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Capability for Encoding Gravitational-wave Sky Localizations with the Multi Order Coverage Data Structure: Present and Future Developments

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Abstract. The IVOA standard Multi-Order Coverage map (MOC) is a data structure based on the HEALPix tessellation of the sky, and it can be used to encode the area within a given probability level contour of a gravitational-wave (credible region) sky localization. MOC encoded credible regions can be created, visualised and manipulated using Aladin Desktop. The Aladin Desktop enables the users to compare the MOC regions with existing electromagnetic surveys and to query the VizieR database. These tasks can also be performed via Python using the astropy affiliated package, mocpy, which are efficiently displayed in javascript applications with Aladin Lite, and integrated within Jupyter notebooks through the ipyaladin widgets.

The paper also describes an enhanced MOC structure which allows us to include temporal information about gravitational-wave events. This data structure, the Space and Time MOC (ST–MOC), provides us with an effective way to develop new multi-messenger data analysis tools which will be necessary when the third-generation interferometric gravitational wave observatories, such as the Einstein Telescope (ET), will begin operation.

1. Multi-messenger astrophysics with gravitational waves

The detection of gravitational waves and the rapid dissemination of their sky localizations has now become a reality with an impressive worldwide effort. Fifty-six low-latency detection candidates are issued during the O3 observational run as reported in the LIGO and Virgo Public Alerts page[1]. A significant increase of the number of events sent in low-latency is expected in the next years with the sensitivity improvement of the existing interferometers and the addition of the fourth interferometer from the KAGRA collaboration.

The developments of tools and software to organize real time strategies and manage the allocated telescope time are becoming more and more pressing. Here we propose to apply the MOC data structure to encode the credible regions of a gravitational-wave sky localization showing the fast integration into the existing IVOA[2] technical specifications and various collaborative tools. We describe practical examples which can be reproduced with a jupyter tutorial provided in a separate document[3].

2. Interoperability and Practical Approaches

The Multi-Order Coverage data structure (Fernique et al. 2014) is able to effectively enclose the area within a given probability level contour of a gravitational-wave sky map. The contours of a gravitational-wave sky localization are constructed as follows. The pixels from most probable to least are ranked, and then summed up to get a fixed level of probability (Singer et al. 2014). In practice, the HEALPix pixels, inside a given contour plot, are extracted, and the MOC coverage is generated from the table made up from the pixels. Every single level of the contained probability can be used as a regular MOC even when the sky localization is irregularly shaped with disjoint regions. Aladin Desktop supports the *MOC-encoding process*, both the standard HEALPix format as well as the multi-resolution HEALPix format[4]. Fig. 1 shows the graphical interface commands to query the VizieR database from the 90% credible region of GW170817[5].

The interoperability with Python-based tools for astronomy (astropy (Price-Whelan et al. 2018), matplotlib (Hunter 2007), ligo.skymap, to name a few) is obtained using the mocpy package. The left panel of Fig. 2 shows three synchronized ipyladin widgets to visualize the 90% credible regions of the sky map generations of GW 190814 with increasing accuracy and computational cost (Abbott et al. 2020). The right panel of Fig.2 shows the localization of the gravitational-wave, gamma-ray, and optical signals of GW170817/GRB 170817/AT2017gfo (Abbott et al. 2017) as a visual representation from Aladin Lite[6].

3. Space and Time MOC in a multi-messenger context

ST–MOC is designed to manage spatial and temporal information simultaneously (Fernique et al. 2020). Fig. 3 shows the generation of a ST–MOC using, as temporal

[1]`https://gracedb.ligo.org/superevents/public/O3`

[2]`https://www.ivoa.net/documents`

[3]`https://l.infn.it/2v`

[4]`https://emfollow.docs.ligo.org/userguide/tutorial/multiorder_skymaps.html`

[5]`https://emfollow.docs.ligo.org/userguide/resources/aladin.html`

[6]`https://www.virgo-gw.eu/skymap.html`

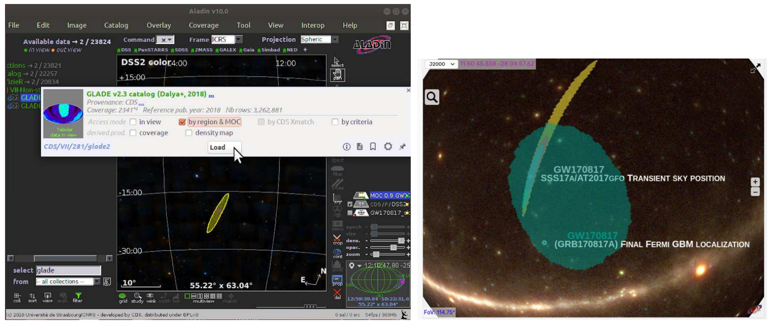

Figure 1. *Left panel*. Example of VizieR database query from a credible region of a gravitational-wave sky localization using Aladin Desktop *Right panel.* Multi-messenger sky localizations of GW170817/GRB 170817/AT2017gfo provided by Aladin Lite.

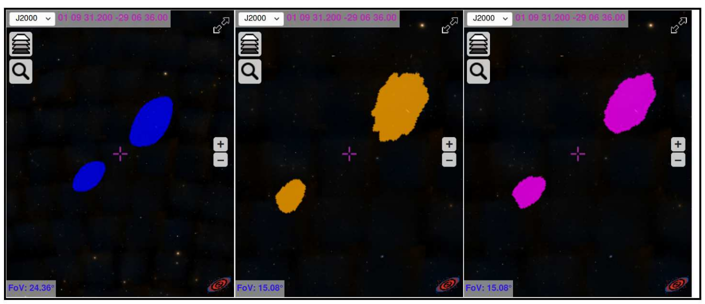

Figure 2. Three synchronized ipyladin widgets to compare the 90% credible region contours of GW190814. *From left to right*: BAYESTAR (GCN 25324; using data from 3 detectors), LALinference (GCN 25333) and the final sky localization presented in (Abbott et al. 2020).

and spatial information, the merger time and the 90% sky-localization credible region, respectively. Using ST-MOC, any operation to search for possible electromagnetic/neutrino counterparts can be computed both in time and in space. Dedicated research can be also performed by choosing a time window around the coalescence time of the compact objects in a binary system.

An experimental example is provided by Berretta (2021) in searching for spatial and temporal coincidence between Fermi-LAT exposure maps and gravitational-wave sky localizations.

4. Conclusion and future perspectives

ET (Einstein Telescope) will investigate the universe with gravitational waves up to cosmological distances. The detection rate will be of the order of 10^5–10^6 black holes and $\sim 10^5$ neutron stars mergers per year (Maggiore et al. 2020). Taking into account the huge gravitational wave trigger release and corresponding electromagnetic data, a

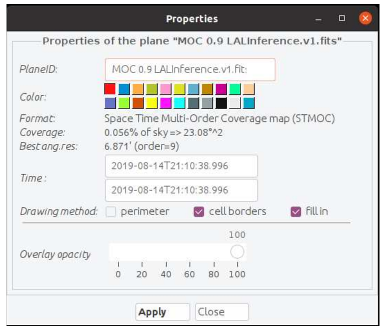

Figure 3. Generation of a ST–MOC from a gravitational-wave sky localization using Aladin Desktop. In the *PlaneID* box a credible region is selected and in the *Time* boxes the event's merger time is added. To search for any electromagnetic emissions before or after the compact binary coalescence, the time values can be modified accordingly producing a new ST–MOC.

fast and real time data access could be provided by encoding the ET sky localizations into ST–MOC and querying them from a specific time range. Electromagnetic/neutrino surveys could explore in real time the ET sky localization through multiple spatial and temporal intersections to identify any electromagnetic/neutrino signals temporally and spatially connected to the in spiral, merger or ring-down phases.

The present paper presents the advantage to encode the credible region of a gravitational wave sky localization using the MOC data structure, and the innovative ST–MOC which are able to specify space and time coverage. The ST–MOC can be used in the current follow-up of gravitational-wave signals. We are working to develop them in the context of the multi-messenger of the next generation of observatories.

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