Virgo Ego Scientific Forum – VESF school 2011

Optical Image Analysis Tutorial by Marica Branchesi

The main goal of present laboratory is to introduce the students to Optical Image Analysis processing for the detection of the electromagnetic (EM) counterparts of gravitational waves (GW) triggers.

Learning Objectives

- **Starting the use of astronomical software:**
  1) **DS9** – image display tool;
  2) **SExtractor** – astronomical source extractor program;
  3) **Catalog-Based Detection Pipeline** – Octave code under development by the LIGO/Virgo collaborations to detect the Optical counterparts of GW triggers

- **Focusing on basic astronomical concepts:**
  1) optical image's characteristics: field of view (FOV), pixel scale, point spread function (PSF);
  2) image astrometry and photometry;
  3) observed and intrinsic properties of detected EM sources: observed flux, magnitude, angular size, luminosity distance, intrinsic luminosity and intrinsic size;
  5) light curve for optical transient sources;
  6) the possible EM counterpart of GW triggers: Long and Short Gamma Ray Bursts and Kilonova objects showing different intrinsic luminosity and light curve features

Introduction

The students are provided with a set of 10 images taken by TAROT telescope observing the same region of the sky during three consecutive nights. Some optical transients have been injected in the images. The injections were done using LONG and SHORT GRB and kilonova models. The transients were injected in nearby galaxies (within the actual LIGO/Virgo horizon, 50 Mpc) with an offset from the galaxy center in the range of the observed ones for GRBs (within 100 Kpc).

Exercises - Operative Steps

Step 1) DS9 –> to view and analyze FITS files

The students are asked to familiarize themselves with **DS9 tools**, optical images characteristics, image header parameters and **DS9-funtools** to evaluate the source counts in a user-defined region of the image. Reference on-line manual: **http://hea-www.harvard.edu/RD/ds9/ref/**

Startup

- Enter working directory DS9
- To run DS9 from the UNIX command window, enter: **ds9 IM_20100918_080533594_000001_35478102.fits**

Some Basics

- To adjust the image appearance in order to highlight interesting image features, use **Zoom Tab, Color Tab** and **Scale Tab**. Moving the cursor up and down or left and right one can change the image contrast and the brightness, respectively. Clicking the middle mouse button moves the region under the cursor to the center of the window.
- Moving the cursor, the pixel count in ADU (**Value**) and coordinate (**FK5**) are indicated in the gray window. The default WCS (World Coordinate System) coordinates are Sexagesimal Right Ascension and Declination
- To visualize the image header: **File** –> **Display Fits Header**
- To draw a region: **Region Tab** where you can select **Shape**, **Color** etc. Clicking once the left mouse button you can put the region over the image. Clicking twice over the region you can open a new window with the region features that can be changed. **Save** and **Load** options allow to save regions as file.reg and load previously defined regions, respectively. For our purpose: save the region in ds9 format and in WCS coordinate system
- To estimate the counts in defined regions: **Analysis** –> **Funtools** –> **Counts in Regions**
- To load more than one image: **Frame** –> **New Frame** –> **Tile Frame**. The images can be aligned by **Match Frame** –> **WCS**.
  Load in a new frame: dss.fits. This fits-file is an image from the Digital Sky Survey (DSS) taken by UK Schmidt telescope in the same sky region as the TAROT one.

DS9 has many other useful tools to analyze electromagnetic images. One con investigate all the potentiality of **DS9** using the different buttons.

Step 2) SExtractor –> to extract and build a catalog of objects from an optical image

The students are asked to understand how the software works by defining some input parameters in the configuration file, running the software and finally analyzing the SExtractor output images and the catalog output parameters. The simple cookbook by Benne Holwerda *"Source Extractor for Dummies"* and *"SExtractor_v2.5"* manual can be used as reference manuals:
http://astroa.physics.metu.edu.tr/MANUALS/sextractor/

Instructions to follow

- Enter working directory SEXTRACTOR
- Open the SExtractor configuration file (config.sex) and set all the free parameters indicated with XXX. These parameters need to be defined on the basis of the features of the observation and of the telescope.
  - MAG_ZEROPOINT is the zeropoint for the photometric measurements, fundamental to calibrate the magnitude scale. An empirical calibration constant is given in the FITS file header, set the parameter with this value. Differently in the step 3) of the Tutorial the MAG_ZEROPOINT is estimated using a comparison with the USNO-A star catalog in order to have the magnitude in the same color system.

- GAIN is the ratio of the number of electrons to the number of ADU. This parameter is necessary to convert image counts into flux. The TAROT telescope GAIN is equal to 2.8.

- PIXEL SCALE is the pixel size in arcsec. Estimate the PIXEL_SCALE using the flowing formula:

$$\text{PIXEL\_SCALE(arcsec per pixel)} = \frac{\text{PIXEL\_SIZE}(\mu\text{m})}{\text{FOCAL\_LENGTH}} \times \text{k\_(radian to arcsec)} \quad (1)$$

  where PIXEL_SIZE(μm) and FOCAL_LENGTH are given in the image header. Verify that the obtained value is consistent with the image header parameter CDELT1,CDDELT2. Using DS9 the PIXEL_SCALE value can be verified directly in the image.

- SEEING_FWHM is the blurring of a point source as a result of the turbulent Earth's atmosphere. The "SEEING_FWHM" of the present TAROT images has been estimated to be 12 arcsec by using a Gaussian fit of the brightness profile for a sample of not saturated stars.

- BACK_SIZE determines the background map. The mean and the σ of the background distribution of pixel values is computed in an area of BACK_SIZE. A large BACK_SIZE allows to exclude extended object flux in the background estimate, on the other hand small BACK_SIZE allows to reproduce the small scale variations of the background. The choice could be done on the basis of the objects present in the FOV: if there are many extended objects it is more appropriate to use large BACK_SIZE, if there are only point sources it is advisable to adopt small BACK_SIZE. Run SExtractor with different values (32, 64, 128) and identify the more correct value for BACK_SIZE by analyzing the output full-resolution interpolated background image: CHECKIMAGE_TYPE BACKGROUND.

  sex TAROT_image.fits -c config.sex -BACK_SIZE 32 -CHECKIMAGE_NAME bkg32.fits -CHECKIMAGE_TYPE BACKGROUND

  sex TAROT_image.fits -c config.sex -BACK_SIZE 64 -CHECKIMAGE_NAME bkg64.fits -CHECKIMAGE_TYPE BACKGROUND

  sex TAROT_image.fits -c config.sex -BACK_SIZE 128 -CHECKIMAGE_NAME bkg128.fits -CHECKIMAGE_TYPE BACKGROUND

  Open and analyze the output images with DS9.

The other configuration parameters represent a standard setting for the analysis under study. SExtractor considers a group of connected pixels that exceed a certain threshold as an object detection. The threshold (DETECT THRESH) is set 3 times the background RMS standard deviations above the background value and the minimum number of pixels above the threshold required to be considered an object (DETECT MINAREA) is set to 5. In the reference manuals you can find all the details for the other input parameters and different analysis setting.

- Once defined the best setting for the configuration file:

–> run SExtractor with CHEKIMAGE=APERTURES, the output map gives the magnitude integration limits for all the detected objects:

sex TAROT_image.fits -c config.sex -CHECKIMAGE_NAME aperture.fits -CHECKIMAGE_TYPE APERTURES

–> analyze and understand the meaning of the columns of the SExtractor output catalog (**catalog.cat**) using the **configuration.param** and the help of the reference manual *"Source Extractor for Dummies"*.

Step 3) Octave-tools by LIGO/Virgo –> for the image characterization

The students are asked to run tools that allow them to obtain: 1) the **time schedule** of EM observations; 2) the **"magnitude zeropoint"** in order to determine the magnitudes in the color system of a reference star-catalog; 3) the image **"limiting magnitude"** by comparing the SExtractor detected-source counts with a reference catalog source counts in the same region of the sky.

Instructions to follow

- Enter working directory **DETECTIONPIPELINE/utils**.
  The set of 10 EM images taken by TAROT are in the directory **../images**
- **Observation Time Schedule**

  Run GNU Octave (http://www.gnu.org/software/octave/) by editing **octave** and then **makelist("path_to_imagedirectory",gwtriggergps)**

  Set *gwtriggergps* taking into account the **GW trigger** happened at **GPS_time=968745763**

  –> Write in the **"Tutorial Report"** the image observation date and the time delay (in seconds) from the GW trigger.
- **Image "Magnitude Zeropoint"**

  octave –> **estimatezeropoint("path_to_imagedirectory",debuglevel)**,
  debuglevel=2 for graphics output

  estimatezeropoint.m evaluates the "magnitude zeropoint" using a linear least squares fit between the reference catalog magnitudes and SExtractor not calibrated magnitudes ($= -2.5 \times \log_{10}$(flux[ADUcounts]) for common stars. The reference star-cataolog used is USNO-A (directory ../data) and the USNO-A red magnitude reference system is R1 (first epoch red magnitude derived from the POSS-I 103aE or ESO-R plate).

  –> Analyze the "zeropoint-plots" (directory PLOT) and write the "zeropoint" for each image and the "mean zeropoint" for all the images in the **Tutorial Report**.

  estimatezeropoint.m writes an output file (zeropoint.dat) in the directory config. This value is used by SExtractor as MAG_ZEROPOINT in order to obtain directly the magnitudes in the USNO-A red reference system.
- **Image "Limiting Magnitude":**

  octave –> **limitmagnitude("path_to_imagedirectory",refcatalog,centralradius,debuglevel)**

where *refcataolog="USNO"* is the reference catalog USNO-A,
centralradius is the radius used to restrict the FOV to a central circular region to avoid problems at image edges. For TAROT images set *centralradius=0.8*.

limitmagnitude.m builds the distribution of the detected object counts vs magnitude and estimates the limiting magnitude from the comparison with a reference-catalog source counts. The limiting magnitude of the observations is estimated by identifying the point where the incompleteness effect starts to take place, that is the point where the source counts (vs magnitude) bends and move away from the power law of the reference catalog.

The output plots (directory PLOT) show:
- the differential number counts in bins of magnitude equal to 0.5 (count(0.5magbin)/sqdegree) (left top panel);
- the cumulative number counts (count($<$ mag)/sqdegree, total number of sources with a magnitude $\leq mag$) (left bottom panel);
- the difference between image and reference catalog counts divided by the combined count error (right panels).

–> Write the "limiting magnitude" of each image in **Tutorial Report**.

Step 4) Catalog-based Detection Pipeline by LIGO/Virgo –> to detect the optical transient counterparts of the GW trigger.
The students will be asked to familiarize themselves with the pipeline by defining the correct input parameters, by running the Octave Code and analyzing the output information about optical transients and nearby galaxies hosting the GW sources.

- Enter working directory **DETECTIONPIPELINE/mfiles**
- Open **analyzedemo.m**, the file calls **analyze.m** that is the core of the Catalog-Based detection pipeline. The parameters to set are *centralradius, matchradius, limitdist, limitslopeidx, gwtriggergps, debuglevel.*
  - *centralradius* is the radius in degree to restrict the region of FOV to the one not affected by aberrations and sensitivity problems. For TAROT set centralradius=0.8;
  - *matchradius* is the distance in arcsec within which the positional cross-check tools look for common objects. It is used: 1) to search for 'known objects' in the FOV, object in common with the reference-catalog (**match.m**) and 2) to search for objects in common to several images (**objectincommon.m**, used to reject rapid contaminating transient like cosmic rays, asteroids and noise). *matchradius* must be chosen on the base of the position uncertainties: for TAROT images *matchradius* = 10 arcsec;.
  - *limitdist* is the distance in Mpc within which **onsource.m** searches for Globular Clusters and Galaxies in the Gravitational Waves Galaxy Catalog (GWGCCatalog.txt directory data). The search volume for the EM counterparts is limited taking into account the LIGO/Virgo horizon: a stellar mass Black hole binary inspiral is detected up to a distance of 50 Mpc.
  - *inflatiofactor* to define the region of the image around the position of nearby Globular Clusters and Galaxies where the EM counterparts are searched:

on-source radius = inflationFactor × galaxy major_semiaxis
In order to take into account the large offset between GRB and galaxy center (up to 100 kpc) an *inflatiofactor*=4 is suggested.

- *gwtriggergps* GPS time of the GW trigger, that is considered the time origin for the EM transient. For the present images *gwtriggergps* = 968745763;
- *limitslopeidx* is used in **checklightcurve.m** tool that select the possible EM transient counterpart from contaminating objects. The objects considered as the possible EM counterparts are the ones that pass a cut defined on the basis of the luminosity dimming expected for SHORT/LONG GRB and kilonova objects. The expected slope index (defined as $(2.5 \times \beta)$ from Luminosity $\propto$ time$^{-\beta}$) for SHORT/LONG GRBs and kilonova objects is around 2.5-3. The code builds the light curve for each potential optical transients and estimates the slope index, it selects as possible EM transient counterparts the ones with a slope index higher than 0.5 (*limitslopeidx*=0.5). This value has been estimated to be appropriate to select the EM counterparts by using Monte Carlo simulations.
- *debuglevel* to set equal to 4 for graphics output (saved in the directory PLOT) and some useful result table (saved in the directory RESULTS).

• Run **octave** –> **analyzedemo**

• Analyze the screen output to follow the different pipeline steps and the results.

• Analyze the plots and the output table. The columns of the "galaxy table" contain the following information: Object Name, Right Ascension(J2000) in degree, Declination(J2000) in degree, Major Diameter in arcmin, Minor Diameter in arcmin, Position Angle (degrees from north through east, all $< 180^o$)), Distance in Mpc. The columns of the "transients' tables" contain: RA(J2000) in degree, Dec(J2000) in degree and the red magnitude estimated in the first image.

• Write in the **"Tutorial Report"** all the required information about optical transients and galaxies within the LIGO/Virgo horizon.

Step 5) Octave-tools by LIGO/Virgo –> to analyze different models of optical transient afterglow for the GW sources

• Enter working directory **DETECTIONPIPELINE/utils**

• Use **TAROT_obervation.m** to plot the expected LONG, SHORT GRB and kilonova optical afterglow for a specified distance in Mpc, the image limiting magnitude and the image observation times from the GW trigger.

–> Open **TAROT_obervation.m** and set the GW source distances (found in step 3), the GW trigger time and the image limiting magnitude (found in step 2);

–> Run **octave** –> **TAROT_obervation**

On the basis of the galaxy distance and the TAROT image limiting magnitude, the students are asked to evaluate what type of transients (LONG, SHORT GRB or Kilonova) can be observed with the present images. This allows them to identify the transients that have been previously injected in the images.

Step 6) DS9 –> to visualize the "Detection Pipeline" results and verify the results directly in the images.

- Use **DS9** to visualize in the image the GW transients and the host galaxies (found in step 4)
- Draw the on-source regions and verify that the transients are within them.
- Use **ds9-funtools** to estimate the image counts for the transient and the local background. Then calculate the transient apparent magnitude using the following formula:

  $$m_R = -2.5\times(\text{net\_source\_counts}) + \text{zeropoint} = -2.5\times(\text{total\_source\_counts} - \text{bkg\_counts}) + \text{zeropoint} \quad (2)$$

  Verify that the estimated value is consistent with the one estimated by SExtractor.

Step 7) - Estimation of the absolute magnitude of the transient and physical offset (in Kpc) from the host galaxy center

The student are asked to calculated the intrinsic properties of a transient by knowing apparent (observed) properties and the luminosity distance of the host galaxy.

- Estimate the red "absolute magnitude" for the transients. The absolute magnitude M is the apparent magnitude the body would have if viewed from a distance of 10 parsecs. Since all stars would be placed at the same distance, absolute magnitudes are a measures of star's intrinsic luminosities. Derive the formula to calculate the "absolute magnitude" (in terms of apparent magnitude m and luminosity distance D) using the luminosity-flux relation:

  $$\text{Luminosity} = 4\pi D^2 f \quad (3)$$

  where D is the luminosity distance in Mpc and f the source flux, and the general definition of the apparent magnitude

  $$m - m_o = -2.5\log_{10}\frac{f}{f_o} \quad (4)$$

  where m_o and f_o are the apparent magnitude and flux at a reference distance. In order that the absolute magnitude is a measure of the real intrinsic luminosity it is necessary to correct the absolute magnitude for our Galaxy and the transient intrinsic extinction, but the students can neglect the corrections for the present Tutorial;

- Estimate the distance (in kpc) between the transient and the host galaxy center by knowing the luminosity distance and the angular size and using geometrical considerations. Since size scale "kpc/arcsec" depends on redshift and cosmological model, use a cosmology calculators (e.g. http://www.astro.ucla.edu/ wright/CosmoCalc.html) to verify your approximate estimation.

Step 8) - If there is still time left...
Enlarge the on-source regions and verify if there are other optical transients that pass the light curve check and could be considered possible EM counterparts. −> Repeat step 4 by using an *inflationfactor =8* −> If there are new transients, repeat the following steps 5) 6) 7) after the injected distances (not associated to nearby galaxies) are revealed.