Pi of the Sky – preparation for GW Advance Detector Era

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Wilga 2014
Gravitational waves predicted by Einstein's theory of general relativity are still undetected. Among possible detectable sources of gravitational waves there are NS-NS mergers, NS-BH mergers and supernovae, which all could give an optical transient in the V band. If an event occurs in gravitational wave detectors and at almost the same time an optical transient is observed from the same direction that the event candidate came from then it might be a good hint that the event candidate might be a real gravitational wave signal. This paper describes methods used by Pi of the Sky for optical transient search within the Looc-Up project and a proposal of the new methods for future Looc-Up science runs.
Gravitational Waves

\[ G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \]

\[ I_{ij} = \int \left( x_i x_j - \frac{1}{3} \delta_{ij} \delta_{km} x^k x^m \right) \rho(x) \, d^3x \]

\[ h_{ij}^{TT} = \frac{2G}{c^4} \frac{1}{R} P_{ijmn} \dddot{\theta}^{mn} \left( t - \frac{R}{c} \right) \]
Binary Coalescence and Supernova Explosions

• Neutron star / Blackhole binaries

• Supernova
Detection of gravitational waves
Range of LIGO and Advanced LIGO interferometer
Pi of the Sky - Scopes

INTA (Spain)
- 4 mounts with 4 cameras that might work in coincidence or not
- Each camera
  - FOV: 20 [deg] x 20 [deg]
  - Limiting brightness: 12 mag
  - Exposition time: 10 s

San Pedro de Atacama (Chile)
- 2 cameras working in coincidence
- Each camera
  - FOV: 20 [deg] x 20 [deg]
  - Limiting brightness: 12 mag
  - Exposition time: 10 s
Overview of Pi of the Sky system used for Looc-Up

• Camera:
  – FOV: 20 deg x 20 deg
  – Exposure time: 10 s
  – Limiting magnitude: 12 mag
  – CCD: 2 K x 2 K

• Observation site:
  – Koczargi Stare near Warsaw, Poland
Looc-Up Project

An observation of an astrophysical event in both gravitational and optical band might bring very significant scientific results and could be the first step toward the direct detection of gravitational waves. The main aim of the LoocUp project, initiated by LSC and Virgo collaborations and several other electromagnetic (EM) observation teams, was to try to find such a coincidence by doing an electromagnetic follow-up of the most promising GW event candidates selected by the low-latency analysis of LIGO and Virgo detector data.

The first Looc-Up science run took place in 2009-2010. Nine astronomical teams and the Swift satellite team took part in it. Scopes of those teams were placed all over the world.

Methods paper was published in 2012.

The was publish in 2014 in ApJS.
FIRST SEARCHES FOR OPTICAL COUNTERPARTS TO GRAVITATIONAL-WAVE CANDIDATE EVENTS

Locating and Observing Optical Counterparts to Unmodeled Pulses

• Search for an optical counterpart to a gravitational waves event
  – to confirm an event
  – to gather more information

• Two past science runs in 2009-2010
Telescopes Involved in Looc-Up Project

<table>
<thead>
<tr>
<th>Name</th>
<th>Band</th>
<th>FOV (square degrees)</th>
<th>Aperture (m)</th>
<th>Exposure Time (s)</th>
<th>Limiting Magnitude</th>
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<tbody>
<tr>
<td>Palomar Transient Factory</td>
<td>Optical</td>
<td>7.3</td>
<td>1.2</td>
<td>60</td>
<td>20.5</td>
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<td>Pi of the Sky</td>
<td>Optical</td>
<td>400</td>
<td>0.072</td>
<td>10</td>
<td>11.5</td>
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<tr>
<td>QUEST</td>
<td>Optical</td>
<td>9.4</td>
<td>1</td>
<td>60</td>
<td>20</td>
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<td>ROTSE III</td>
<td>Optical</td>
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<td>0.45</td>
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<td>17.5</td>
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<td>SkyMapper</td>
<td>Optical</td>
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<td>1.35</td>
<td>110</td>
<td>21</td>
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<tr>
<td>TAROT</td>
<td>Optical</td>
<td>3.4</td>
<td>0.25</td>
<td>180</td>
<td>17.5</td>
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<tr>
<td>Zadko Telescope</td>
<td>Optical</td>
<td>0.15</td>
<td>1</td>
<td>180</td>
<td>20</td>
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<tr>
<td>Liverpool Telescope</td>
<td>Optical</td>
<td>0.0058</td>
<td>2</td>
<td>3600</td>
<td>21</td>
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<tr>
<td>LOFAR</td>
<td>Radio</td>
<td>~25</td>
<td>N/A</td>
<td>14400</td>
<td>N/A</td>
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<tr>
<td>Swift</td>
<td>X-ray</td>
<td>0.15</td>
<td>N/A</td>
<td>200-5000</td>
<td>N/A</td>
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<tr>
<td>Swift</td>
<td>UV, Optical</td>
<td>0.078</td>
<td>0.3</td>
<td>200-5000</td>
<td>24</td>
</tr>
</tbody>
</table>
A Simplified Flowachart of the Online Analysis [1.]
Sky localization
Models of possible sources

- Long GRB
  - Long GRB off-axis
- Short GRB
  - Short GRB off-axis
- Supernovae
- Kilonovae
- Other …
Pipeline

• For analysis we used catalog based pipeline
• As a seed for star catalog we used Guide Star Catalog with stars up to 11 mag
• For each exposition we add all recognized stars to the databases with their brightness measurements
  – Normalization of brightness to V magnitudes from the TYCHO catalog
Transient Search for Looc-Up

• Transient search using PotS nova algorithm:
  – Looking for new objects that fulfill quality constrains
  – Looking for objects that suddenly increase their brightness more than 2 mag
  – All transients are undergoing human inspection

• Objects that are suspected to be transients were cross-correlated with INTA images taken few months later
Pipeline Efficiency

Steps of Pi of the Sky analysis

- New Star
- NOVA > 1
- NOVA > 5

Efficiency [-]

Magnitude [mag]
Lesson Learned

• With Pi of the Sky system it is possible to image huge part (1200 deg^2) of the sky within less than an 15 minutes taking multiple images of each field

• On-line transient recognition might be helpful in next run for effective transients observation and recognition
  – And possibly to provide transient for other scopes
Improving efficiency for possible events

• Lowering constrains for events that are in most probable regions of a sky maps of gravitational event candidate

• Inspecting all objects that are near to galaxies that might be a source of gravitational waves (closer than 100 MPc)
Advanced Detector Era

• Currently Virgo and LIGO detectors are being upgraded and they should become operational in 2015 (2016)

• For the upcoming years, till the end of decade, detector’s sensitivity curve are planned to be improved

• Continuous observation of sky in gravitational wave band are planned to start from 2019+
Outline of planned science runs

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Estimated Run Duration</th>
<th>$E_{GW} = 10^{-2}M_\odot c^2$ Burst Range (Mpc)</th>
<th>BNS Range (Mpc)</th>
<th>Number of BNS Detections</th>
<th>% BNS Localized within 5 deg²</th>
<th>% BNS Localized within 20 deg²</th>
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<td></td>
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<td>Virgo</td>
<td>LIGO</td>
<td>Virgo</td>
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<td>2015</td>
<td>3 months</td>
<td>40–60</td>
<td>–</td>
<td>40–80</td>
<td>–</td>
<td>0.0004–3</td>
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<tr>
<td>2016–17</td>
<td>6 months</td>
<td>60–75</td>
<td>20–40</td>
<td>80–120</td>
<td>20–60</td>
<td>0.006–20</td>
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<td>2017–18</td>
<td>9 months</td>
<td>75–90</td>
<td>40–50</td>
<td>120–170</td>
<td>60–85</td>
<td>0.04–100</td>
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<td>2019+ (India)</td>
<td>(per year)</td>
<td>105</td>
<td>40–80</td>
<td>200</td>
<td>65–130</td>
<td>0.2–200</td>
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<tr>
<td>2022+ (India)</td>
<td>(per year)</td>
<td>105</td>
<td>80</td>
<td>200</td>
<td>130</td>
<td>0.4–400</td>
</tr>
</tbody>
</table>
Advanced Detector Era
False Alarm Rate

- additional conformation might be need for low frequency burst signals
EM Follow-up

• EM Follow-up of GW triggers would be carried out by LSC-Virgo and astronomical partners

• MOUs are already been signed and about 60 teams were interested. Next call for MOU is planned in 2015. (Pi of the Sky signed MOU)

• After four successful detections of GW all trigger are going to be publicly available
Gravitational Wave Galaxy Catalogue
PREPARATIONS
Fast cross-correlation with GWGC

• The first step towards AdE would be to allow easy correlation of observed transients with GWGC

• All alerts could be cross-correlated with GWGC and shifter could get immediate information about correlation

• For data taken for EM Follow-up 2009-2010 about 80 objects was associated with GWGC for one alert. So this data was easy for human inspection.
Enhancing On-line Algorithm

• Transient candidates, connected with GWGC objects, that passes very basic cuts would be considered as valid. Information about failed quality cuts would be added do results.

• Implementation of this algorithm is tricky to make it work in low-latency (it requires px,py -> ra,dec)
  – But under the assumption that for every fifth frame astrometry is done it is possible
Enhancing Off-line Algorithm

- Identify transients connected to GWGC objects
- Transients that are linked with GWGC, would be added to results with information about the cuts that their failed, if any.
Object from GWGC catalogue visible for Pi of the Sky

• In order to prepare for Advanced Detector Era, it would be worth to gather information about objects that are visible to PotS and estimate their brightness (min, max, median value)

• Estimation of brightness of GWGC objects would allow to construct better algorithms for online and offline transients search in AdE
Summary

• Pi of the Sky took part in LSC-Virgo EM Follow-up Project 2009-2010 (Results are published in ApJS in 2014) and have signed MOU for AdE time

• The system would be most helpful in the first few runs science runs of EM Follow-up project

• Enhanced data analysis algorithms or methodologies might be used as well for other teams