Electromagnetic Follow-Up of Gravitational Wave Transient Signal Candidates

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The goal of LIGO and Virgo interferometers is the first direct detection of gravitational waves from ENERGETIC ASTROPHYSICAL events:

- Mergers of Neutron Stars and/or Black Holes
  - SHORT GRB
  - Kilonovae
  - EM burst

- Core Collapse of Massive Stars
  - Supernovae
  - LONG GRB

- Cosmic String Cusps

Main motivations for joint GW/EM observations:

- Increase the GW detection confidence;
- Get a precise (arcsecond) localization, identify host galaxy;
- Provide insight into the progenitor physics;
- In the long term start a joint GW/EM cosmology.
Low-latency GW data analysis pipelines allow the use of GW triggers in real time to obtain prompt EM observations and to search for EM counterparts.
The first program of EM follow-up to GW candidates has been performed during two LIGO/Virgo observing periods:

Dec 17 2009 to Jan 8 2010 – Winter Run
Sep 4 to Oct 20 2010 – Summer Run

The EM-follow-up program in S6-VSR2/3 is a milestone towards the advanced detectors era where the chances of GW detections are strongly enhanced.

Presentation Highlights:

- GW-data analysis for a prompt EM follow-up
- EM-observation strategy
- Image analysis procedures to identify the EM-counterpart
GW Online Analysis

- LIGO (H1 and L1) and Virgo (V1) interferometers
- For Unmodeled Bursts
- For signals from Compact Binary Coalescence

“LIGO/Virgo Search Algorithms”

to identify the GW-triggers

GW-TRIGGER ARCHIVE

“LIGO/Virgo Software”
to identify the GW-trigger for the EM follow-up

10 min.

Event Validation

30 min.

Send alert to telescope

• Select Statistically Significant Triggers
• Determine Pointing Locations
Requirements to select a trigger as a candidate for the EM follow-up:

- Event occurring in simultaneous observations of all three detectors
- Power above a threshold estimated from the distribution of background events:
  
<table>
<thead>
<tr>
<th>Season</th>
<th>False Alarm Rate</th>
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<tbody>
<tr>
<td>Winter Run</td>
<td>&lt; 1.00 event per Day</td>
</tr>
<tr>
<td>Summer Run</td>
<td>&lt; 0.25 event per Day for most of optical facilities</td>
</tr>
<tr>
<td></td>
<td>&lt; 0.10 event per Day for PTF and Swift</td>
</tr>
</tbody>
</table>

GW Source Sky Localization:

- low SNR signals are localized into regions of tens of square degrees possibly in several disconnected patches
- Necessity of wide field of view telescopes

LIGO/Virgo horizon:

- a stellarmass BH/ NS binary inspiral detected out to 50 Mpc, distance that includes thousands of galaxies
- GW observable sources are likely to be extragalactic

EM-observation is restricted to the regions occupied by Globular Clusters and Galaxies within 50 Mpc

(GWGC catalog White et al. 2011, CQG 28, 085016)
Nearby galaxies and globular clusters (< 50 Mpc) are weighted to select the most probable host of a GW trigger:

\[
P = \frac{\text{Mass} \times \text{Likelihood}}{\text{Distance}}
\]

- **Likelihood** based on GW data
- **Mass** and **Distance** of the galaxy or the globular cluster

**Probability Skymap for a simulated GW event**

- Black crosses → nearby galaxies locations
- Rectangles → pointing telescope fields chosen to maximize the chance to detect the EM counterpart
Observed **on-axis LONG and SHORT GRB** afterglows peak **few minutes** after the EM/GW prompt emission

**Kilonova model** afterglow peaks about **a day** after the GW event

To discriminate the possible EM counterpart from contaminating transients

→ EM observations as soon as possible after the GW trigger validation

→ EM observations a day after the GW trigger validation

→ repeated observations over **several nights** to study the light curve
Ground-based and space EM facilities observing the sky at Optical, X-ray and Radio wavelengths involved in the follow-up program

**Optical Telescopes**

1. **TAROT SOUTH/NORTH** 3.4 sq. degree FOV
2. **Zadko** 0.17 sq. degree FOV
3. **ROTSE** 3.4 sq. degree FOV
4. **QUEST** 9.4 sq. degree FOV
5. **SkyMapper** 5.7 sq. degree FOV
6. **Pi of the Sky** 400 sq. degree FOV
7. **Liverpool telescope** 21 sq. arcminute FOV

**X-ray and UV/Optical Telescope**

1. **Swift Satellite** 0.15 sq. degree FOV

**Radio Interferometer**

1. **LOFAR** 30 - 80 MHz
2. **EVLA** 5 GHz - 25 sq. arcminute FOV
3. **Liverpool telescope** 21 sq. arcminute FOV
4. **Palomar Transient Factory** 7.8 sq. degree FOV
5. **QUEST** 9.4 sq. degree FOV
6. **Zadko** 0.17 sq. degree FOV
7. **ROTSE** 3.4 sq. degree FOV
8. **TAROT SOUTH/NORTH** 3.4 sq. degree FOV
9. **Pi of the Sky** 400 sq. degree FOV
Winter run → 8 candidate GW triggers, 4 observed by at least one telescope
Summer run → 6 candidate GW triggers, 5 observed by at least one telescope

Analysis Procedure for Wide Field Optical Images

Limited Sky localization of GW interferometers

Wide field of view optical images

Require to develop specific methods to detect the Optical Transient Counterpart of the GW trigger

Main steps for an EM-counterpart Detection Pipeline:

1) Detection of all “Transient Objects” visible in the target images
2) Discriminate the EM-counterpart from “Contaminating Transients”
LIGO/Virgo collaborations with partner astronomers are actually testing and developing several Image Analysis Techniques to 1) identify the “Transient Objects” based on:

- **Image Subtraction Methods**
  (for Palomar Transient Factory, ROTSE and SkyMapper)

- **Catalog Cross-Check Methods**
  (for TAROT, Zadko, QUEST and Pi of the Sky)

Followed by the 2) “EM counterpart identification” from the background/contaminating events based on:

- analysis of transient light curves

The removing of contaminating transients is one the main challenges due to the “large sky area” to analyze image areas occupied by globular cluster and galaxies (< 50 Mpc) that take into account the possible offset between the host center and the transient
The next 5 slides focuses on a **Fully automated “Catalog-based Detection Pipeline”** developed for images taken with **TAROT** and **Zadko telescopes:** methodology and preliminary results obtained using images where simulated transient are injected.

**TAROT South/North**
- **0.25 meter** telescope
- **FOV 3.4** sq. degrees
- **Single Field** Observation of **180 s** exposure
- Red **limiting magnitude** of **17.5**

**Zadko**
- **1 meter** telescope
- **FOV 0.17** sq. degrees
- **Five Fields** Observation of **120 s** exposure
- Red **limiting magnitude** of **20.5**

**Afterglow Light Curves** (source distance $d=50$ Mpc)

**“Afterglow light curves”** for LONG/SHORT and Kilonova transients at a distance of 50 Mpc

<table>
<thead>
<tr>
<th>Time (days)</th>
<th>Apparent Red magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-1}$</td>
<td>30</td>
</tr>
<tr>
<td>$10^{1}$</td>
<td>25</td>
</tr>
<tr>
<td>$10^{2}$</td>
<td>20</td>
</tr>
<tr>
<td>$10^{3}$</td>
<td>15</td>
</tr>
</tbody>
</table>

- **LONG GRB**
- **SHORT GRB**
- **KILONOVA**

- **TAROT limiting magnitude**
- **Zadko limiting magnitude**
**Catalog-based Detection Pipeline** – Octave Code

- **detect sources in each image**
- **select “unknown objects”**
- **Magnitude consistency**
- **search for objects in common to several images**

**SExtractor** ➔ build catalog of all the objects visible in each image

**Match** (Valdes et al 1995; Droege et al 2006) ➔ to identify “known stars” in **USNO catalog** (catalog of stars)

Recover possible transients that overlap with “known objects”:

\[ |\text{USNO}_\text{mag} - \text{TAROT}_\text{mag}| > 4\sigma \]

**Spatial cross-positional check**

- **ON-SOURCE** ANALYSIS
  - regions occupied by galaxies with a distance within 50 Mpc

- **ALL-FOV ANALYSIS**
  - select objects with magnitude brighter than a threshold

  - reject “contaminating objects” (galaxy, variable stars, false transients..)

**“Light curve” analysis: slope index**

- reject cosmic rays, noise, asteroids
- reject background events
"Light curve" analysis - cut based on the expected luminosity dimming of the EM counterparts

Recall magnitude \( \alpha [-2.5 \log_{10} (\text{Luminosity})] \)

Expect luminosity \( \alpha [\text{time}^{-\beta}] \rightarrow \text{magnitude} = [2.5 \beta \log_{10}(\text{time})]+k \)

Slope index = measurement of \((2.5 \beta)\) to discriminate expected light curve from "contaminating events"

The expected slope index for SHORT/LONG GRB is around 2.7 and kilonova is around 3

Optical counterparts the ones with slope index > 0.5

Contaminating objects that could pass the cut are only variable AGN or Cepheid stars

Coloured points = Optical LGRB Transients
Black squares = contaminating objects
used a set of 10 test TAROT images (180 sec exposure)
limiting magnitude of 15.5 for all images

Image Limiting Magnitude:
point where Differential/Integral Source Counts distribution (vs magnitude) bends and moves away from the power law of the reference USNOA
Preliminary results on Sensitivity: obtained by running the Detection Pipeline over images with injections of Fake Transients

Monte Carlo simulations at the Computing Center in Lyon:
- Time origin (time of GW trigger) set 1 day before the first image
- Time latency for the images 1, 2, 3 days after the GW trigger

**SHORT/HARD GRB**

**LONG/SOFT GRB**

**Kilonova Objects**

Efficiency loss at low distances is an artifact of the "injection code" not able to reproduce saturated objects

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SGRB, LGRB $\rightarrow$ intrinsic luminosity range parametrized by a magnitude offset $0 \div 8$
SGRB, LGRB: random offset $0 \div 8$
SGRB0, LGRB0: offset set to 0
SGRB8, LGRB8: offset set to 8

Distance_50% horizon (Mpc):

<table>
<thead>
<tr>
<th>Object</th>
<th>SGRB</th>
<th>SGRB0</th>
<th>SGRB8</th>
<th>Kilonova</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30</td>
<td>230</td>
<td>------</td>
<td>15</td>
</tr>
</tbody>
</table>

0.8
0.6
0.4
0.2
1

Efficiency vs. Distance (Mpc)

10^1
10^2
10^3
10^4

10
10^1
10^2
10^3
10^4

10
10^1
10^2
10^3
10^4
### Observation Strategy:

- possibility to observe **five 0.15 sq. degree XRT-FOV** for each GW-trigger
- **two-time** observations: time latency few months
- **exposure time**: 10 ks to split within fields necessary to cover the target

### X-ray image analysis:

- detection of the **X-ray sources** visible in the FOV
- **comparison with the number of serendipitous sources** expected in the FOV
  that is estimated using the 2XMMi-DR3 catalog source counts
- **light curve** of each source to investigate the variability

### Optical and UV analysis:

- search of the **UVOT counterparts** of the X-ray sources detected with XRT
- **cross-check with DSS** catalog to identify “unknown objects” or objects that show flux variations
- **light curve** to investigate source variability in the images
Radio Interferometers

Radio-band Advantages:
- observations in daylight and no obscuration by dust
- radio arrays (nowadays LOFAR) cover multiple sky patches of few tens of sq. degrees in a single observation
- Possibility to observe EM-counterpart not detected in other EM-bands

LOw Frequency ARray

- currently 36 antennas: Core in the Netherlands + stations across Europe
- Frequency range: 30-80/110-240 MHz

5 candidate GW-trigger alerts sent and observed by LOFAR

Observation Strategy:
- Four-hour observation in LOFAR high frequency band ➔ 25 sq. degree FOV

Analysis Strategy (LIGO/Virgo + LOFAR Transients Key Project members):
- transient detection and estimation of astrophysical/technical radio background

“Technical Challenges”:
- automated analysis procedure to detect transients still under development
- low-frequency sky: noise transients from the atmosphere (like meteor trail) and time/space varying ionosphere

The analysis of radio data for the 5 target fields is on-going
Expanded Very Large Array

- Array of **27 antennas**, each of which **25 meters** in diameter
- Point-source sensitivity after one hour observation between **2 and 6μJy** (1 and 50 GHz)
- FOV of **25 sq. arcminutes** at 5 GHz

**Observation Strategy:**

- **Low-Latency Follow-up** (October 14 to 20) → No Science GW-trigger
- **High-Latency Follow-up** → 2 GW-triggers (first days of October)

**Observation Latency:** 3 weeks, 5 weeks + 8 months later

**Observation Frequency:** 5GHz, bandwidth 128MHz

**TARGET:** 3 most likely host galaxies (< 50 Mpc) for each GW-trigger

Mosaic of pointings if galaxy size exceeds 5 arcmin

**Integration Time:** 30 minutes for each galaxy

**Analysis Strategy** (LIGO/Virgo + radio-astronomers):

- detection of the **radio sources** in the FOV
- light curves for variability study
- identification of contaminating **radio sources**, like Radio Active Galactic Nucleii

Fox et al. 2005, Nature 437,835
Conclusions:

- The first EM-follow-ups to GW candidates have been performed by the LIGO/Virgo community and several Partner EM-Observatories.

- Different procedures to detect the “EM-counterpart” of a GW-candidate event 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 analysis of the images observed during the Winter/Summer LIGO/Virgo run is on-going.
Extra Slide
Selection of model stars nearby to the injection position in order to take into account the PSF variations.

Injection by normalizing the star magnitude to the magnitude expected for on-axis SHORT/LONG GRB or Kilonova object at different times after the GW/EM prompt event.