propagates in the form of waves that move at the speed of light. The EM signals carry information that is difficult or simply impossible to extract from an observation with only GW detectors. The position information from the EM observation can be used to identify a host galaxy or constrain attempts to fit templates to the GW data.

The combined observation of the electromagnetic and gravitational waves correlate in time and direction, they are considered counterparts and are essentially complimentary. Benefits of observing both the EM and GW from the same source increase confidence in the astrophysical origin of the GW event, and a lower threshold than the GW search, allowing and increased observational horizon. We are also able to obtain more information about the host galaxy and its distance, this information can lead to more stringent constraints on source models. Any distance estimate derived from the EM data would then set the overall scale for the energy contained in the GW signal [3].

In this paper we discuss the method and steps of image subtraction and procedure to use it for finding electromagnetic transients. The images used to test the process are from the Maidanak observatory located in the Republic of Uzbekistan and images that came with a downloaded package of *XConvolve*. Maidanak images were taken over a period of several days, at the same time of day with an exposure time of 120 seconds. And after the methods and process were well understood, we used them on images taken by the QUEST telescope.

Once we find what part of the sky we would like to analyze, we obtain images using a telescope that records the image in a charge coupled device, otherwise known as a CCD chip in a fits file with other relevant information. Once the image and its information are obtained, they are considered *raw data*. From here we run the image through a series of procedures know as *preprocessing*. After the preprocessing is completed, the image moves onto *post-processing.* The post-processing procedure includes sub-procedures that involve correction, calibration and photometry among others. Both the preprocessing and post-processing are known as data reduction, which is simply removing unwanted and unnecessary data. Following the data reduction is the analysis of the resulting image. The analysis includes determining if an EM transient has gone through the specific part of the sky,

2. PURPOSE

Our goal is to identify any electromagnetic transient within the given images. The transient would be evident as excess brightness after we subtract the images that were taken throughout several days and find changes. In other words, if our resulting subtracted images are blank, the original images were identical and there was no transient.

3. PROCEDURE

3.1 Preprocessing

The entire preprocessing system is done with the program IRAF. IRAF stands for Image Reduction and Analysis Facility and it is basically a general-purpose software system for the reduction and analysis of astronomical data.

Images are preprocessed in order to remove unnecessary data to obtain better image quality before the post-processing where the image subtraction is done. This is done because the CCD chips are not perfect, and it is our job to only obtain *pure* data. It is important to remember that when choosing what images to analyze, they must all be of the same filter, in our case; we used the "V" filter. And before we can start improving the images, we must calculate some necessary parameters, the red noise and gain. These will be constantly asked for throughput both the preprocessing and post-processing procedures.

$$Gain = \frac{(F_1 + F_2) - (B_1 + B_2)}{(\sigma_{F12}^2 - \sigma_{B12}^2)} \quad F_{12} = (F_1 - F_2) \quad B_{12} = (B_1 - B_2) \quad RN = Gain * \frac{\sigma_{B12}}{\sqrt{2}}$$

The values for all of the variables, including the standard deviation can be found when using the function *imhead lo+*, this is the data of the image can be seen. σ is the standard deviation of the image, the B is for the bias and the F is for the flat. Any two images within the same filter can be chosen, one is assigned the number one, and the other two.

3.1.1 Zerocombine

The first step we take in preprocessing is combining the bias frames into an average frame. This has to be done to remove the current accumulated before the exposure. To combine the bias frames we use the *zerocombine* option within IRAF. The parameters that we would like to change are done using the command *epar*, which simply stands for editing parameters. The default parameters result with all images with the type *zero* being averaged together, but with the highest value being ignored when forming the average for any given pixel. In other words, if we have ten bias frames, nine will be averaged in producing the value for each pixel in the resulting *zero* image. This step helps us keep radiation events out of our average bias frame. The final *zero* image will be a 32-bit real image.

Figure 1: Screen shot for setting parameters for zerocombine in IRAF

3.1.2 DarkCombine

After the *zerocombine* process is completed, we move onto the *darkcombine*. The dark frames are long exposures taken with the shutter closed. Dark current accumulates with along with exposure time and is an addition to random and unwanted noise. The good thing about the *zerocombine* feature is that it is smart enough to select only the dark frames and will combine them scaling by the exposure times if they are different. But in the particular set of data that we are working with, the Maidanak images and the QUEST images, there was negligible dark current due to short exposure times and high quality CCD chips.

3.1.3 Flatcombine

The next step is *flatcombine*. This process is much like the *zerocombine* and it processes all of the flat field images. The purpose of this step is to correct for non-uniform sensitivity and be able to obtain uniform brightness throughout the image. This also allows for the possibility that lamps providing the flat-field illumination have varied during the series for exposures, an assumption that is often true. By scaling these to a common value we obtain a less biased average given that we are rejecting some pixels. After obtaining the flat images, we are able to apply *flatcombine* to obtain one average flat image.

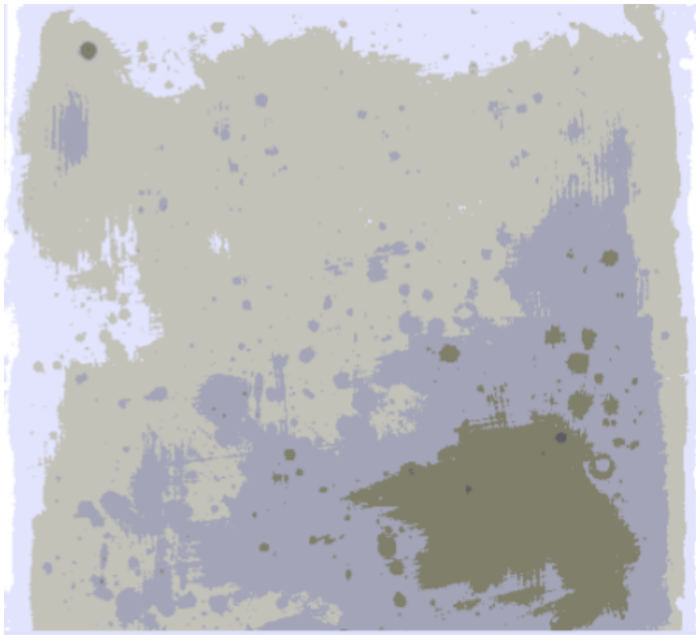


Figure 2: Screen shot of a flat combine image

3.1.4 Object Correction

After we use all of the "combines" we proceed to *Object Correction.* Object correction is simply the process in which the *zerocombine* and *flatcombine* images are subtracted from the raw images. This image is then opened up in the fits viewing softwareDS9 alongside an original image without any type of correction to visually compare, and see for ourselves that everything is going as expected.

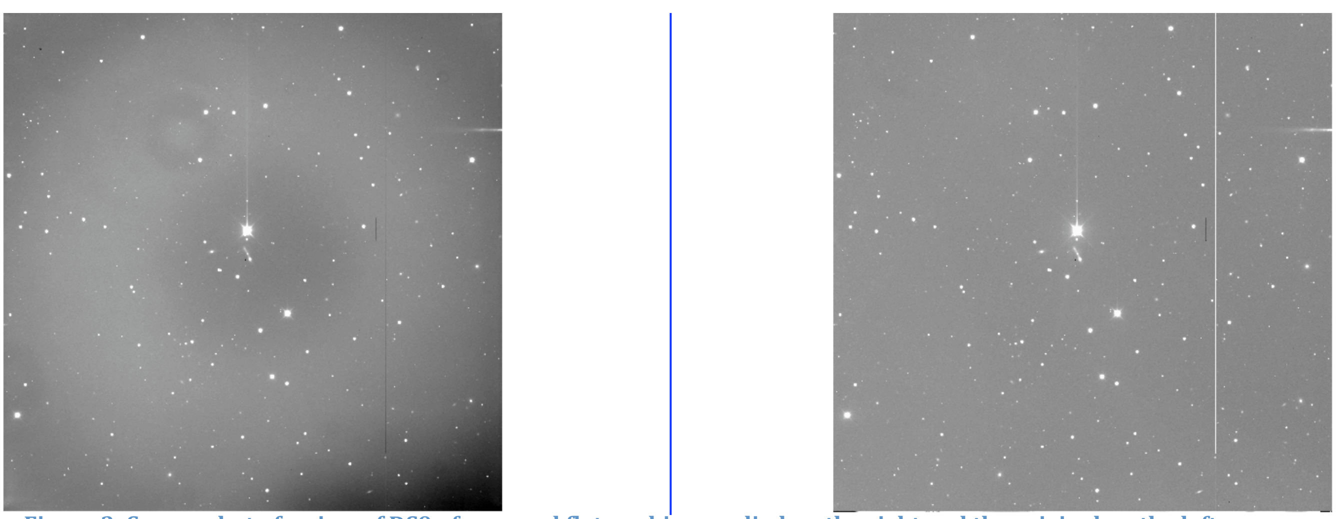


Figure 3: Screen shot of a view of DS9 of zero and flatcombine applied on the right and the original on the left

3.1.5 Object Combine and Align

The next step after the *object correction* is to align and combine the images. This is done because the telescopes we are using to obtain the images are not perfect. They can easily be moved over the course of several days enough to alter the position in the sky that it is pointed to. All of the images may look the same to the naked eye, but we must test to make sure. Here we will combine images to create a reference image so that we can be able to compare to all others for the transients.

We must now create a reference image. The reference image consists of the combinations of images, and the more images that we combine, the better the reference image. By the end of this step we should have a reference image and several uncombined object images.

In order to align the images, we must first choose an image to use as a reference. After choosing an image, we use the function *epar imexam* in IRAF. This function allows us to obtain the coordinates of different stars in the same image and store them in a coordinate file. This is then repeated with the rest of the images that we are analyzing.

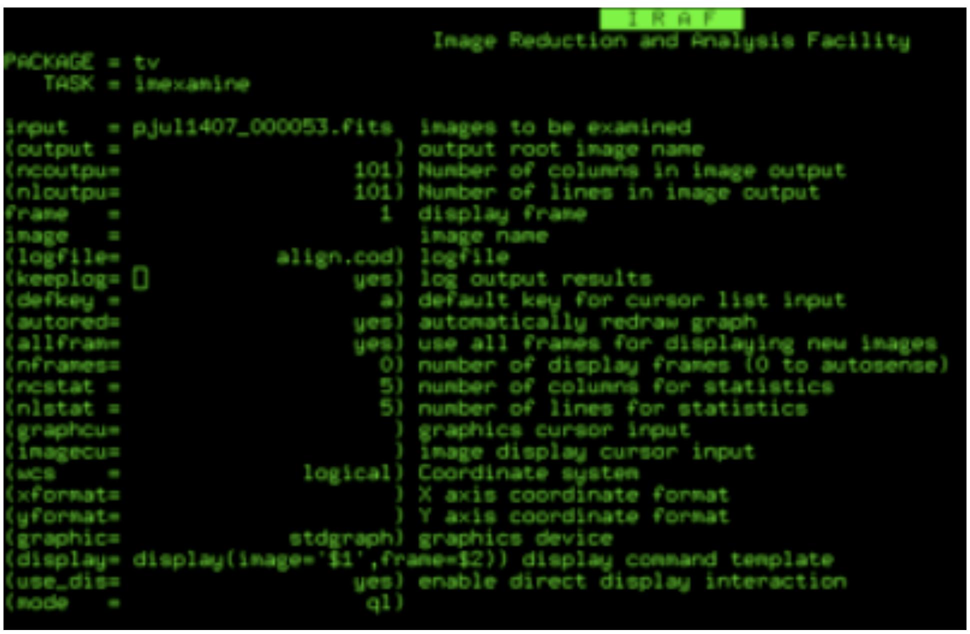


Figure 4: Screen shot of parameter settings in IRAF for imexam, they determine where the data will be stored

After obtaining the coordinates from several images of the same stars, we use an Excel spreadsheet to find the difference in the location of the stars. Once the differences are acquired we place them in an *.shf* file then use it in the function *epar imcombine,* which is where all of our images become one.

Figure 5: Screen shot of parameter settings in IRAF for the alignment of images

3.2 Post-processing

3.2.1 Source Extractor

The first step in post-processing is to run the object and reference image that resulted from the preprocessing, through a program that is called Source Extractor. Source Extractor, abbreviated Sextractor, is used to build a catalogue of objects from an astronomical image. It was designed for the reduction of extensive galaxy-survey data, but it is also good for more crowded star fields. It has pixel-to-pixel photometry, which is perfect for our research.

The way that Sextractor works is by passing through the data twice. The first time it goes through, a model is built and global statistics are estimated, and the second time the background is subtracted, filtered and thresholded. Detections are then de-blended, cleaned, photometered, classified and finally written into an output catalog. This catalog contains, among other things, the position and magnitude of identified bright objects [4].

The great thing about Sextractor is that we can easily set the parameters and then run the program. Below are screen shots that show the parameter settings and also an example of the command to run it.

```
NUMBER

#FLUX_ISO
FLUXERR_ISO
#MAG_ISO
#MAGERR_ISO

#FLUX_ISOCOR
#FLUXERR_ISOCOR
#MAG_ISOCOR
#MAGERR_ISOCOR

#FLUX_APER(1)
#FLUXERR_APER(1)
#MAG_APER(1)
#MAGERR_APER(1)

FLUX_AUTO
FLUXERR_AUTO
 MAG_AUTO
#MAGERR_AUTO

#FLUX_BEST
#FLUXERR_BEST
#MAG_BEST
#MAGERR_BEST

#KRON_RADIUS
#BACKGROUND

#THRESHOLD
#MU_THRESHOLD
#FLUX_MAX
#MU_MAX
#ISOAREA_IMAGE
#ISOAREA_WORLD

#XMIN_IMAGE
#YMIN_IMAGE
#XMAX_IMAGE
#YMAX_IMAGE

X_IMAGE
Y_IMAGE
X_WORLD
Y_WORLD
ALPHA_SKY
```

Figure 6: Screen shot of parameter catalog settings in SExtractor

```
# Default configuration file for SExtractor 2.5.0
# EB 2006-07-14
#

#-------------------------------- Catalog ------------------------------------

CATALOG_NAME     turtle.cat       # name of the output catalog
CATALOG_TYPE     ASCII_HEAD     # NONE,ASCII,ASCII_HEAD, ASCII_SKYCAT,
                                # ASCII_VOTABLE, FITS_1.0 or FITS_LDAC
PARAMETERS_NAME  default.param  # name of the file containing catalog contents

#------------------------------- Extraction ----------------------------------

DETECT_TYPE      CCD            # CCD (linear) or PHOTO (with gamma correction)
DETECT_MINAREA   5              # minimum number of pixels above threshold
DETECT_THRESH    1.5            # <sigmas> or <threshold>,<ZP> in mag.arcsec-2
ANALYSIS_THRESH  1.5            # <sigmas> or <threshold>,<ZP> in mag.arcsec-2

FILTER           Y              # apply filter for detection (Y or N)?
FILTER_NAME      default.conv   # name of the file containing the filter

DEBLEND_NTHRESH  32             # Number of deblending sub-thresholds
DEBLEND_MINCONT  0.005          # Minimum contrast parameter for deblending

CLEAN            Y              # Clean spurious detections? (Y or N)?
CLEAN_PARAM      1.0            # Cleaning efficiency

MASK_TYPE        CORRECT        # type of detection MASKing: can be one of
                                # NONE, BLANK or CORRECT

#------------------------------ Photometry -----------------------------------

PHOT_APERTURES   5              # MAG_APER aperture diameter(s) in pixels
PHOT_AUTOPARAMS  2.5, 3.5       # MAG_AUTO parameters: <Kron_fact>,<min_radius>
PHOT_PETROPARAMS 2.0, 3.5       # MAG_PETRO parameters: <Petrosian_fact>,
                                # <min_radius>

SATUR_LEVEL      50000.0        # level (in ADUs) at which arises saturation

MAG_ZEROPOINT    0.0            # magnitude zero-point
MAG_GAMMA        4.0            # gamma of emulsion (for photographic scans)
GAIN             8.7            # detector gain in e-/ADU
PIXEL_SCALE      0             # size of pixel in arcsec (0=use FITS WCS info)

#------------------------- Star/Galaxy Separation ----------------------------

SEEING_FWHM      1.2            # stellar FWHM in arcsec
"default.sex" 75L, 3602C
```

Figure 7: Screen shot of the SExtractor output files and image settings

```
[cinthia@smpcluster sextractor]$ sex ref.fits -c default.sex
----- SExtractor 2.8.6 started on 2011-07-28 at 14:53:13 with 8 threads

Measuring from: "NGC6205_F3"  / 4096 x 4096 / 0 bits FLOATING POINT data
(M+D) Background: 40.8885    RMS: 3.94019    / Threshold: 5.91028
> Line: 3952  Objects:     3871 detected /     2961 sextracted
> WARNING: Pixel stack overflow at position 1335,3953

Objects: detected 5072     / sextracted 4660
> All done (in 4 s)
[cinthia@smpcluster sextractor]$
```

Figure 8: Screen shot of the command to run SExtractor

After the parameters are set and the program is run the outputs include a catalog file and a fits image. The catalog file now contains information such as the magnitude and coordinates of the stars, essential for data analysis. The fits image is simply to separate the background from detected stars. In the screenshot, the image on the left is the original after preprocessing, and the right is the Sextractor output.

```
#   1 NUMBER          Running object number
#   2 FLUXERR_ISO     RMS error for isophotal flux                        [count]
#   3 FLUX_AUTO       Flux within a Kron-like elliptical aperture         [count]
#   4 FLUXERR_AUTO    RMS error for AUTO flux                             [count]
#   5 MAG_AUTO        Kron-like elliptical aperture magnitude             [mag]
#   6 X_IMAGE         Object position along x                             [pixel]
#   7 Y_IMAGE         Object position along y                             [pixel]
#   8 FWHM_IMAGE      FWHM assuming a gaussian core                       [pixel]
#   9 FLAGS           Extraction flags
         1   61.06298    -10161.1   26.43159  99.0000   420.850   20.833    6.49   3
         2   50.33757    -9597.26   33.43361  99.0000   492.921   22.171    5.41   3
         3   103.9155   -348905.8   51.07068  99.0000   432.001   19.249    7.72   3
         4    191.628    154029.3   191.4292 -12.9690   436.994   37.656   33.77   2
         5   55.55867   -253.9026   20.47382  99.0000   485.609   10.532    4.87   3
         6   115.0653   -44190.22   37.37991  99.0000   463.769   16.369    9.00  19
         7   97.63102   -131777.6   39.98854  99.0000   469.692   17.977    9.73   3
         8   91.63225   -22506.84   31.52151  99.0000   487.383   19.417    7.78   3
         9   69.46169   -815.1674   21.21856  99.0000   482.207   11.772    5.02   3
        10   111.0535   -80331.74   44.40367  99.0000  1914.197   22.837   10.80   3
        11   153.2514   -385750.4   74.96719  99.0000  1950.502   20.625   13.81  19
        12      103.1    -44449.4   35.24212  99.0000  1953.051    7.972    8.66  19
```

Figure 9: Screen shot of SExtractor's output catalog

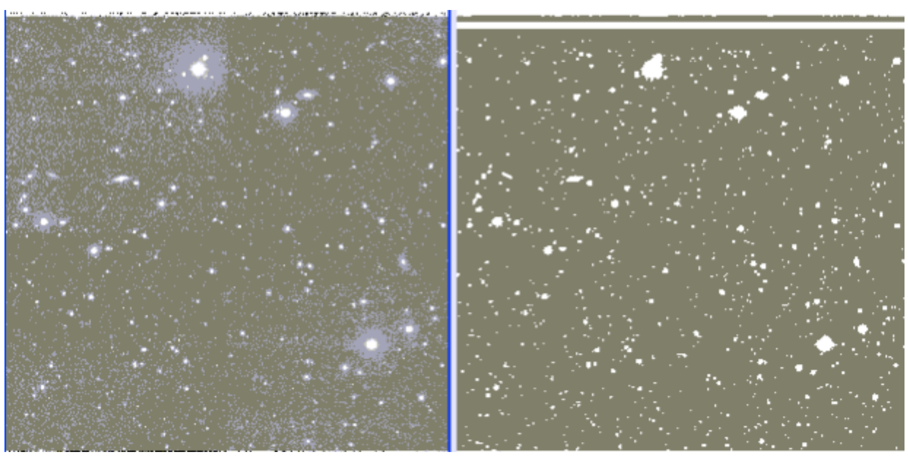


Figure 10: Screen shot of SExtractor's image output next to the original image

3.2.2 Xconvolve

After the catalog files are completed, the following step is image subtraction by cross-convolution. Cross convolution is when two convolution kernels are generated to make a test image and a reference image separately transform to match as closely as possible. We were able to locate a pre-written source code that runs within the program IDL that would make the cross convolution very simple. IDL is a programming language for the creation of scientific data visualization from complex numerical data. The aim of the cross-convolution code, known as Xconvolve, is primarily for the reliable identification of transients in a very large database, not precise photometry [1].

Flat field images are processed in the previous step with Sextractor to create object lists with precise stellar coordinates. The Xconvolve routine uses the IDL function “POLYWRAP” to warp the images and overlay stellar objects as closely as possible. Then a valid pixel map is made to avoid pixels close to the image perimeter and screen against saturated values. Then the code performs image flux normalization to equalize the mean values of the two images under comparison, thus the subtraction.

When it comes to image subtraction, done in the cross-convolution process, it is important to know what is happening to the background because if it is not well taken care of, it can appear to be a transient when it is only bad background reduction. Although most background sky intensity is estimated in Sextractor, it tends to be poorly estimated around the cores of bright galaxies. This problem was addressed in the code by removing the background differences between the two images instead of removing them individually. After, the sky images are scaled so that stellar fluxes match a sky difference map is generated by first performing pixel-to-pixel subtraction [2].

Like most source codes, Xconvolve does what it can and the rest is up to us. This is especially true when working with imperfect images. At this point, visual inspection is crucial. We must now open the resulting convoluted image in the visual DS9 program to identify possible transients.

The following image is an example of one after subtraction. The outlined stars are the only ones that are considered to be possible transients.

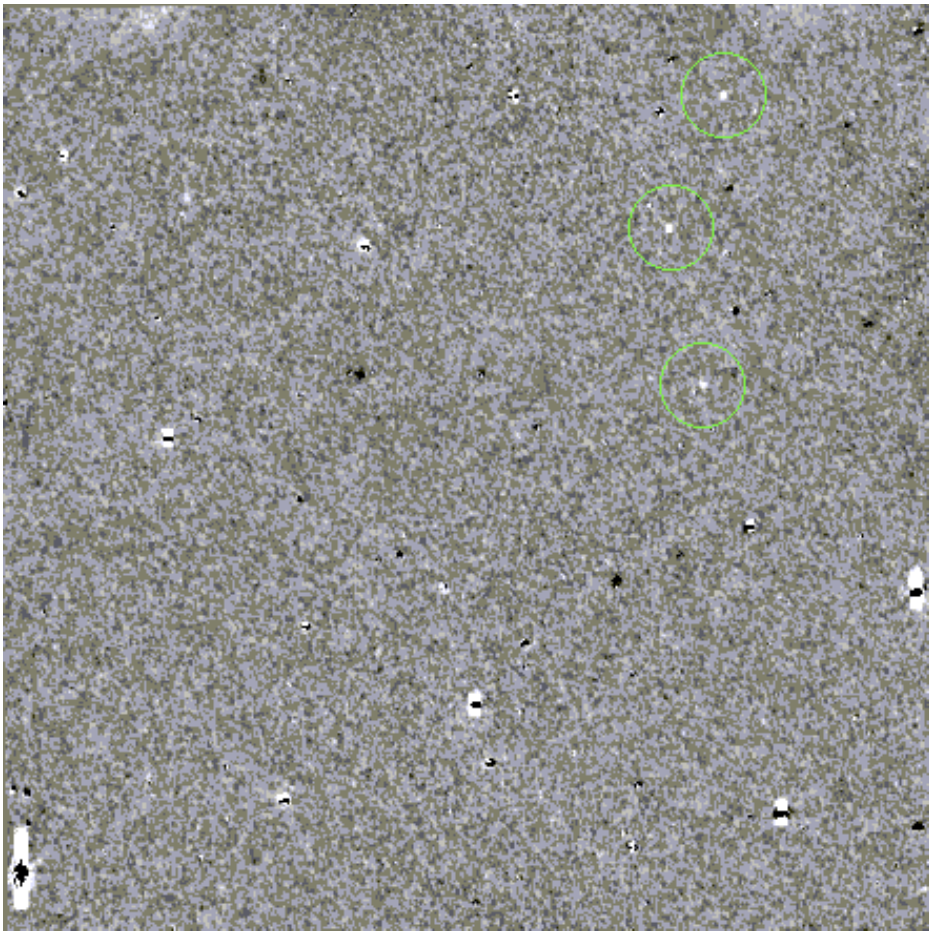


Figure 11: Screen shot of XConvolve's output image

The reason that the others can be easily excluded is that once visually analyzed, we see that they are cause by either overexposure or because the images were not aligned properly.
Figure 12 is an example from the previous image of saturation. Figure 13 is an example of the result when images are not properly aligned, and finally the figure 14 is our possible transient.

Figure 12: Saturated section

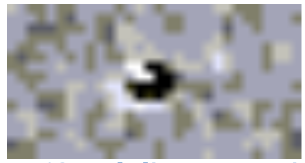


Figure 13: Bad alignment section

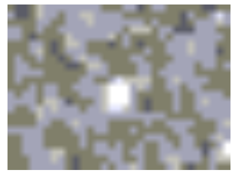


Figure 14: Possible transient

Following the cross-convolution process we run the image through SExtractor. This is so that we can obtain the data from all of the apparent transients (including the ones that we already ruled out). We then locate the possible transients on the new catalog file whose coordinates we obtained from visual inspection in the DS9 program and create a graph of pixels versus ADU's that represents a light curve. Light curves are useful because they can be compared to astrophysical models to help us identify the transient source. The subsequent graph below is the light curve of a possible transient.

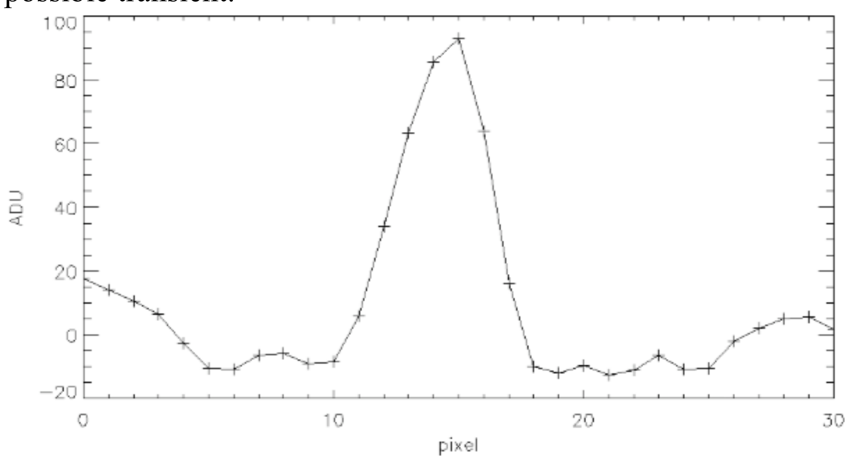
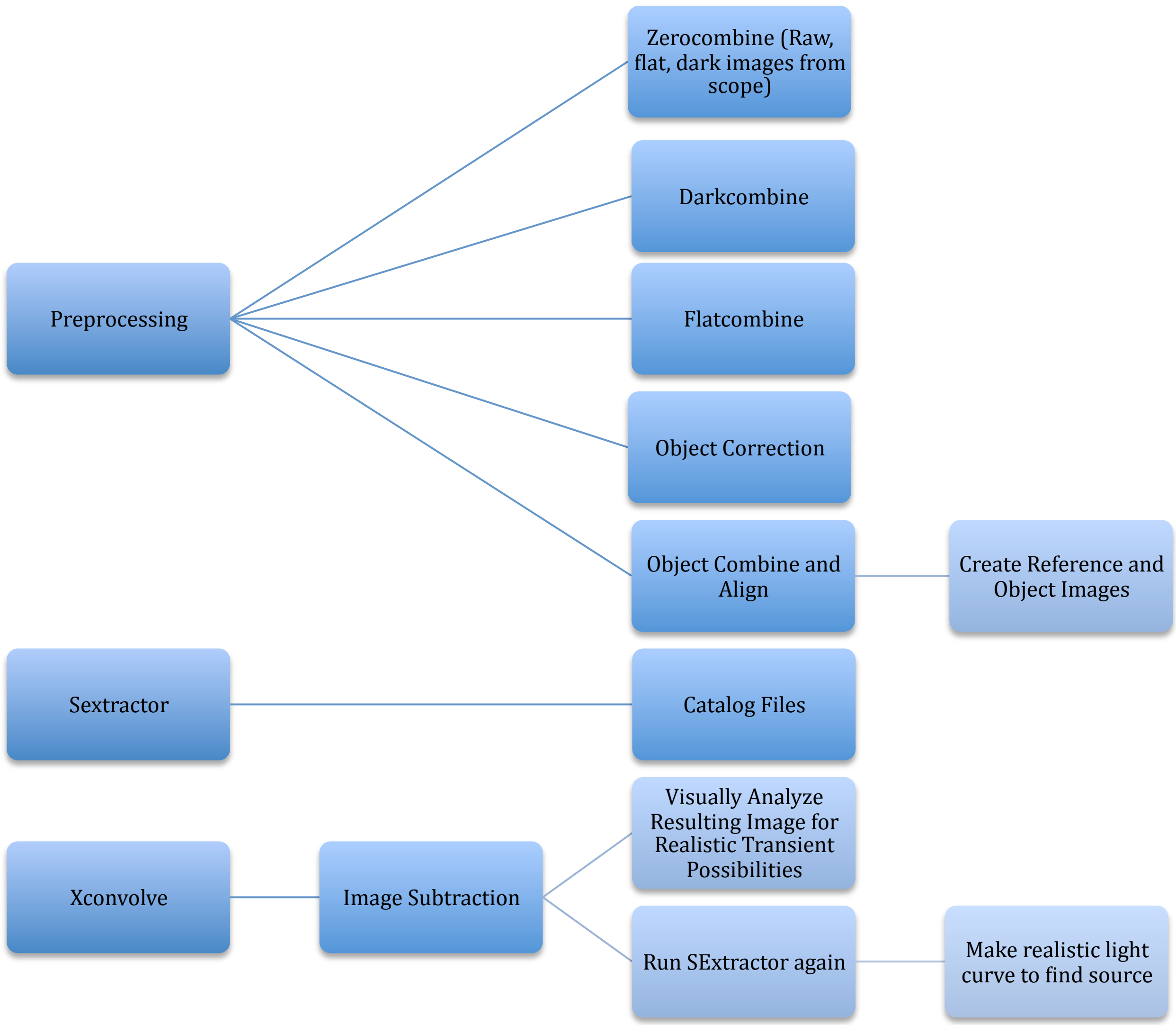


Figure 15: Screen shot of graph made in IDL. It represents a possible transient source's light curve

4. SUMMARY

The entire process can be summarized in the following figure.



5. CONCLUSION

It is important to understand that I am unable to share any of the actual QUEST telescope images that are the property of LIGO and whether we found any real electromagnetic transients that pointed us to gravitational waves. With that aside, this paper describes in detail the methodology used to find optical electromagnetic transients. Studies show that, while the GW position reconstruction is imprecise, it is sufficiently accurate for most even source positions to be observed with technology that is used now and an aggressive observing plan. Reports on the analysis of the QUEST images will be reported in future publications. The scientific rewards of joint GW and EM observations are immense and will become accessible in the near future.

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