Transient localization web service based on open gravitational-wave data for the multi-messenger community

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Abstract

We present here a web service `https://virgo.pg.infn.it/maps` integrated in the environment of the International Virtual Observatory Alliance (IVOA) and we sketch its implementation. The application has been developed in accordance with the FAIR (Findability, Accessibility, Interoperability, and Reusability) principles, allowing the efficient exchange of essential information between various partners in multi-messenger campaigns. The web tool provides an immediate and accurate visualisation of credible areas of a gravitational-wave sky localization issued by the the LIGO-Virgo-KAGRA network (LVK). With this tool, any gravitational-wave source localisation, where a transient event is expected, can be intersected with the area available for a telescope providing the region of interest wherein a potential electromagnetic counterpart sits. Finally, we will point out the technological advantages of our service, from the point of view of future technical challenges, due to the anticipated exponential increase of gravitational transient detections as well as to the growth of a heterogeneous multi-messenger community.

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1 Introduction

The LIGO-Virgo-KAGRA O4 observing run will bring the amount of gravitational wave (GW) detections to an unprecedented level [1]. The full exploitation of this opportunity will be possible, only if innovative tools for quick data analysis using intuitive graphical user interface [2] are provided. In particular this approach is important in the electromagnetic follow-up decision process, as the time spent on investigating the level of interest of an alert must be short [3].

Here we combine modern web technologies with Virtual Observatory standards to create and visualize credible areas of gravitational-wave sky localizations directly in most popular web browsers without having to install additional software. Moreover, the web service offers a palette of operations to be performed on the displayed sky areas: footprint plot of various shapes (box, circle, ellipse, etc.); union, intersection, difference and subtraction between two shapes and display electromagnetic transients within gravitational-wave credible areas.

2 VO standard and Web service technologies

The Multi Order Coverage (MOC) data structure, used to code GW sky localizations [4–6], makes the application of these innovative web technologies possible. There are two versions of the MOC. The earlier one `1.0` [7], which only describes the sky area, and the second one, which also takes time into account `2.0` [8]. The second version is also known as space-time MOC (ST-MOC). Due to differences in their functionality, IVOA (International Virtual Observatory Alliance) recommends the use both versions depending on the application. Regardless of the version MOC, IVOA supports the standard with a dedicated python package [9] and a java library. In particular, the MOC visualisation is facilitated by the Aladin Desktop software[1].

The web service we are describing makes use of MOC version `1.0` and two main Virtual Observatory libraries developed at the Centre de Données astronomiques de Strasbourg (CDS); they are `MOCWasm`[2] and `Aladin Lite v3` [10]. `MOCWasm` is a WebAssembly library made to load, create, manipulate and save MOCs via JavaScript, using the HTML interface. `Aladin Lite` is a JavaScript library running natively in the browser for professional and interactive sky map visualisations. Among the graphical Aladin Lite functionalities, there is the ability to display MOC.

`MOCWasm` runs without additional dependencies in most popular browsers and its output is interactively displayed in Aladin Lite with an extremely high computing efficiency. The `MOCWasm` project is open source and installation instructions are available on github[3].

3 Web service functionalities

The Graphical user interface of the web service is shown in Fig. 1. The functionalities are grouped into three main categories: (*i*) Load a gravitational-wave sky localization, (*ii*) Draw MOC sky regions (*iii*) Sky operations.

In the first category, one can upload a credible area coverage file. The credible area is contained in the MOC format inside an open format Flexible Image Transport System (FITS) file. Such file can be produced by Aladin sofware or downloaded from a dedicated websites. FITS file can be uploaded either directly, provided via an URL from GraceDB or selected from the existing catalogues or alerts. The second group of functionalities allows the user to create regions of various shapes (box, circle, ellipse, ring and zone) filling out custom-built popup forms. Any loaded region the user creates in the previous steps (credible areas or shapes) appears in the Aladin Lite layer manager. The last group of functionalities allows the user to perform a set operations: union, intersection, symmetric difference and subtraction (relative complement) between the regions present in the Aladin Lite layer manager. An hypothetical procedure to localise electromagnetic transients could be as follows: insert among the lasers the credible area; insert the field of view of the telescope; insert possible obstacles like moon

[1] `https://emfollow.docs.ligo.org/userguide/resources/aladin.html`
[2] `https://adass2021.ac.za/uploads/X9-011/upload/X9-011_latest.pdf`
[3] `https://github.com/cds-astro/cds-moc-rust/tree/main/crates/wasm`

Figure 1: The Graphical user interface of the web service **Gravitational-wave sky localizations: online calculator and interactive viewer of credible areas** - `https://virgo.pg.infn.it/maps`. The website is divided in two parts: the upper one contain the description and a banner with the latest alert issued by the LVK collaboration. In the lower part on the left there is the Aladin lite panel interactively showing the sky map, while on the right there is a list of functionalities. The functionalities are grouped into three main categories: (*i*) Load a gravitational-wave sky localization, (*ii*) Draw MOC sky regions (*iii*) Sky operations. For each item, a video tutorial is provided by clicking on the **Demo** button.

or dust and perform suitable operations. Finally, within a gravitational-wave credible area, point out the candidate by supplying information in the popup form from **Drawing and filtering** button.

4 Future implementations

Upcoming versions will offer the ability to add temporal information to the regions created in the web service using the Space and Time MOC (ST-MOC), that is to say, the MOC version `2.0`. This will allow to locate electromagnetic transients simultaneously in a specific space coverage and in a proper time window.

Moreover, in preparation for the next LVK observing run O4, a drop-down menu will be updated whenever a new gravitational-wave sky map is released. Finally, we are also providing support to ingest Gamma Ray Burst error boxes when these localizations are encoded in a HEALPix format.

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References

[1] B. P. Abbott, R. Abbott, T. D. Abbott, et al., Prospects for observing and localizing gravitational-wave transients with Advanced LIGO, Advanced Virgo and KAGRA, Living Reviews in Relativity 23 (1) (2020) 3. `doi:10.1007/s41114-020-00026-9`.

[2] S. D. Wyatt, A. Tohuvavohu, I. Arcavi, M. J. Lundquist, D. A. Howell, D. J. Sand, The Gravitational Wave Treasure Map: A Tool to Coordinate, Visualize, and Assess the Electromagnetic Follow-up of Gravitational-wave Events, The Astrophysical Journal 894 (2) (2020) 127. `arXiv:2001.00588`, `doi:10.3847/1538-4357/ab855e`.

[3] M. W. Coughlin, Lessons from counterpart searches in LIGO and Virgo's third observing campaign, Nature Astronomy 4 (2020) 550–552. `doi:10.1038/s41550-020-1130-3`.

[4] G. Greco, M. Branchesi, E. Chassande-Mottin, M. W. Coughlin, G. Stratta, G. Dálya, G. Hemming, L. Rei, E. Brocato, P. Fernique, T. Boch, S. Derriere, M. Baumann, F. Genova, M. Allen, Working with Gravitational-Wave sky localizations: new methods and implementations, PoS Asterics2019 (2019) 031. `doi:10.22323/1.357.0031`.

[5] G. Greco, et al., Capability for encoding gravitational-wave sky localizations with the Multi Order Coverage data structure: present and future developments, in: J.-E. Ruiz, P. Federici (Eds.), ADASS XXX, Vol. 525 of ASP Conf. Ser., ASP, San Francisco, 2021.

[6] G. Greco, M. Punturo, M. Allen, A. Nebot, P. Fernique, M. Baumann, F.-X. Pineau, T. Boch, S. Derriere, M. Branchesi, M. Bawaj, H. Vocca, Multi order coverage data structure to plan multi-messenger observations, Astronomy and Computing 39 (2022) 100547. doi:https://doi.org/10.1016/j.ascom.2022.100547.

[7] P. Fernique, T. Boch, T. Donaldson, D. Durand, W. O'Mullane, M. Reinecke, M. Taylor, MOC - HEALPix Multi-Order Coverage map Version 1.0, IVOA Recommendation 02 June 2014 (Jun. 2014). arXiv:1505.02937, doi:10.5479/ADS/bib/2014ivoa.spec.0602F.

[8] P. Fernique, A. Nebot, D. Durand, M. Baumann, T. Boch, G. Greco, T. Donaldson, F.-X. Pineau, M. Taylor, W. O'Mullane, M. Reinecke, S. Derrière, MOC: Multi-Order Coverage map Version 2.0. IVOA IVOA Proposed Recommendation 01 November 2021, https://ivoa.net/documents/MOC/20211101/index.html (2021).

[9] T. Boch, M. Baumann, et al., MOCPy 0.10.0 documentation, https://cds-astro.github.io/mocpy/ (2021).

[10] T. Boch, P. Fernique, Aladin Lite: Embed your Sky in the Browser, in: N. Manset, P. Forshay (Eds.), Astronomical Data Analysis Software and Systems XXIII, Vol. 485 of Astronomical Society of the Pacific Conference Series, 2014, p. 277.