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Search for Spatial and Temporal Coincidence Between *Fermi*-LAT Exposure Maps and Gravitational Wave Sky Localizations

Alessandra Berretta,[1] Sara Cutini,[2] Giuseppe Greco,[2] Gino Tosti,[1] Pasquale Lubrano,[2] Stefano Germani,[1] Marica Branchesi,[3] Michele Punturo,[2] Pierre Fernique,[4] Thomas Boch,[4] Matthieu Baumann,[4] Francois-Xavier Pineau,[4] Sébastien Derriere,[4] Ada Nebot,[4] and Mark Allen[4]

[1]*Università degli Studi di Perugia and INFN Perugia, Perugia, PG, Italy,* `alessandra.berretta@pg.infn.it`

[2]*INFN Perugia, Perugia, PG, Italy*

[3]*Gran Sasso Science Institute, L'Aquila, AQ, Italy*

[4]*Université de Strasbourg, CNRS, Observatoire astronomique de Strasbourg, Strasbourg, France*

Abstract. We describe a practical method for searching for spatial and temporal coincidence of the *Fermi*-LAT exposure maps over a gravitational-wave sky localization. The method provides in output the overlap region between multi-frequency sky areas within a proper time window selected by the user. This approach offers a prompt setting of the observational strategies for searching for potential electromagnetic candidates as well as for a fast cross-matching between the LAT and the LIGO, Virgo and KAGRA databases for dedicated post-processing analysis. The tasks are performed using the encoded standard method named Multi Order Coverage Map and visualized in the Aladin Desktop.

1. Introduction

On August 17th, 2017, we were able to observe the first Gravitational Wave (GW) event, produced after the merge of two Neutron Stars (NSs), and its electromagnetic counterpart, in the form of a short Gamma-Ray Burst (sGRB) and a following kilonova (Abbott et al. 2017c,a,d). This event led the foundations of Multi-Messenger astronomy.
The typical localization area of a GW is of the order of hundreds of square degrees, so localizing an electromagnetic counterpart with gamma-rays telescopes, such as *Fermi*, is very challenging. For this reason, more and more advanced tools are continuously developed, in order to support the follow-up of GW events. The Multi Order Coverage (MOC) method is particularly suitable for this purpose because it allows the user to reconstruct and make logical operations between different sky regions, obtained from various experiments, in an intuitive way (Fernique et al. 2014).

2. Multi Order Coverage map method

The MOC method is one of the standard algorithms developed within the International Virtual Observatory Alliance context. The MOC procedure can reconstruct a sky region and compute logical operations such as the intersection, the union and the equality between different maps. The MOC is based on HEALPix (Gorski et al. 2005) and makes use of the nested indexing scheme which characterizes the sky location and the HEALPix order of each cell on the MOC map. MOC maps can be created at a given resolution by the choice of the highest order indexes. A MOC is then represented as a list of pairs (level, indexes) that can be stored in a file.
In this study we used a particular extension of the MOC method called Space Time MOC (STMOC), in which the space and time coverage are connected in order to easily understand where and when the observations took place (Durand et al. 2019).

3. LAT exposure map and LIGO/Virgo GW170104

The LAT exposure map (*Fermi* LAT Collaboration 2008) can be seen as an Aitoff projection of the sky seen by the telescope in a certain time window after a chosen trigger, in which you can find the total exposure - area multiplied by time - for a given position on the sky. Since the expected number of events is a function of the photons' energy, also the exposure map has a dependency on the energy. In this sense the counts produced by a source, at any given position, can be estimated by integrating the source flux and the exposure map at the same position.
We used the example of the GW170104 event (Abbott et al. 2017b), downloaded from the public LIGO/Virgo database called Gravitational Wave Open Science Center (Abbott et al. 2019). Then we obtained the LAT exposure map in 10000 s after the trigger time of GW1701004.

4. STMOC intersection map of LAT exposure map and LIGO/Virgo skymap

We used the Aladin interface to visualize and make logical operations between the MOC map Fig. 1. The first step consisted in selecting all the most exposed pixels in the LAT exposure map, in order to compute the Spatial MOC map. We decided to consider only the pixels with values greater than 10^7 cm^2 s. After that, we read, from the header of the LAT file, the start and the end time of the observation, to provide a range over which a discretization of the temporal extension of the map can be performed. We then obtained the STMOC map.
Since we want to estimate the spatial and temporal intersection between the LAT map and the LIGO/Virgo event, we computed the STMOC map related to GW 170104 (Greco 2021). We firstly selected a probability threshold of 0.9 to obtain the spatial MOC map. Then, after reading the trigger time from the fits header of the file and copying it in the appropriate Aladin window, we were able to obtain the STMOC for the GW event, as can be seen in Fig. 2.
The final step was to produce the intersection map. We selected the STMOC maps obtained for the LAT map and the one obtained for the GW skymap and then computed the intersection map displayed in Fig. 3. As can be seen from the time plot, the intersection takes into account both the spatial and temporal coverage overlap.

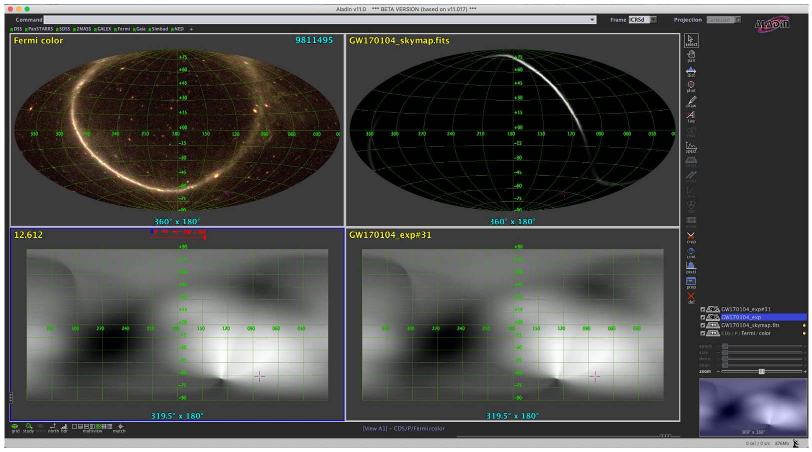

Figure 1. The visualization on Aladin of, turning clockwise, the sky seen by *Fermi*, the GW170104 skymap, the 31st energy bin of the LAT exposure map and the total exposure map.

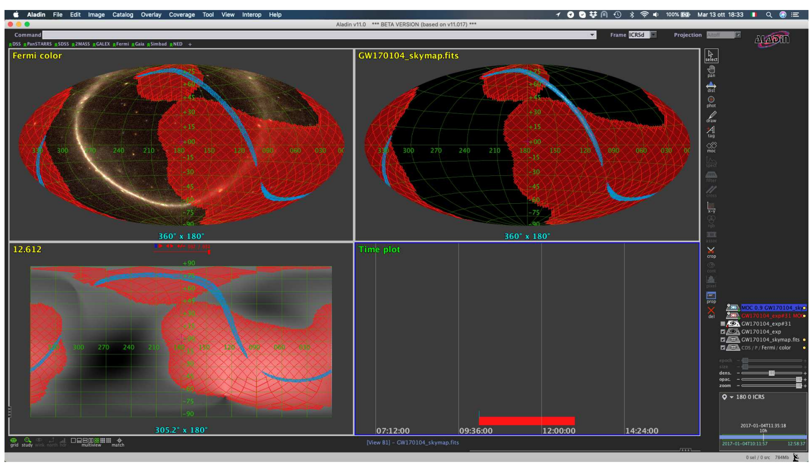

Figure 2. STMOC of the LAT exposure map.

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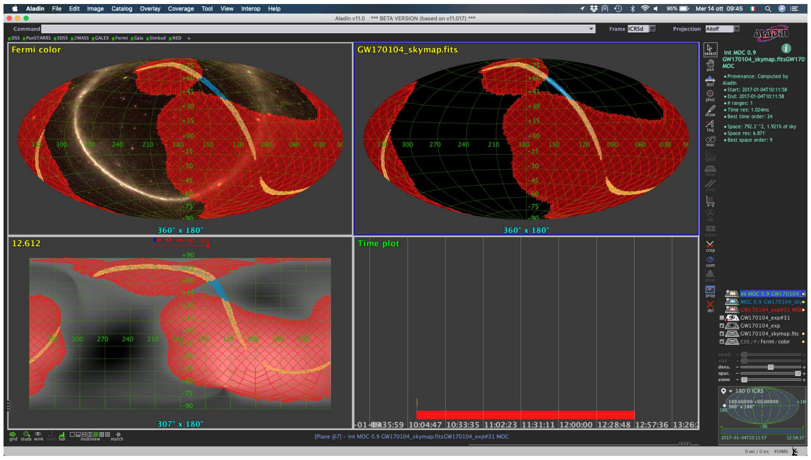

Figure 3. Intersection map between LAT map and LIGO/Virgo skymap.

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