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Building a Prototype of a Multi-messenger Platform

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Abstract

Recently, there has been an increase in collaborative multi-messenger (MM) astrophysics, both for pre-planned observations and for observations in response to transients. Transient phenomena are the next "big thing" in MM astrophysics. Gravitational wave detectors such as LIGO and Virgo and future observations done by the LSST and SKA will generate millions of raw events per night. These will require follow-up, and the current question is how to coordinate this efficiently.

The MM platform project used the ASTERICS network and aimed to play a coordinating role in translating ideas and tools into a platform to serve the MM community. The platform will facilitate collaborative follow-up observing by joining together and adding to the available tools.
Currently, many components focusing on the various parts of the overall process of MM astrophysics exist, but there is no coordinated plan. The MM platform aims to join them together to make an end-to-end process.

The goal of this project was to create a first prototype for a MM platform that serves the needs of both data providers and data users, and that would be useful for multi-observatory observations of both pre-planned and transient targets. With the platform, a central place for anyone interested in doing MM science would be created. This document describes the current state of the field, the potential added value of the MM platform, and presents a prototype version.

I. COPYRIGHT NOTICE

II. DELIVERY SLIP

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IV. APPLICATON AREA

This document is a formal deliverable for the GA of the project, applicable to all members of the ASTERICS project, beneficiaries and third parties, as well as its collaborating projects.

V. TERMINOLOGY

A complete project glossary is provided at the following page: https://www.asterics2020.eu/glossary/

VI. PROJECT SUMMARY

The EU funds a number of astronomical facilities that are members of the `European Strategy Forum for Research Infrastructures', ESFRI. The `ASTtronomy Esfri and Research Infrastructure CluSter', ASTERICS, is a €15 million project funded by the European Horizon 2020 framework, which aims to address the cross-cutting synergies and common challenges shared by the various astronomy ESFRI facilities (e.g SKA, CTA, KM3NeT and ELT).

CLEOPATRA, that is `Connecting Locations of ESFRI Observatories and Partners in Astronomy for Timing and Real-time Alerts', is one of the five work packages in ASTERICS. Its aim is to develop scheduling schemes that maximise the scientific gain from the facilities. The problem domain ranges from scheduling multi-frequency, multi-messenger observations using several facilities to the scheduling of complex, many-element detector arrays at a single facility.

VII. EXECUTIVE SUMMARY

This document reports the analysis carried out to evaluate how multi-facility observations are coordinated today and concludes that the process will be insufficient for the flood of transient follow-up campaigns expected in the era of gravity wave, cosmic ray and neutrino detectors, and the LSST. A survey of the efforts currently underway to resolve the problem shows much good work but a lack of overall coordination. The conclusion of the report is that, even without a master plan, the various separate components that have been built, plus new ones not yet considered, could be assembled to make a web 'platform' that would be a useful aid to coordinated observing in the future.

On the other hand, a pilot use-case is used to develop a plan for that platform and a simplified prototype has been constructed.

A future roadmap for the development of such a platform is proposed for the benefit of the Multi-Messenger science programmes running around the world. A grid-based model is envisioned and several tools are identified as building blocks for this new operational paradigm supported by the coordination of multiple observatories and considering all the infrastructures (ground- and space-based) that are willing to promote cooperation among them. The possibility to connect individual users is also very valuable and promoted within the same platform scheme.

Finally, the ASTERICS network has become a building block to create connections among different communities. The latter, together with the increasing open research procedures, paved the road for the aforementioned new paradigm that is the base for the construction of the MM platform. Therefore, the work done and described in this report would not have been possible without such an important initiative. A similar one should exist in the near future to transform the outcome of this report and the implemented prototype in a fully operational platform, which would have an outstanding impact in the astronomical community for the ultimate benefit of the scientific research and the society.

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Introduction

Multi-Messenger Science

Many, if not all the astrophysical processes in the Universe spread their signatures across the electromagnetic spectrum. Thus, observations obtained at a specific wavelength can be all but a snapshot of a bigger picture. Only when multi-wavelength (MW) observations are obtained, the full context of the source or a phenomenon can become clear and new science can be learned.

The study of astronomical transients (ATs), namely, short-lived astronomical phenomena, has traditionally suffered from the lack of temporal coincidence of the observations acquired at different wavelengths. Fast trigger of a telescope's follow-up after alert provides just a partial remedy to the problem: ATs are associated to phenomena with such short timescales that non-simultaneous astrophysical observations can affect critically our knowledge, leading to an erroneous physical interpretation. Still, observing ATs is key to understand many of the energetic processes of the violent Universe, and maximizing the chances of observing ATs simultaneously at different frequencies is a topic of great interest.

MW campaigns are costly, but have provided the most detailed astrophysical information we have on all source classes. In an ideal world, however, all astrophysical observations and not just those of ATs, are multi-frequency. Dreaming of a single telescope capable of covering at once all (or several) bands of the electromagnetic spectrum, despite how impractical this is, is likely an unconscious wish in the minds of all astronomers. The usefulness of having multi-band coverage has been greatly clarified along the last decades. MW observations of ATs are needed to study, for instance, gamma-ray bursts, active galactic nuclei, magnetars, or X-ray binaries. To give just an example, we recall the localization of the acceleration region in the M87 radio galaxy. Radio and gamma-ray observations of M87 revealed a period of strong gamma-ray are accompanied by an increase of the radio flux from its nucleus. From these observations, it was concluded that charged particles were accelerated to very high energies in the immediate vicinity of the black hole, and not elsewhere. In the absence of simultaneous MW observations, this result would have never been found.

Recently, the need of not only MW observations but also multi-messenger (MM) observations has been highlighted in view of the last experimental results. MM observations are crucial to provide a more complete phenomenological picture of several cosmic processes using information obtained from different probes. The latest results obtained by following up alerts triggered by gravitational waves (GWs) and in particular by high-energy neutrinos have provided important insights to our knowledge of the Universe. Moreover, several well-known high-energy astrophysical sources that are expected to produce high-frequency GWs likely also drive relativistic outflows (e.g. gamma-ray bursts resulting from merging compact objects, core-collapse supernovae with rapidly rotating cores, flares from soft gamma repeaters), which can emit high-energy (GeV-PeV) neutrinos. For all these type of transient events, tools that facilitate carrying out joint MW/MM observations will have a high impact on the scientific output.

The need for simultaneity also includes observations of steady sources, since, on the one hand, probably nothing in the universe is actually steady if observed with enough sensitivity, and on the other hand, multifrequency observations of steady sources have proven key to developing and testing models. MW/MM observations should then become the norm rather than the exception.

References and a more extensive description of the scientific use cases are given in ASTERICS deliverable 5.12.

MM Science in ASTERICS: Building the Community and Tools

The goal of ASTERICS, a 4-year project that was started in 2015, is to bring together astronomers and astroparticle physicists to cooperate on technological progress and common challenges of multi-messenger science. More specifically, the goals are to:

- Work together on common solutions for shared challenges by different research infrastructures, instead of solving them for each research infrastructure independently.
- Share and expand knowledge, experience and developments to advance innovation and science.
- Collaborate to make exchanges among people and instruments and create the right conditions for multi-messenger astrophysics.

Task 2 within CLEOPATRA (Work Package 5 of the ASTERICS project) focuses on MM Science and on tools that facilitate the generation and distribution of transient events, and how to react to them for helping coordinate follow-up observations. Task 4, on the other hand, is focused on planning and scheduling tools based on AI technologies for the efficient operation of large, complex (i.e., with sub-arrays) and coordinated observatories. Multi-observatory planning is identified as a key ingredient to promote MM science in an efficient way. However, it must be complemented with the other components, in order to obtain the expected change and make the collaborative operation of large astronomical facilities and space missions a reality. Deliverables 5.2 and 5.8 from task 2 and deliverables 5.9 and 5.12 from task 4 pointed out several use cases and tools that should be considered to promote the MM Science. In particular, a MM platform is an example of a tool that facilitates collaboration between different communities in astronomy and astro(particle) physics. Finally, the work done in the VO framework, which was extensively covered within DADI (Work Package 4 of the ASTERICS project), turned out to be another important building block for this platform.

Early 2018, conversations about a multi-messenger platform were started in the community (e.g. at the Gravitational Wave Town Hall meeting in Amsterdam, https://wiki.gw-astronomy.org/OpenLVEM/TownHallMeetings2018). The ASTERICS project was mentioned as a possible context in which a MM platform could be developed. The community of 26 European partners that was built during the ASTERICS project and the community's connections to other external stakeholders offered the possibility to play a coordinating role in the creation of a MM platform. Such a platform could facilitate collaborations and continue to do so after the end of the ASTERICS project.

As a first step, the ASTERICS Management Support Team initiated two video conferences with a group of interested internal and external parties to define the needs of the community. These video conferences took place in the spring and summer of 2018. Following these discussions, a proposal to include the work on a MM platform prototype in the final months of the ASTERICS project was prepared.

Proposal for a MM Platform

Goals

The goal of the project was to create a prototype MM platform that serves the needs of both data providers and data users, and that would be useful for both pre-planned multi-observatory observations and reactive observations following transients. With the platform, a central place for anyone interested in doing MM science would be created.

The following steps were planned:

1. Define the minimum requirements for a platform and rapidly translate this into a first prototype.
2. Look how existing tools and developments can be linked to the platform, both for the current prototype and for extensions of it at a later stage.

These two steps were carried out in parallel due to the limited time available for the project. The aim of step 2 is to show where interfaces are required and which gaps need to be filled. This is done by complementing and adding to existing tools, not by competing with these tools.

Team

The ASTERICS partners that were involved in the MM platform prototyping activity are listed below, together with a summary of the identified roles:

• **ASTRON:** ASTRON is the Netherlands Institute for Radio Astronomy. Its mission is to make discoveries in radio astronomy happen, via the development of novel and innovative technologies, the operation of world-class radio astronomy facilities, and the pursuit of fundamental astronomical research. ASTRON designed, built and operates the International LOFAR Telescope (a pathfinder for SKA). ASTRON plays a major role in various consortia contributing to the SKA Design Phase. ASTRON's role in the MM platform activity was advisory, participating in the design discussions and review of the design, and building and maintaining a network of stakeholders.

• **GTD:** GTD Systemas de Informacion SAU is an SME company with over 25 years of experience working alongside major contractors in the aeronautical and space sectors. GTD delivers embedded systems and software components for civil and military aircraft and spacecraft programs, develops global solutions for the space sector and develops Ground and On-Board Systems for Spacecraft platforms. GTD participated in several R&D European Framework Programmes projects. It is also involved in the development of the scheduler for CTA and is a Full Member in the Telescope Manager work package for the SKA project. GTD's role in the MM platform activity was capture of requirements, platform design and implementation.

• **IEEC:** The Institute for Space Studies of Catalonia is a private non-profit foundation devoted to research on space science and technology and its applications. IEEC participates in different European networks and consortia (e.g. ASTRONET, APPEC, KOPERNIKUS, E-GEM) and in various space missions (e.g. GAIA, LISA pathfinder, Euclid, Paris-IOD, PAZ and CHEOPS). IEEC also plays a role in the construction of CTA. IEEC's expertise in telescope and observatory control software and, in particular, AI-based scheduling applications for telescope time management and robotic operation is being applied to projects. IEEC's role in the MM platform activity was capture of requirements, definition and prioritization of use cases, tools for information sharing and multi-observatory coordination, test cases, platform design and implementation, and prototype validation.

• **JIVE:** The Joint Institute for VLBI in Europe is the central node of the European VLBI Network (EVN), a distributed array of radio telescopes in and outside of Europe. JIVE excels in research and development to innovate VLBI and related radio astronomy techniques. There is an overlap between the digital program at JIVE and the requirements of SKA and JIVE is actively involved in a number of SKA work consortia. JIVE's role in the MM platform activity was advisory, participating in the design discussions and review of the design.

• **STFC:** The UK Astronomy Technology Centre (part of STFC) is the UK's national center for the design and production of world leading astronomical telescopes, instruments and systems. It has delivered hardware and software to space missions (e.g. Herschel and JWST) and telescopes (e.g. the European Southern Observatory (Chile), the Isaac Newton Group of Telescopes (La Palma), Gemini (Chili/Hawaii) and ALMA (Chile)). It is engaged in the pre-construction phase of the SKA project, working on the systems engineering for the Central Signal Processor and leading the work on the Observation Management software for the Telescope Manager. STFC's role in the MM platform activity was capture of requirements, definition and prioritization of use cases, tools for information sharing and multi-observatory coordination, test cases, platform design and implementation, prototype validation.

• **UEDIN:** The University of Edinburgh hosts a leading astronomy research center at the Royal Observatory with the University's Institute for Astronomy (IfA). The IfA, as well as conducting front rank research in cosmology, active galaxies, galactic structure, and star and planet formation, operates the Wide Field Astronomy Unit (WFAU), which provides state of the art science archives for some of the world's largest astronomical databases, such as SuperCosmos, UKIDSS, VISTA, GAIA and EUCLID. UEDIN is also involved in LSST and the VO. UEDIN's role in the MM platform activity was capture of requirements, definition and prioritization of use cases, tools for information sharing and multi-observatory coordination, test cases, platform design and implementation, prototype validation and providing links with the VO.

Internal Communication and Working Tools

Following a kick-off meeting on 11 January 2019, the team held a weekly video conference to discuss the progress and outstanding issues, until the end of April 2019. In addition, face-to-face meetings took place in Barcelona on 21 February 2019, at the 5th ASTERICS DADI Technology Forum in Strasbourg (France) from 26-28 February 2019 and at the conference "The New Era of Multi-messenger Astrophysics" in Groningen (the Netherlands) from 25-29 March 2019. The ASTERICS project manager presented the MM platform project at the AMON Workshop in Chiba (Japan) from 21-22 May 2019.

Redmine was used to share documents and notes, and Slack and email were used for communication between the weekly video conferences.

A Github repository was created to share the developed code for the platform prototype (https://github.com/mm-astro/astericsh2020-multimessenger_platform).

Analysis

Why now? Why ASTERICS?

Recently, there has been an increase in collaboration in MM astrophysics, both for pre-planned observations and for observations in response to transients. Transient phenomena are the next "big things" in MM astrophysics. Gravitational wave detectors such as LIGO and Virgo and future observations done by the LSST and SKA will lead to millions of raw events per night. These events require follow-up, and the current question is how to coordinate this efficiently.

The MM platform project used the ASTERICS network to try and coordinate the translation of ideas and tools into a platform to serve the MM community. The platform aims to facilitate collaborative, follow-up observing by joining together and adding to the available tools.

Currently, many components focusing on the various parts of the overall process of MM astrophysics exist, but there is no coordinated plan. The MM platform will join them together to make an end-to-end process.

The ASTERICS network has become a building block to create connections among different communities. The latter, together with the increasing open research procedures, has paved the road for a new paradigm that is the base for the construction of the MM platform:

New paradigm Grid and collaborative operation of large astronomical facilities and space missions driven by:		
MM Science	**Link Users**	**Link Infrastructures (Ground & ESFRIs & ESAs)**

The implementation for such a new paradigm is supported upon **Data Gathering and Data Sharing** procedures. These are illustrated in the figure below (Figure 1) and are aligned with the Open Access policies included in the Responsible Research and Innovation actions recommended and promoted by the European Union.

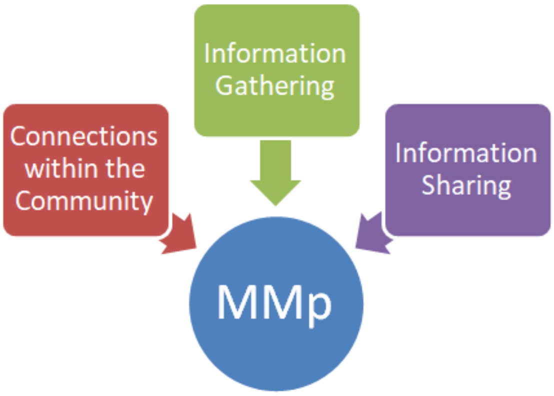


Figure 1. The MM platform (MMp) is a central place where community connections, information gathering and information sharing come together.

Stakeholders

The network of stakeholders representing various ASTERICS partner organizations involved in the MM platform project was very important for getting input on what a platform should look like. Their support and extended networks will be helpful in moving the work forward when the ASTERICS project has come to an end.

The table below shows the stakeholders (organizations or communities and the people that represented them) and their feedback. They provided input for the content of the MM platform in the two video conferences organized by the ASTERICS Management Support Team, and in additional communication by email and phone (Table 1).

Table 1. Stakeholders that participated in the two video conferences organized to collect input for what was needed in a MM platform, and additional communication around the video conferences. The table shows the feedback that was received from each stakeholder.

Stakeholder	**Feedback**
Astrophysical Multimessenger Observatory Network (**AMON**) *Represented by Douglas Cowen*	• Needs collaborations to complement their work and to increase the number and type of observatories that are involved. • Can provide information on AMON's activities and current status.
European Space Agency at the European Space Astronomy Centre (**ESA/ESAC**)	• Need data users. • Need use cases from scientists. • Can provide standards on visibility of observatories and planning information.

Represented by Jan-Uwe Ness, Matthias Ehle, Carlos Gabriel, Aitor Ibarra, Peter Kretschmar, Erik Kuulkers, Jesus Salgado, Celia Sanchez and Richard Saxton	
European Southern Observatory (**ESO**) *Represented by Maria Diaz Trigo (ALMA)*	● Need initiatives that promote multi-messenger astrophysics. ● Need people that do the operational work on e.g. a platform. ● Can provide connections with the (astronomical) community. ● Can provide science use cases for multi-messenger astrophysics. ● Can provide links with large infrastructures.
International Astronomical Union (**IAU**), commission D1 on gravitational wave research *Represented by Marica Branchesi*	● Need initiatives that promote multi-messenger astrophysics. ● Need people that do the operational work on e.g. a platform. ● Can provide connections with the (astronomical) community.
Laser Interferometer Gravitational-Wave Observatory (**LIGO**) & **Virgo** *Represented by David Shoemaker (LIGO) and Marica Branchesi (Virgo)*	● Need standardized protocol with a database of information on transients to find counterparts and filter out contamination. ● Need a place to announce their status. ● Need a place where they can see the status and planning for transient observing facilities. ● Need complement to GCNs to send out low-latency alerts and sky maps. ● Need a way to receive low-latency triggers of events that have some chance of correlation with gravitational waves. ● Can provide connections with the ((astro)physical) community. ● Can provide information on LIGO-Virgo observing rounds and status (quasi real time, and planned outages and observing schedules).
Scientists	● Need collation of observations.

*Represented by Phil Evans (**SWIFT**) and Antonia Rowlinson (**LOFAR**)*	● Need a tool to share information about observations of the same object. ● Need a way to connect to other scientists. ● Can provide feedback on their needs, especially on transient follow-up. Common and key science programs would also be considered. ● Can provide information on the current way of transient follow-up: what is working and what is missing?
Virtual Observatory (**VO**) *Represented by Mark Allen, Eric Chassande-Mottin, Giuseppe Greco and Ada Nebot*	● Need applications that use VO tools. ● Can share experience from their work on interoperability and standardization of astronomical data. ● Developed sky map tools (e.g. GWSky).
ASTERICS Management Support Team *Represented by Rob van der Meer and Marjan Timmer*	● Need input about wishes and investments from interested providers and users. ● Need to communicate ASTERICS results to the “outside world”. ● Can play the role of connector through collaborations and connections in the project.
ASTERICS work packages *Represented by Mark Allen, Cristiano Bozza, Alan Bridger, Josep Colomé, Mark Kettenis, John Lightfoot and Ada Nebot*	● Need input from data providers and data users. ● Involved in creating tools that are useful for multi-messenger astrophysics.

Benchmarking: Tools and Initiatives

This is currently a very active field, with many efforts underway to prepare for the expected flood of transient events when the LSST and SKA come on line. These can be grouped together as follows:

Umbrella Projects

These are large programs, which push forward on a wide range of fronts. ASTERICS was one such project in Europe.

- ***SCiMMA*** The 'Scalable Cyberinfrastructure Institute for Multi-messenger Astrophysics' is a U.S. project supported by the NSF with a website at https://scimma.org. The project grew out of the workshop '*Multi-messenger Astrophysics: Harnessing the Data Revolution*' at U. Maryland in May 2018, and brings together a number of people from across America with the aim of identifying and building the infrastructure required for efficient MM astrophysics. Development is at an early stage but many of the aims of the project are similar to those behind the MM platform; quoting from the aims of a workshop held in January 2019 in New York, these are to answer the questions:
    - How do the MM astrophysics science cases drive particular cyberinfrastructure requirements?
    - What are the best practices for distributed data-handling, computing, analysis, and collaboration services/systems to enable discovery, education, and innovation?
    - What are optimal cyberinfrastructure services to enable enhance cross-field knowledge sharing?
    - How could an institute best unify and serve those cyberinfrastructure needs?

Event Brokers

Originally meant to relay event streams from facilities to subscribers, these increasingly do much more. For example:

- ***Lasair*** is a prototype broker being developed in the UK by Edinburgh University and Queen's University, Belfast for the LSST. It can:
    - Store user 'watch lists' that filter the event stream according to their selection criteria.
    - Add value to the event by inserting a likelihood estimate that the transient is a supernova.
    - For GW alerts, as an aid to follow-up, display the alert sky map with catalogue galaxies within the alert distance range superimposed, ranked in order of host likelihood.
- ***AMON*** It may be a stretch to describe AMON as a broker but it does work to add value to event streams. The 'Astrophysical Multi-messenger Observatory Network' is currently under development at The Pennsylvania State University, in collaboration with U.S. and international observatories. AMON seeks to perform a real-time correlation analysis of the high-energy signals across all known astronomical messengers – photons, neutrinos, cosmic rays, and gravitational waves – in an effort to:
    1. Enhance the combined sensitivity of collaborating observatories to astrophysical transients by searching for coincidences in their sub-threshold data; and
    2. Enable rapid follow-up imaging or archival analysis of the putative astrophysical sources.

    AMON started as a way of raising the significance level of triggers by searching for correlations between independent detection. The project has also developed the idea that follow-up observations for a given trigger should themselves be reported as events, related to the initial trigger. In this, it is possible to see the beginning of a messaging system for coordinating follow-up campaigns.

Many other event brokers are available or under development, each with their particular focus and array of strengths.

Collaboration Building

Two different approaches that have been followed in the past years:

- ***ENGRAVE*** This is an example of the classic way of working, where the collaboration is formed before telescope time is obtained. ENGRAVE is a consortium of more than 240 scientists from ESO member states that obtained an allocation over several semesters of VLT 'target of opportunity' time for GW alert follow-up. ENGRAVE will probably run like a ship, with a hierarchical structure, specialisms, someone always on watch, etc. It has some personnel in common with PESSTO, an earlier programme for following-up supernovae, which used a private web application, the 'Marshall', for internal communication and data display.
- ***SmartNet*** This is a web app (http://www.isdc.unige.ch/smartnet) that developed out of the 2015 Leiden workshop `Paving the way to simultaneous multi-wavelength astronomy' in Leiden (Middleton et al. 2017, https://arxiv.org/abs/1709.03520). It is a tool for enabling collaboration, aiming to bring together people who have knowledge of and access to a wide range of instrumentation, and an interest in making coordinated observations, but no contact with each other. In SmartNet people with access to telescope time form a collaboration around a particular target.

  The process works as follows:

  1. People interested in collaboration join SmartNet.
  2. A member with a potential target starts an 'observing campaign', creating a site page with a timeline on which observations made or planned can be viewed, discussed, etc.
  3. Emails are automatically sent to members to advertise the campaign, and people join the collaboration by contributing data.
  4. Data exchange and decisions on the analysis and publication process are handled offline.

Tools

Specific pieces of software that perform a useful function related to coordinated observing.

- ***TOM Toolkit*** According to the TOM toolkit website (https://lco.global/tomtoolkit/):

  > 'Astronomical surveys are producing ever increasing catalogs of new discoveries at ever faster rates and astronomers have found it necessary to build database-driven systems to handle the flood of information on their targets, observations, and data products - Target and Observation Managers or TOMs.

TOM systems offer users a powerful way to display and interact with their own data through a browser or GUI. These systems are rapidly becoming more powerful and are able to submit requests for observations directly to networked telescope facilities and harvest data products. When coupled with the astronomer's own analysis software, these systems are capable of conducting entirely automated follow-up programs, including rapid response to new target alerts.

Until now, building a TOM system has required specialist expertise in database and software development, restricting it to a subset of larger projects.

The TOM Toolkit is an open-source software package which enables users to easily build a TOM system and customize it for their science. Built by LCO's own team of professional software engineers in collaboration with scientists, the Toolkit can be used as a stand-alone package to build a TOM from scratch, or as a library of useful functions, astropy-style.

The Toolkit comes with a wide-range of functions to support observing programs and is designed to be extended - community contributions are welcome. We are currently working with a number of other observatories to integrate support for observations on their facilities, as well as external broker services.'

- ***ESASky*** is a web tool that gives public access to the data archive of all ESA astronomical satellites, and to the publications that have been derived from them (sky.esa.int). The tool is built on Aladin Lite and provides an intuitive gateway to target objects and through them to the databases that contain information on them.

- ***Aladin Lite*** is a tool that runs in the browser and is geared towards simple visualization of a sky region. It allows one to visualize image surveys (JPEG multi-resolution HEALPix all-sky surveys) and superimpose tabular (VOTable) and footprints (STC-S) data.

  Aladin lite is powered by the HTML5 canvas technology, currently supported by any modern browser. Aladin lite is easily embeddable on any web page and can also be controlled through a Javascript API. Because it can so easily be incorporated into other platforms, Aladin Lite has become widely used.

- ***IVOA Interface Protocols*** In the same way as access to data archives was transformed by the development of interface protocols by the IVOA, new draft protocols will enable access to telescope observing schedules and target visibility information.

  The two relevant protocols are the Object Visibility Access Protocol (ObjVisSAP) [http://ivoa.net/documents/ObjVisSAP/index.html] and the Observation Locator Table Access Protocol (ObsLocTAP) [http://ivoa.net/documents/ObsLocTAP/index.html].

  The ObjVisSAP protocol allows us to query each instrument provider to discover whether the target position we are interested in would be visible within the instrument's field of view. The protocol simplifies the process to ask a simple question, "is the target position visible at that instrument between start and end time?". Standardising the query|response web service interface makes it easy for users to ask the same question of multiple instruments without needing detailed knowledge about the physical telescope and/or spacecraft. Each service provider uses their instrument expertise to provide an accurate answer.

In the same manner, the ObsLocTAP service enables us to ask simple questions "was (or will) the instrument be observing the target location between start and end dates?". In this case, the answer to a relatively simple question in fact requires access to, and detailed understanding of, the political process for scheduling observations on a specific instrument, and the technology of the IT systems used to implement that process. Again, standardising the query|response interface enables us to ask the same question to multiple instruments without knowing the details of the observation scheduling process for each instrument.

By combining the results of these services from multiple instruments, we can build a picture of which instruments were, or will, be observing the target position in the time period of interest. In addition, we can look back in time to find which instruments were able to see the target position and which instruments were actually making observations then. This identifies the instruments we would need to contact to access the raw data from those observations. It also enables us to identify the gaps in a future schedule where a particular instrument would be able to see the target position, but currently no observations are planned at that point in time.

User Stories

A set of user stories was created to capture the initial feedback received from the community, as collected in the conversations with the stakeholders mentioned above. The full set of user stories can be found hereafter, grouped in different fields of interest. In addition to discussions with the MM community, user stories were extracted from ASTERICS deliverable 5.9. The user stories were informative, but not everything was and could be used to build a prototype, also given the limited time available for the project. The user stories were filtered and a selection was used to create the prototype and taking a representative case to show the added value of the MM platform.

Stories Grouped by User Profile

As a professional astronomer working in multi-messenger science...

1. I want to be able to see which follow-up observations have been made in a given wavelength range following the detection of a transient or gravitational wave.
2. I want to be able to see which follow-up observations have been made in a sky region following the detection of a transient or gravitational wave.
3. I want to be able to see which follow-up observations have been made in a given time interval following the detection of a transient or gravitational wave.
4. I want to be able to present completed observations.
5. I want to be able to find completed observations.
6. I want to be able to present/view/find transients detected in a fully automated way.
7. I want to be able to search a database of information on transients to find counterparts.
8. I want to be able to find information and to connect with colleagues to coordinate observations that are planned in advance (i.e. blazars, SGRA*, variable reflection nebulae).

9. I want to be able to bring data together after an event of observations (i.e. active galactic nuclei, stellar coronal activity) by finding information on completed observations and connecting with colleagues.
10. I want to be able to find information on requesting observation time for different instruments.
11. I want to be able to find information about conferences, workshops, etc. related to multi-messenger science.
12. I want to be able to find information about the visibility of different instruments.
13. I want to overplot observed regions on the LVC sky map, colourised by gamma ray, X-ray, optical, IR and radio, and an option to turn on/off for each category.
14. I want to use VOEvents and GCN notices where available to input information automatically.
15. I want to use GCN circulars.
16. I want to use a user entry form, so I can manually add information if it is only distributed via GCN circulars, potentially with a user login or manual checking to prevent people messing about.
17. I want to find optimal common observation slots.
18. I want to be able to contact colleagues working on multi-messenger science.
19. I want to see the collection of relevant scientific information (latest results and outstanding papers).
20. I want to gather all reports of possible EM counterparts to an EM event (ideally with time of detection, bandpass, and brightness).
21. I want to have details from the LVC sky map at the position of each source (i.e. probability, and the distance mu/sigma values).
22. I want to have details from "alternative" LVC sky maps (i.e. convolution of LVC sky maps with galaxy catalogues, which reweights the LVC probability according to where the galaxies that could host gravitational wave events are. I would like to see the probability from this map for each EM source.
23. I want to find galaxy information along the line of sight to each source.

As a professional astronomer new to multi-messenger science…

1. I want to find information about what is happening in the multi-messenger science field.
2. I want to be able to connect with colleagues to start working on multi-messenger science.
3. I want to be able to point the display to a favourite object and see what transient events and follow-up observations have occurred in its vicinity.
4. I want to be able to find information without creating an account.

As an organisation involved in multi-messenger science…

1. I want to be able to announce the status of my instrument on several time scales (quasi real time, and planned outages and observing schedules).
2. I want to be able to see the status and planning for transient observing facilities.
3. I want to have any complement to GCNs to send out low-latency alerts and sky maps.
4. I want to have a way to ensure that we receive low-latency triggers of events that have some chance of correlation with gravitational waves.
5. I want to have a login account to make sure that the information published by organisations is reliable.
6. I want to publish news and events from my organisation.

As a member of the public…

1. I want to watch the VOEvent event flow to be able to see what is happening in the sky now. I want to be able to zoom, pan, click on events to see details, perhaps filter events to select ones related to a primary event.
2. I want to replay major event sequences, such as a GW detection, its follow-up observations and publications, so that I can see how the discovery unfolded and learn about the subject.
3. I want to be able to find information about multi-messenger science without creating an account.

As a solar system astronomer...

1. I want to be able to verify detection of object from VOEvents, for example by viewing the image sequence behind the trigger.
2. I want to access orbit parameters for the object, to help determine the object type and know where to target follow-up observations.
3. I want to be able to detect cometary activity by seeing a light curve.

Key Case Story: Multi-observatory Coordination and Scheduling

One set of user stories was worked out in more detail, to demonstrate what the MM platform could do in multi-observatory coordination and scheduling (Figure 2).

1. The location of an object can be entered in a form on the MM platform. This queries object visibility services to find out which location is visible for each instrument. In addition, information on sources that were identified at that location, what the surrounding area looks like and which measurements were taken in the past can be retrieved, using database services in the VO.
2. Observation locator services can be queried to find out which instruments are planning to observe at the location of interest in the future.
3. Information about visibility and future observation plans can be displayed. If needed, historical information from step 1 can be displayed as well. This allows for coordination of the best times to request new follow-up observations.
4. The system will plan and track new observation proposals for the target object.

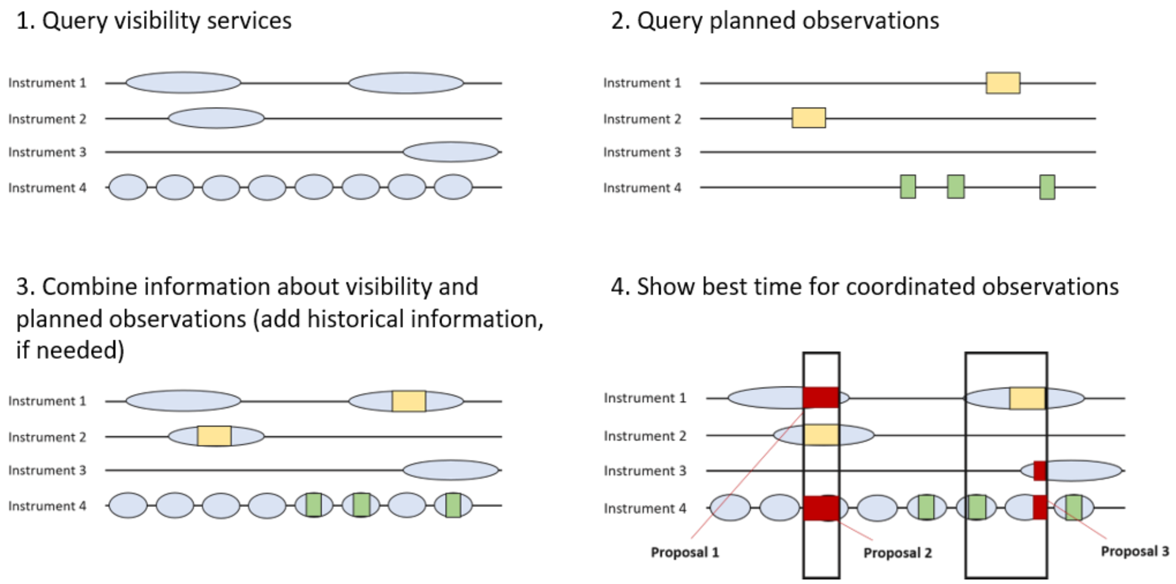


Figure 2. The four steps from entering the location of an object in the MM platform to getting observation proposals for the target object: (1) the visibility of four different instruments, (2) the planned observations for these instruments, (3) combined information about visibility, planned observations and historical information, (4) the best time for coordinated observations using these instruments and three resulting proposals.

The table format from the IVOA ObsLocTAP protocol could form the basis for a common interchange format for describing multi-instrument observation plans and schedules. In this scenario, the MM platform would not only consume data from ObsLocTAP services to learn which instruments are planning observations of the target. The same table structure could also be used to publish proposed observation plans created by the MM platform to downstream consumers such as robotic follow up instruments or submitted to observatory scheduling committees.

Platform Design

General View

The MM platform is devoted to connect the scientific community with the observatories by contributing to a coordinated collaboration for MM Science programmes. This general view of the platform architecture is given in the figure below (Figure 3).

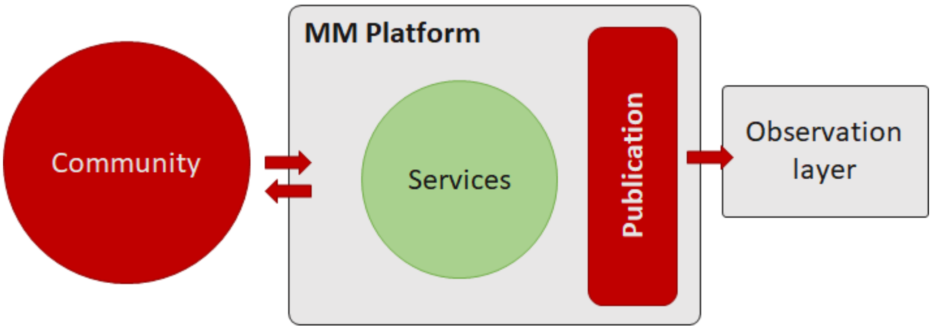


Figure 3. General view of the platform architecture design.

The basic elements in this general view are:

- The **community**: it is composed of different people or groups interested in a collaboration.
- The **interfaces** to connect with the community and to efficiently publish the results from the different services to the observation layer.
- The **services** provided by the platform: these services are in the end responsible to make the collaborative decision-making a success.
- The **observation layer** composed by ground and space-based facilities that are in charge of the observation management and data archiving.

The analysis, described in the previous section, has shown that there are various tools and initiatives that focus on parts of the overall process of MM science. However, a coordinated plan is missing. The MM platform could join the components together to make an end-to-end process, as illustrated in the following figure (Figure 4).

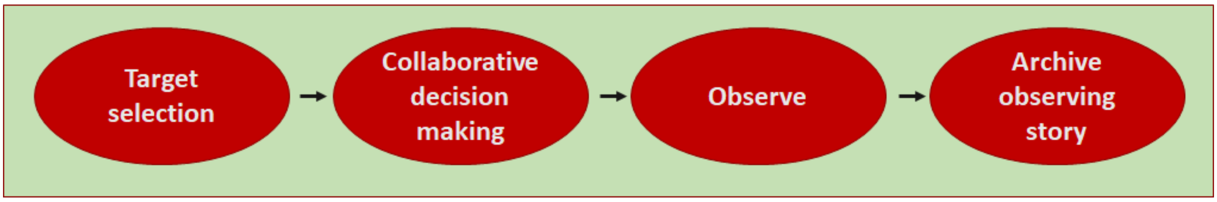


Figure 4. The MM platform joins together components to make an end-to-end process from target selection through to archiving the observing story.

The MM platform can be assembled from components that each specialize in one particular aspect of the target selection / observing follow-up cycle.

Architecture

Gathering the possible elements in the aforementioned structure quickly leads to a more complex picture, shown below (Figure 5).

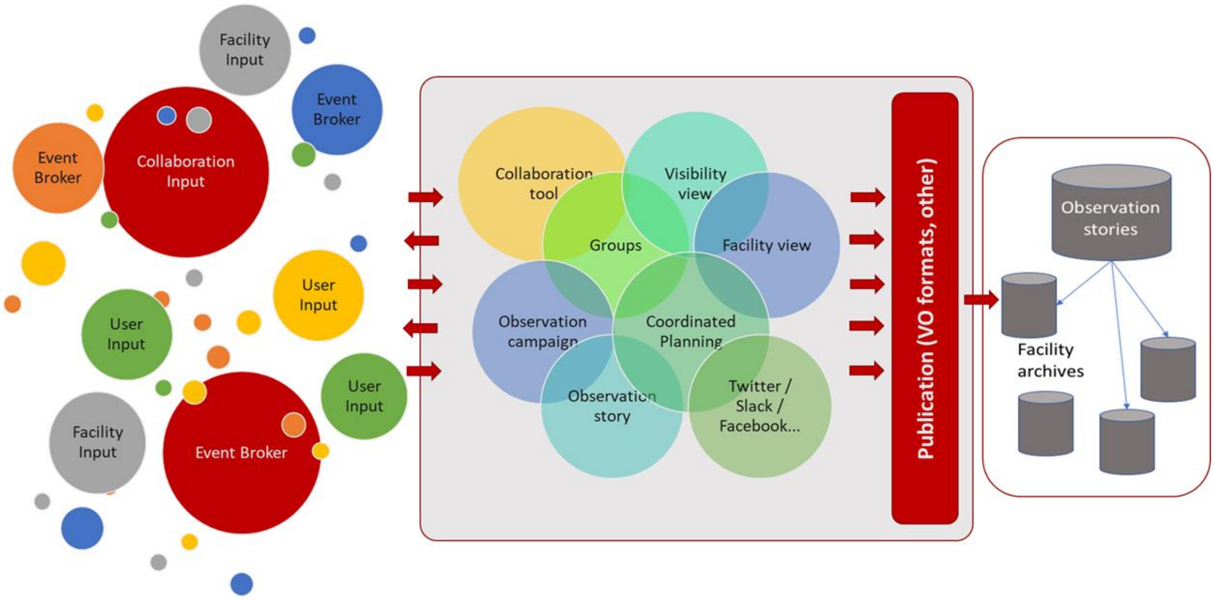


Figure 5. Detailed view of the platform architecture design.

Community

This is made up of all parties interested in MM observing: individual users, collaborations interested in particular targets, facilities making the observations, and developers working on relevant software e.g. event brokers, data display services etc.

Services - Community Connection and Collaboration

One set of services promotes the development of communities that share the same interests, and the formation of collaborations.

Types of data to be shared include:

- Information about facilities, their MM policies and proposal submission procedures.
- Publication of events, conferences, workshops.
- Advertising MM platform and similar initiatives.
- Submission of user data to the MM platform or of data to be published: registration data (for users, facilities, collaborations), scientific programmes of interest, etc.
- Database retrieval: archived observation results, facility schedules, target visibilities, etc.

Access to some of this information will be constrained by privacy policies, so the MM platform will have to implement different access levels, some requiring registration. The baseline is to maximize public access to data, where possible.

To aid the formation and working of collaborations the MM platform will understand the concept of ‘groups’, private areas where users can work together on common targets, observation planning, data exchange and communication. Tools will also be developed to help collaborative observing.

Services - Dashboard

The idea of the dashboard is to give users easy access to all the information that might be useful in carrying out coordinated follow-up observing.

Skyview/Visibility view

This is a graphical representation of (part of) the sky with layers that can be turned on and off. Filtering on time and sky position is needed. Various layers are considered:

- "Visibility" of instruments: one layer is defined per instrument.
- "Scheduled observations" of instruments: one layer is defined per instrument. This includes also observations from the recent past.
- Target layer: it displays a target position entered by the user.
- Event layer: it displays positions from a VOEvent stream; multiple layers are considered for different streams and/or event types.

Facility View

Graphical representation of (part of) the Facility Space (ground and space-based) with layers that can be turned on and off. Facilities that have registered are shown and information associated with them can be retrieved through the view. Filtering on time / position / messenger / accessibility is needed.

Different layers are considered:

- Identification of observatories and space missions subscribed to the platform.
- One layer for each messenger that shows all the facilities associated with it.
- One layer for public observations, one for proprietary. Users should be able access proprietary data when allowed.

Services - Tools

The MM platform should provide tools that facilitate the organization, scheduling and analysis of collaborative observations. Some examples are described below.

Coordinated Planning

A scheduling tool is considered for developing a plan that simultaneously fulfils the scientific aims of different participating facilities, maximizing the time for which MW/MM coverage of a source is obtained. The software uses the object/source visibility, the shared schedules from the telescopes, and other operational and observational constraints, in order to obtain a common optimization. An additional constraint, added to promote the MM science programme, is that of maximizing coincident observations with the involved facilities or minimizing the distance between them.

This is an inexpensive new approach for maximizing simultaneous observations to obtain efficient MW/MM coverage. This approach optimizes in a dynamical way the simultaneous observations of sky patches, at the level of scheduling of the different facilities, prior to the observation runs. The multi-observatory coordinated planning can be obtained on the fly by transient triggering events, or can be computed to prepare an observation campaign prior to its submission to different facilities.

The features of the STARS framework (see ASTERICS deliverable 5.9) for telescope time scheduling cover the multi-observatory coordinated scheduling. The optimization algorithms take into account the sky visibility of different facilities to obtain a proposed schedule for a MM Science programme. Figure 6 illustrates different scenarios for SKA and CTA coordination. They have proven good performance for the testing cases considered (see ASTERICS deliverable 5.12 for more details).

The coordinated plan is obtained in an IVOA standard format that can be exported from the MM platform and submitted to different facilities to get observing time. The format is compliant with the one used in the TOM Toolkit. Other formats will be considered.

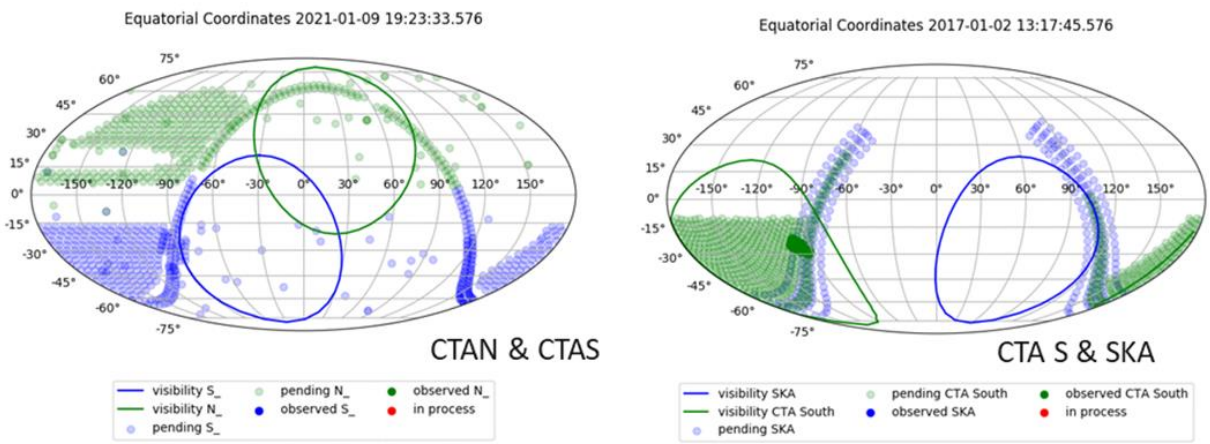


Figure 6. CTA North and South (left) and SKA and CTA South (right) sky visibilities considered for MM science programmes coordination.

Observation Campaign / Story

The MM platform will need a structure that can store the component observations of an observing campaign. The basis for this has already been developed as the IVOA ObsLocTAP protocol, lacking only the ability to store observations from more than one Observatory.

In addition to adding an 'Observatory' column to the ObsLocTAP table, the MM platform will also investigate ways to store ancillary information, ideally notes and comments that might illuminate the story of how and why the observing campaign developed as it did - this we would call the 'observation story'. Such metadata could be useful in future when the observing campaign is retrieved from archive.

Alert Correlation

Transient alerts are not isolated events. Any important alert will be followed by others, e.g. reporting position updates, follow-up measurements, localization of an EM counterpart. Some phenomena may generate near simultaneous alerts via more than one messenger. The MM platform will collate alerts that are linked and look for temporal correlations between independent alerts.

AMON may well provide the required functionality so the MM platform will look to incorporate its output.

Publication / Archive

Data from individual facilities will, in most cases, be kept safe in the archive for that facility. However, some of the value of a follow-up observing campaign lies in the fact that various bits of data from different facilities were collected on a particular target, for reasons that were clear at the time. This information is held in the 'observation campaign' structure, or 'observation story' if we manage to store metadata as well.

If the collection of data into a campaign or story is deemed valuable, then that collection should be archived as well as the component data. The MM platform will do this.

Software Design

Platform Front-end

The 'front-end' is the public face of the MM platform.

The architecture will be relatively light, with much of the information organized behind parallel tabs.

Much of the information accessible through the MM platform will be public. This will include information about ASTERICS, project partners, the development of the MM platform itself, general observatory information, ESA data archives, etc. This will be obtainable without the need to have a username or login.

Some information, however, will belong to or only be accessible to an MM platform 'group', and should only be visible to members. To access this, a user will have to prove group membership, which will require login.

Platform Back-end

The 'back-end' is the interface of the MM platform to various sources of data, from event brokers, to data archives. In all possible cases, IVOA standards will be used. In particular:

- Target visibilities will be accessed via the draft ObjVisSAP protocol.
- Observatory schedules will be accessed via the draft ObsLocTAP protocol.
- Transient alerts will be VOEvents.

Where new interfaces have to be developed, we will endeavour to base them on existing VO protocols. In particular, the structure to hold an observing campaign will be developed from ObsLocTAP.

The 'back-end' will also incorporate the service modules devoted to data processing that will contribute with added value outcomes to foster MM programmes. An example of these services is the coordinated planning that will be based on the STARS framework. This framework can be extended to provide the coordinated plans by considering different observing facilities and delivering it in an IVOA standard.

Stand-alone Services and Complementary Development with Existing Initiatives

The software development of the MM platform will enable the stand-alone use of the services/tools in order to promote the work in cooperation with the aforementioned existing initiatives (Figure 7). However, a web-based integrated tool will be also fostered to cover all functionalities and reusing the existing solutions to problems, as described hereafter:

- For data visualization with layers, we will use **Aladin Lite**, which is widely used for such work.
- The **TOM toolkit** provides much that we can reuse. Our target visibility display will follow its lead. We will use the TOM database to store target data.
- For alert correlation and collation, we will use **AMON**, whose main purpose this is.
- For tools to aid collaborative observing, we will use **SmartNet** as a model. We cannot use their code, but they have a useful 'observing campaign' display that is worth building upon.
- Filtering of transient alerts, and the display of useful supporting data, is a problem being attacked by many alert broker developers. It would be wasteful and indeed not possible to duplicate this work, so we intend to build the MM platform such that it can 'contain' a range of brokers, bringing together their various capabilities. **Lasair**, with whose developers we are in contact, is one example.
- MM platform 'groups' can be public or private.

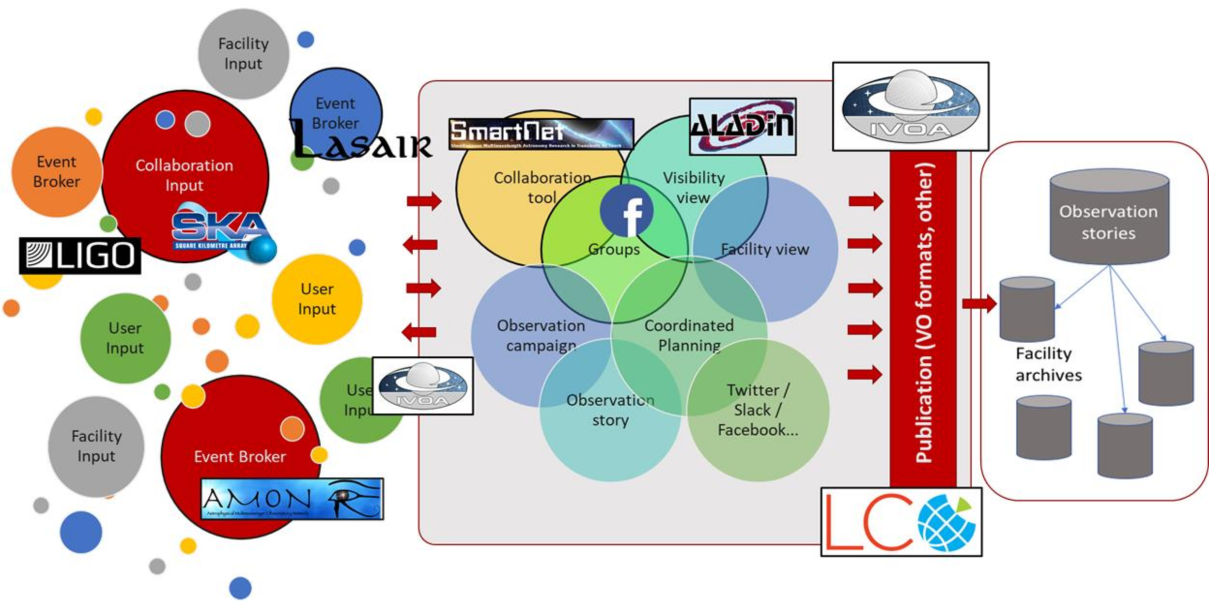


Figure 7. The MM platform shown in the context of stakeholders and already existing initiatives.

Platform Prototyping

The prototyping activity was done in parallel with the analysis thread activity. A compromise was found to start building the prototype just considering those use cases that can be clearly consolidated to specify the features to implement with enough level of detail.

Uses Cases and Requirements Collector

The use cases and requirements considered for the prototype are given in the following table.

Front-end Features			Back-end Features	
Community connections	**Dashboard**	**Tools**	**I/O**	**I/F**
COM-01 User management (access permissions, platform configuration and preferences)	***DASH-01*** Sky view with filtering layers and dynamic time variation	***TOOL-01*** Information about facilities vs messengers	***IO-01*** User pre-allocated/scheduled observations (input: users)	***IF-01*** ESA/ESAC visibility protocols (object constraint-free visibility intervals – ObjVisSAP; facility planned observations - ObsLocTAP)
COM-02 Creation of science driven groups (i.e., based on Facebook, Slack, other)	***DASH-02*** Sky View - SB/observations layer: non-transient, transients, messenger selection	***TOOL-02*** Information about proposal submission (facility policies, main facility messenger and submission procedures)	***IO-02*** User scheduled observations (input: users or facilities)	***IF-02*** VOEvents protocol
COM-03 User publication of calls for shared MM proposals or request to	***DASH-03*** Sky View - Facility layer: visibility & availability, messenger selection	***TOOL-03*** Publication of events, conferences, workshops	***IO-03*** Consortium program observations (input: facilities)	***IF-03*** LVC alerts, GBM and GCN protocols

contribute observations				
COM-04 Subscription to facility data levels (sky visibility, new transient alerts, nominal operation schedules, etc.)	***DASH-04*** Sky View - Filtering features: visibility, sensitivity, messenger, facility source, user source	***TOOL-04*** Advertising MM platform and similar initiatives	***IO-04*** Facility/satellite visibility (input: facilities)	
COM-05 Subscription to messenger data (GW, EM,...) from user groups & facilities		***TOOL-05*** Scheduling tools (observatory constraints, object visibility intervals, multi-observatory scheduling algorithms)	***IO-05*** Facility transients SBs/observations (input: facilities)	
		TOOL-06 Database retrieval: observations (transients, non-transients, etc.), facility plans (visibility), user plans	***IO-06*** Facility non-transients & scheduled pointing (input: facilities)	

Functional Specification and System Requirements

The functions shall be defined to cover the main goals of the MM platform:

- Include functions and tools developed in the frame of ASTERICS (e.g. STARS scheduler).
- Use data formats and communication protocols commonly used in the astronomy community.
- Enable the alert handling and availability for the community.
- Trade-off between maximizing the knowledge dissemination and respecting data property.

1. FRONT-END

1.1. COMMUNITY CONNECTION

1.1.1. User management

COM-01

01. Access permission: Google login, ORCID (TBC) and email/password.
02. Facebook has been discarded mostly due to negative publicity recently, also in terms of privacy issues. Google may be a bit more neutral.
03. Types of users:
    a. professional / followers;
    b. visitors.
04. Confidentiality and permissions management: in the version beta 0.1 everything is considered public.
05. The platform provides a user form to create access to the platform.
06. The platform shall provide basic information and access to data to users without creating an account. In the version beta 0.1 everything is considered public: view the facilities that are subscribed to the platform (and share data with the platform), view calls for joint programmes from other users or view calls from observatories that share programmes with the community.

1.1.2. Social network: science-driven groups inside the platform / Scientific and community agenda

COM-02, TOOL-03, TOOL-04

07. The Platform shall allow to share data through social and public networks.
08. Everything that can be shared via a url link is prioritized (data, images, contacts, congresses, papers...).
09. The platform provides a form for the submission of congress, event, seminar,...
10. The social networks shall maximize the dissemination and the scientific results to population. Facebook and Twitter are priorities.
11. The platform shall allow the creation of science-driven groups inside the tool itself.
12. The users shall be able to configure the preferences:
    a. The users owning the data define the data status between public/private. For version beta 0.1 only public is considered.
    b. The users are able to “follow” events, infrastructure news, projects agenda,...
    c. The users are able to publish events, conferences, workshops and news.

1.1.3. Information about facilities vs messengers

TOOL-01

13. The platform provides the capability of filtering the infrastructures with the purpose of showing information about observations and events, past and future.
14. The platform provides a form to collect infrastructures information, that will be used for presentation purposes and filtering purposes:
    a. General information.
    b. Projects and scientific.
    c. Messenger info.
    d. Scheduled events and observations (URL for VO services).
    e. Visibility.

15. The platform provides a form to collect information from a facility necessary about proposal submission (facility policies, main facility messenger and submission procedures):
    a. A facility can inform about a future observation:
        i. "all followers" of an infrastructure, project, messenger,... shall receive the notification.
    b. A facility can propose in the platform for a particular observation:
        i. all "followers" of that facility, project or any characteristic of the event proposed shall receive that proposal.

This requirement is considered for future evolutions of current version 0.1, which is prepared to implement it in future versions.

1.1.4. Share/Request MM proposals

COM-03, COM-04, COM-05, TOOL-02, TOOL-05

16. Users shall be able to find information and to connect with colleagues through the platform to coordinate observations that are planned in advance for a particular target.
17. Calls for shared observations: scheduled events:
    a. Provide a "My Zone" area where user preferences, events following, etc,... are registered (not now potentially useful).
    b. Manage confidentiality and privileges of your own observations to share it with identified infrastructures with cross-interest. In the version beta 0.1 everything is considered public.
18. Platform messages handling:
    a. Between users / Between infrastructures / Between infra-users.
    b. Share mean: the users shall be able to choose the mean to receive alerts Email standard.
19. Keep a record (in the version beta 0.1 everything is considered public) of past/future coordinated observations between infrastructures in order to promote/stimulate/encourage that practice and success:
    a. Connected programs to show MM contribution level for facilities.
    b. Advertising Platform and similar initiatives.
    c. The users shall be able to find the requested observations inside the platform (if they have the appropriate level of confidentiality).
20. The platform provides a form to Subscribe/Follow to messenger data (GW, EM,...).
21. The platform provides a form to Publish planned/scheduled observations: Users shall be able to publish planned observations of a specific target.
22. The platform provides the capability of interfacing event data to capture it into scheduling tools.

1.2. VIEWS

DASH-01, DASH-02, DASH-03, DASH-04, TOOL-06

1.2.1. Facilities filtering

23. The information from observatories events shall be listed/filtered dynamically:
    a. Filtering features: visibility time interval and RA-DEC position.
    b. Scheduling Block (SB)/observations layer: scheduled events (past/future) in a timeline for all facilities with events in the filtered features.

c. Show past events in the SkyView.
d. Provide the multi-messenger coordinated information petition for future scheduled events.

1.2.2. Layers

Graphical representation of (part of) the sky with overlays that can be turned on and off. A certain amount of filtering (time/position) is probably needed.

24. The SkyView shall show the following layers:
    a. "visibility" of instruments; one layer per instrument. These layers would show the “footprint” on the sky of the instrument, e.g. the field of view of a telescope, calculated for the selected time window.
    b. "scheduled observations" (planned and executed) of instruments within the selected time window; one layer per instrument. This could include observations from the recent past.
    c. target layer that displays a target position entered by the user.
    d. event layer that displays positions from a VOEvent stream, within the selected time window; multiple layers for different streams and/or event types?

25. The SkyView is based on Aladin Lite.

An existing solution that could possibly be adopted/adapted for use in the MM platform is Aladdin Lite:

https://aladin.u-strasbg.fr/AladinLite/

This seems to come with documentation and a list of several projects that use the interface.

1.3. TOOLS

26. The Platform shall allow to export data outside the tool (download).
27. Scheduling tools: Scheduling tools (observatory constraints, object visibility intervals, multi-observatory scheduling algorithms).
28. VOEventSterams / VOEvent / VOEventDB: subscribing to private VOEventStreams, would the tool need to simply prompt the user for a password.
29. TOMtoolkit (https://tomtoolkit.github.io/)

Implementation

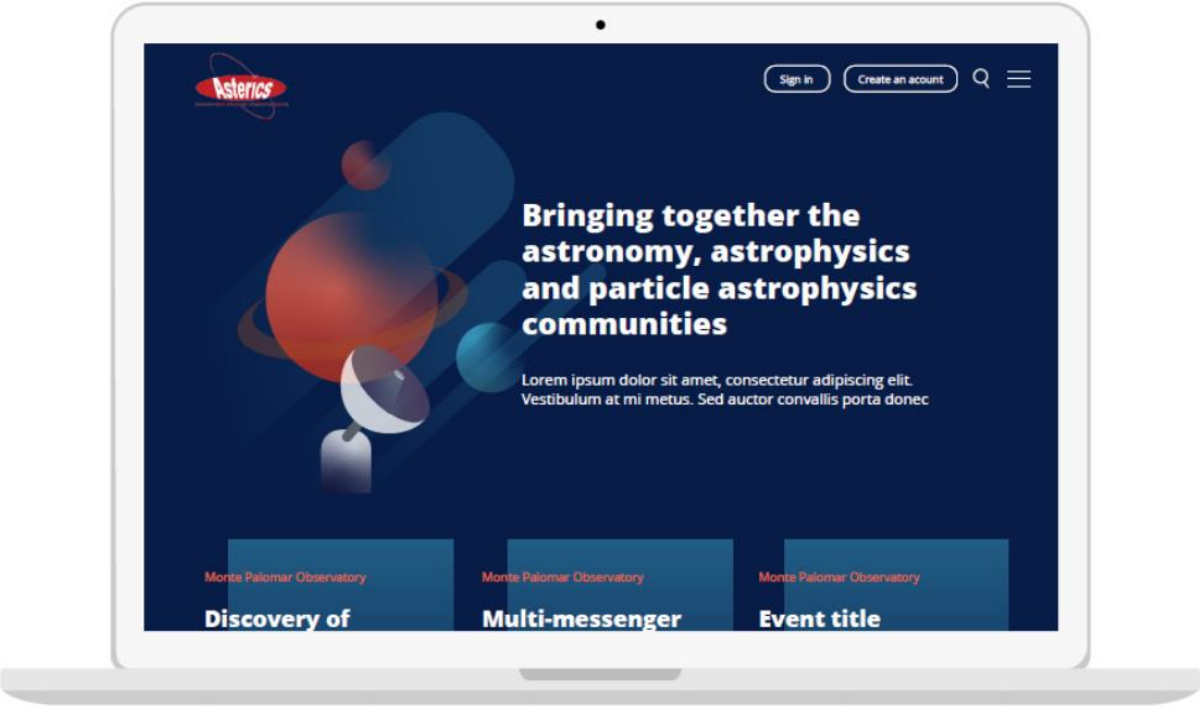
The implementation is focused on the main topic of the task: the capability of the platform to enable and potentiate the collaboration between scientific infrastructures aiming at event observation through coordination of multi-messenger.

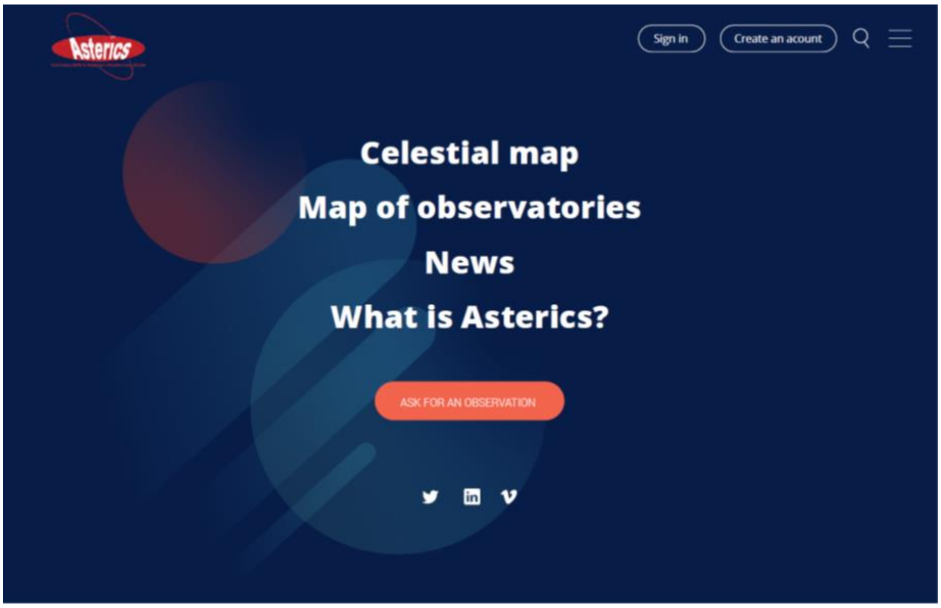
In the presentation screen, the front-end shows a main menu with the:

1. Celestial Map (ALADIN Lite)
2. Map of observatories
3. News

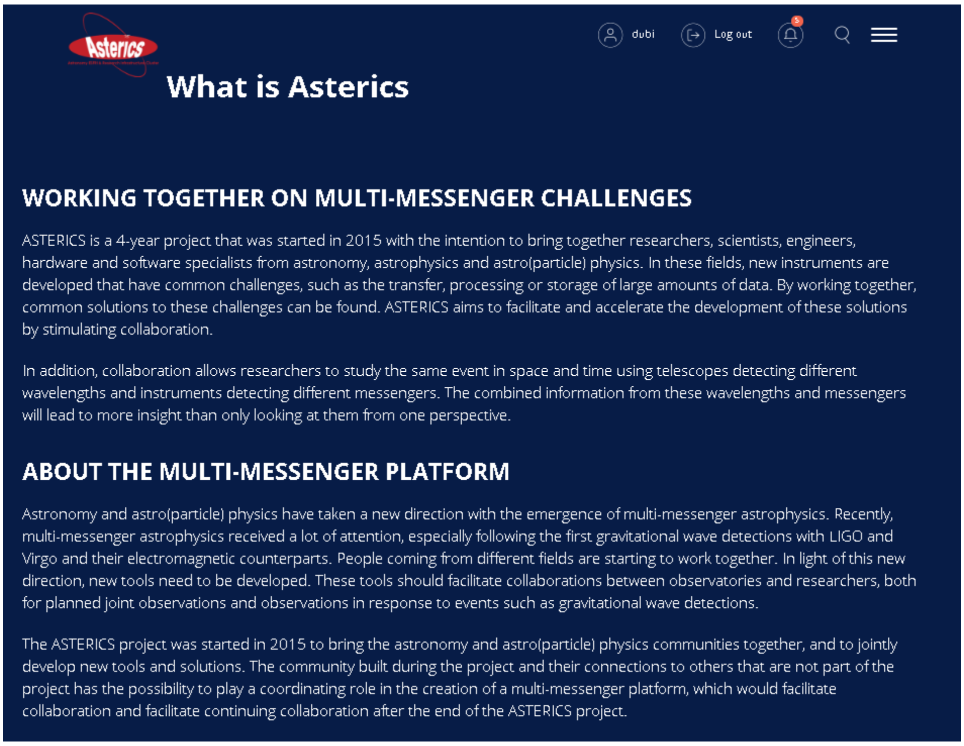
4. About ASTERICS

The first view shows the functions available for a visitor. At the same time, in the right top corner a user can create an account and log in the platform to access the functionalities devoted to professionals. ***[COM-01]***

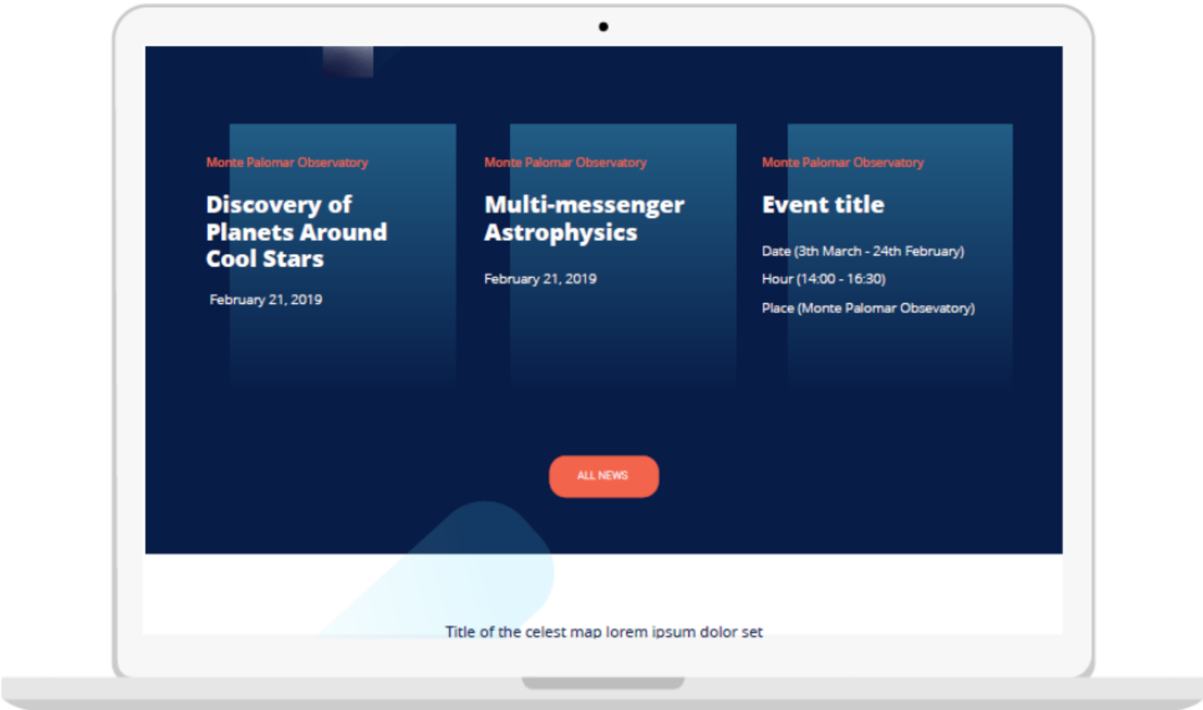




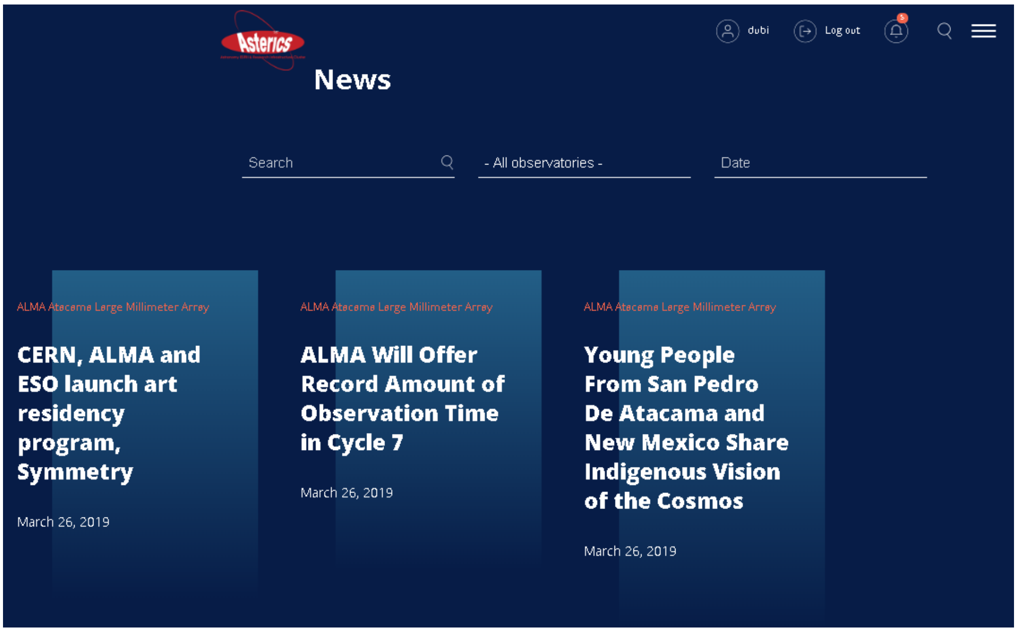
The ASTERICS description and the main objectives of the platform are detailed in the following screen ***[TOOL-04]***:



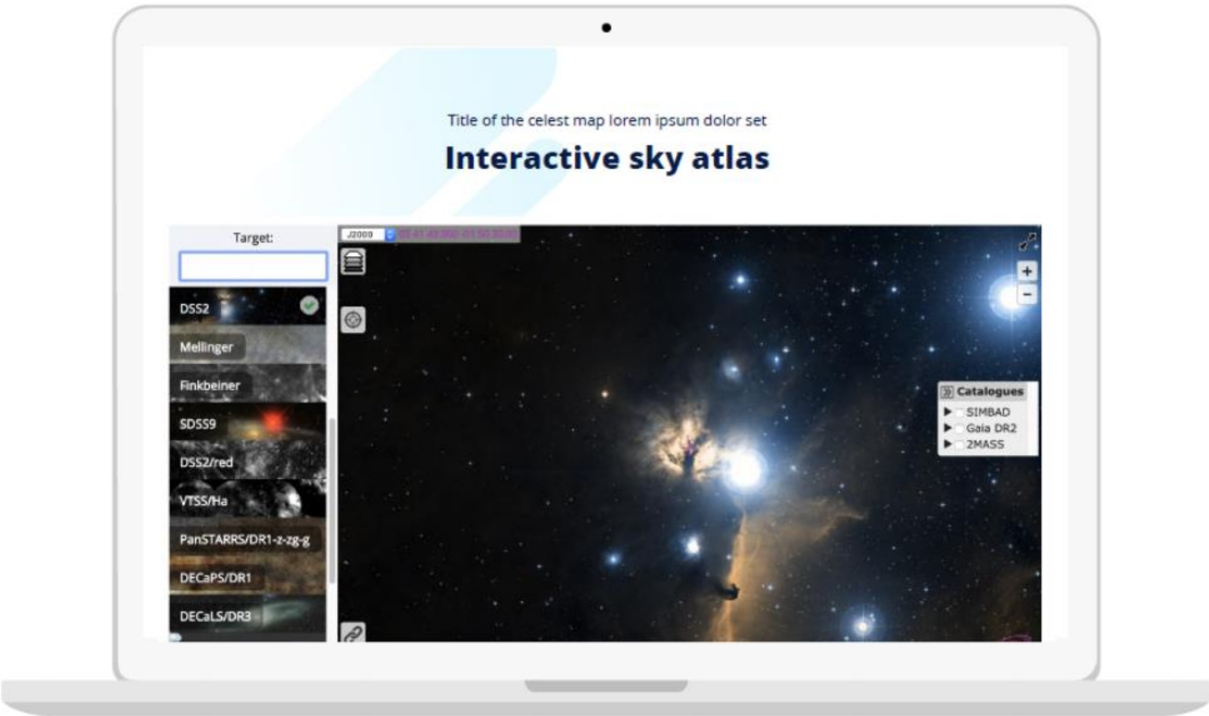
The most recent News appear in the initial screen, with the availability of filtering all the news in the platform ***[TOOL-03]:***



The filtering can be done by observatory that posted the news, by year or by keyword:



The news can be shared then shared on Facebook, WhatsApp, Twitter and LinkedIn.

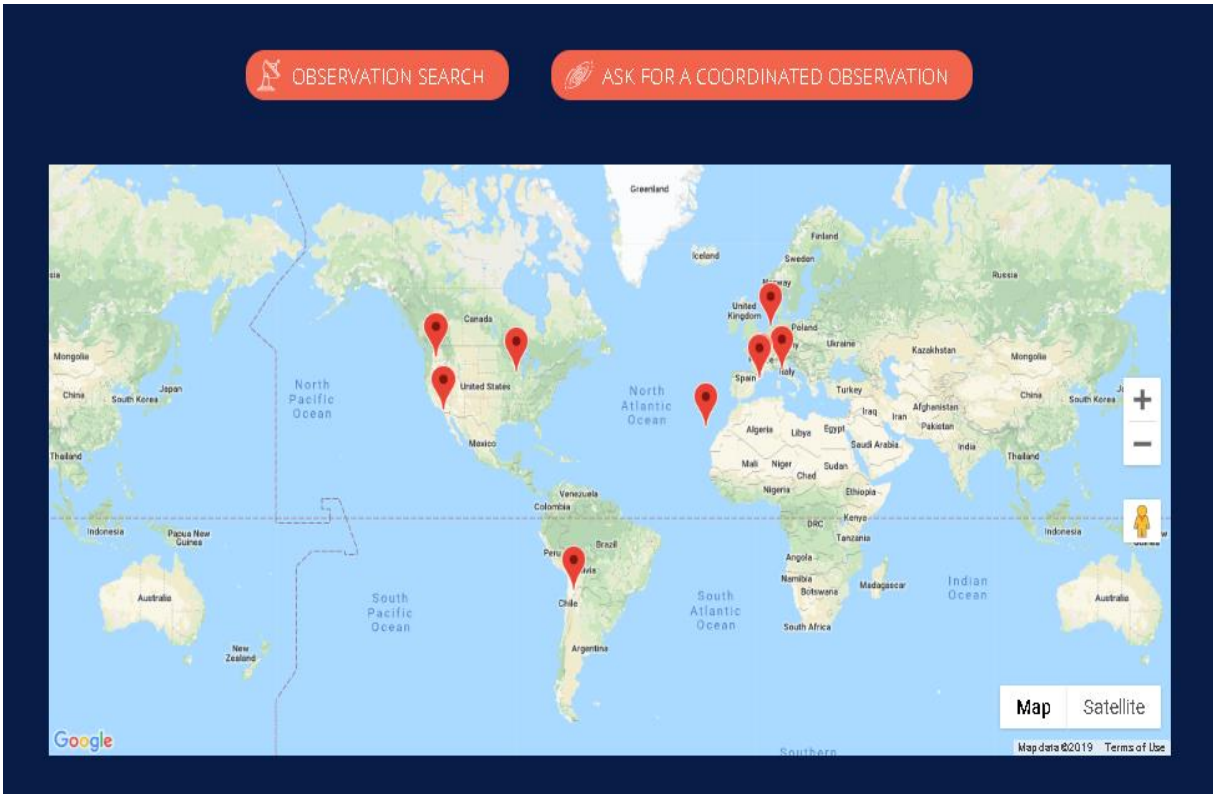


A main goal of the platform is the capability of integrating existing tools or tools under development in the community. The platform shall be designed to be adaptable, if not still with available tools, to be capable of integrating those tools in the near future. The development and programming choices are in that direction. In the prototype, the ALADIN Lite tool is already fully integrated ***[TOOLS-06].***

The infrastructures are shown in an interactive map. In the map it can be:

DASH-01, DASH-02, DASH-03, DASH-04

- Showing information of the infrastructures clicking in the map.
- Filtering the events (past and future) looking for potential interests of coordination observations.
- Ask directly for a coordinated information.

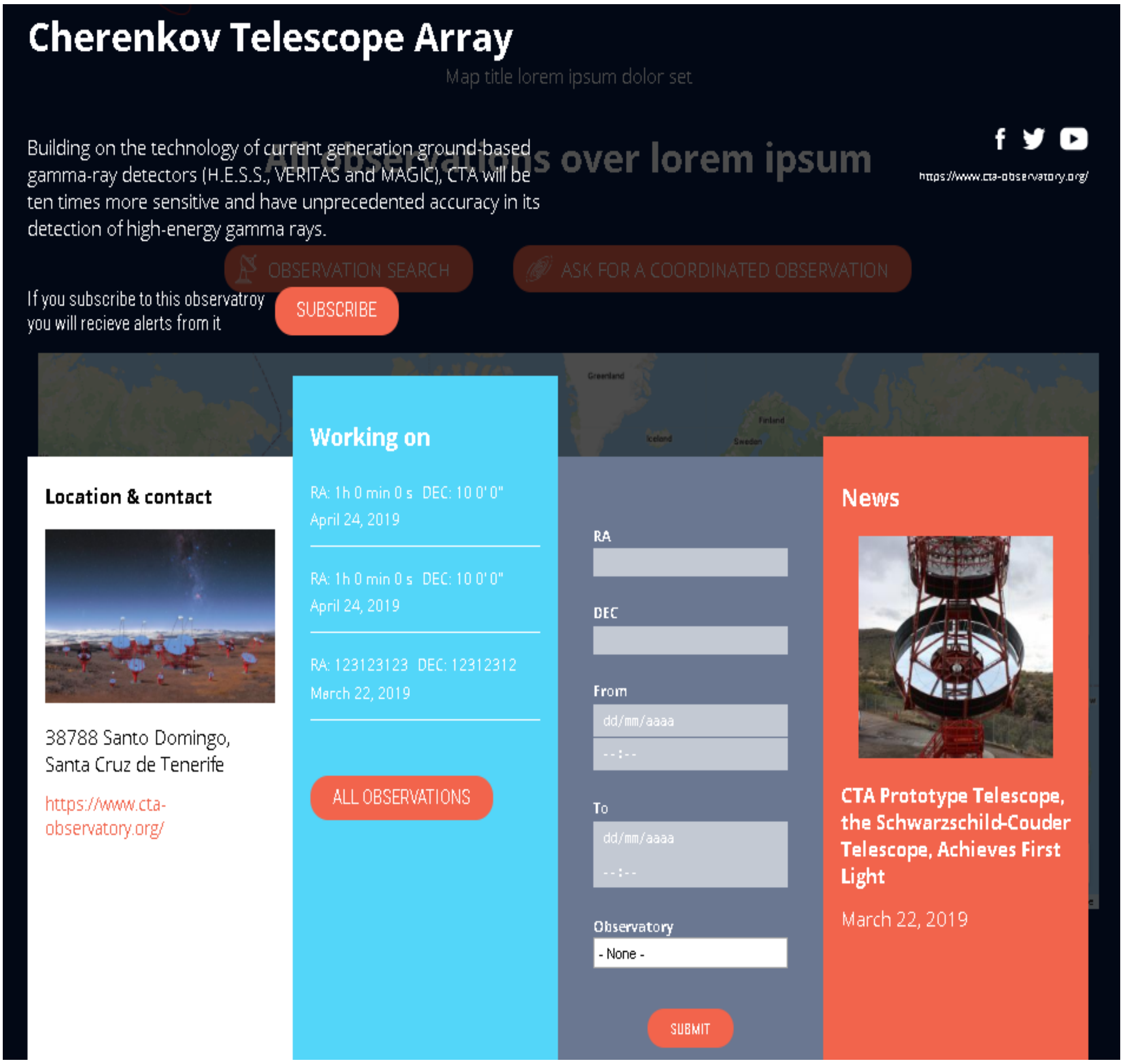


The image below shows the first point of infrastructures information:

COM-03, COM-04, COM-05, TOOLS-01, TOOLS-02

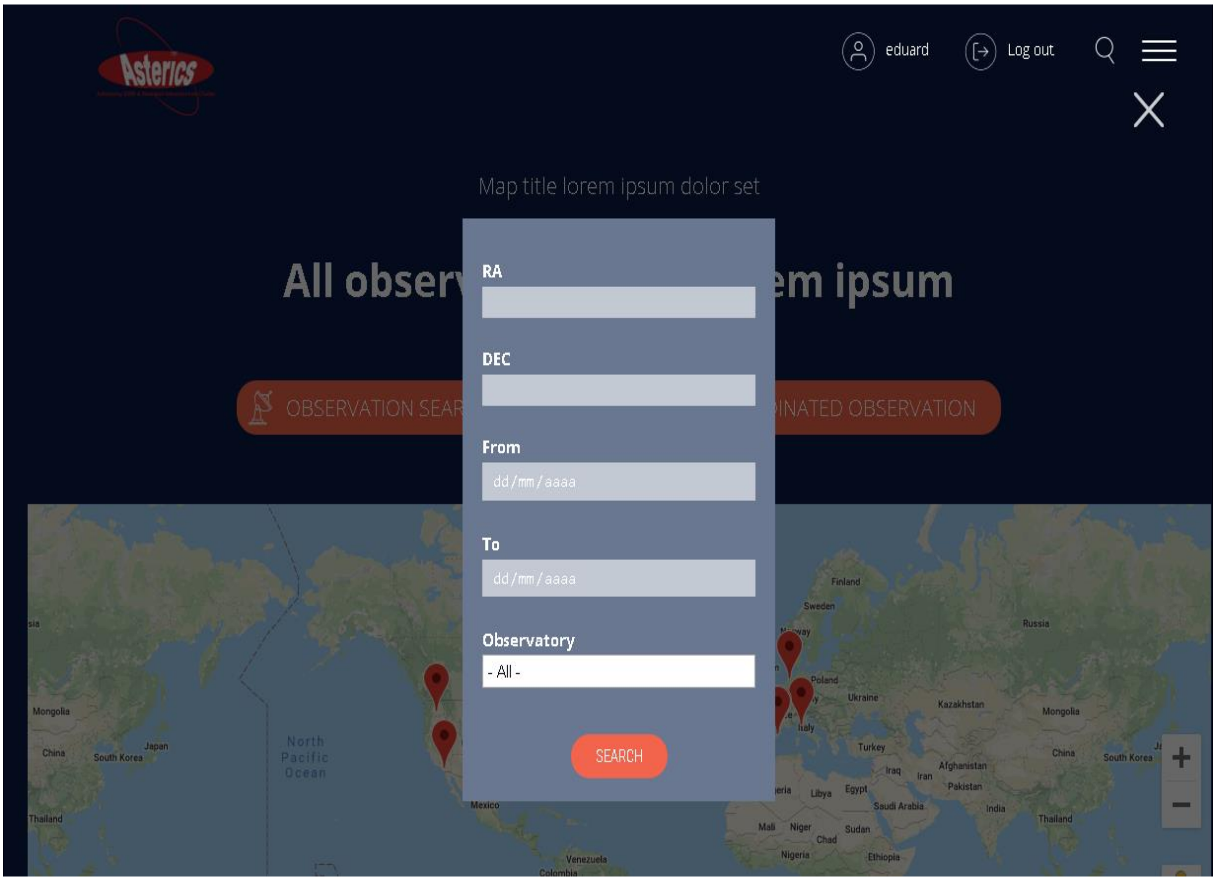
- the description of the infrastructure
- the current projects
- the posted news
- the option to ask for a coordinated observation
- the option to subscribe to that infrastructure

The subscription to an infrastructure implies that the user receives at its “My Zone” and is alerted by email about all news, projects, events related to that infrastructure (see My Zone in section below).



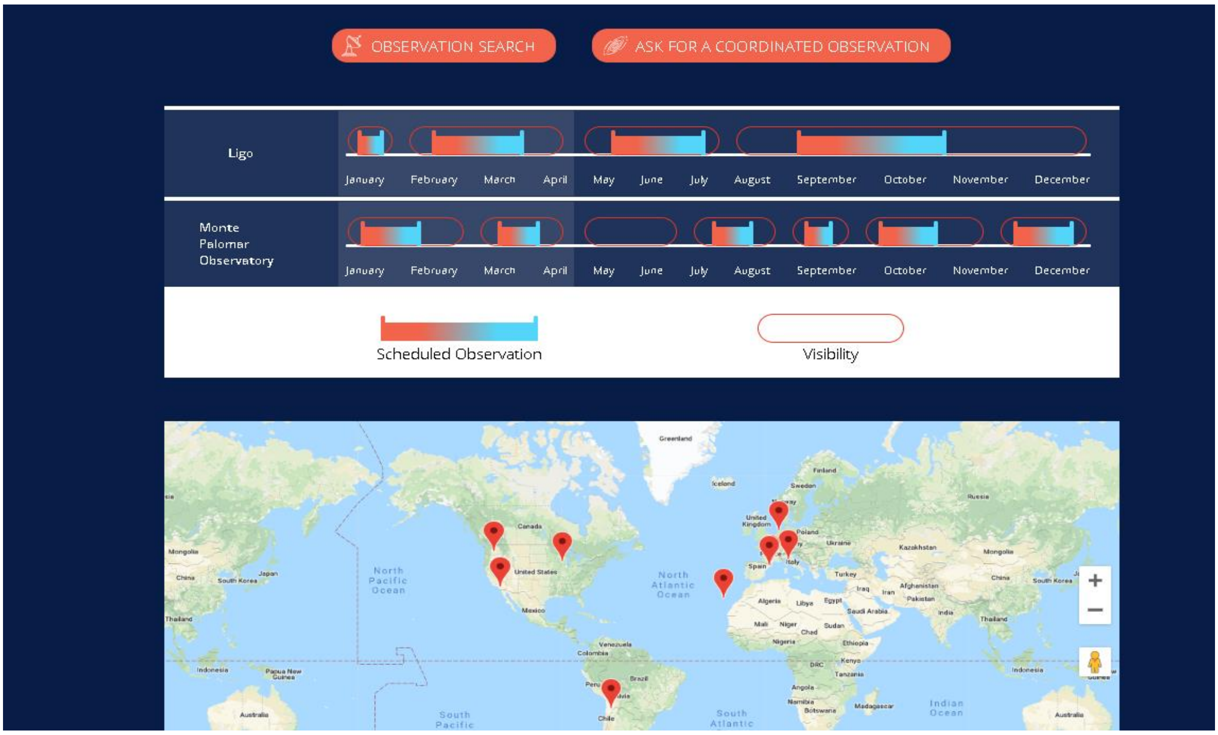
The filtering parameters of second point of the Map are:

- RA-dec: position in the sky
- initial and end date to set the interval
- the particular observatory or a search among all observatories

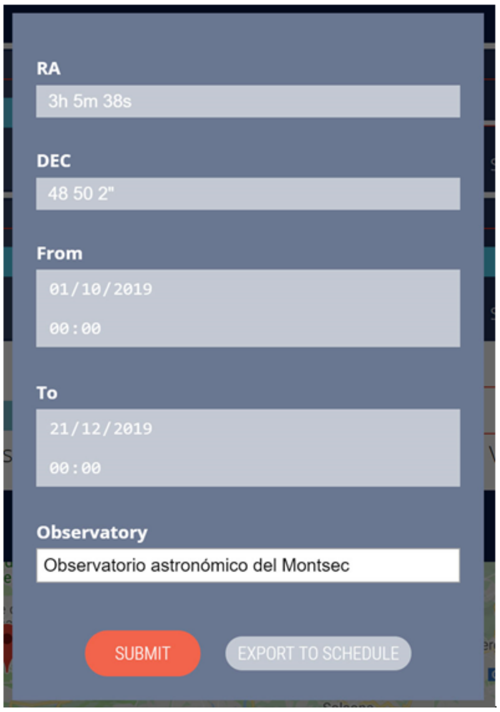


That search leads to a diagram representing:

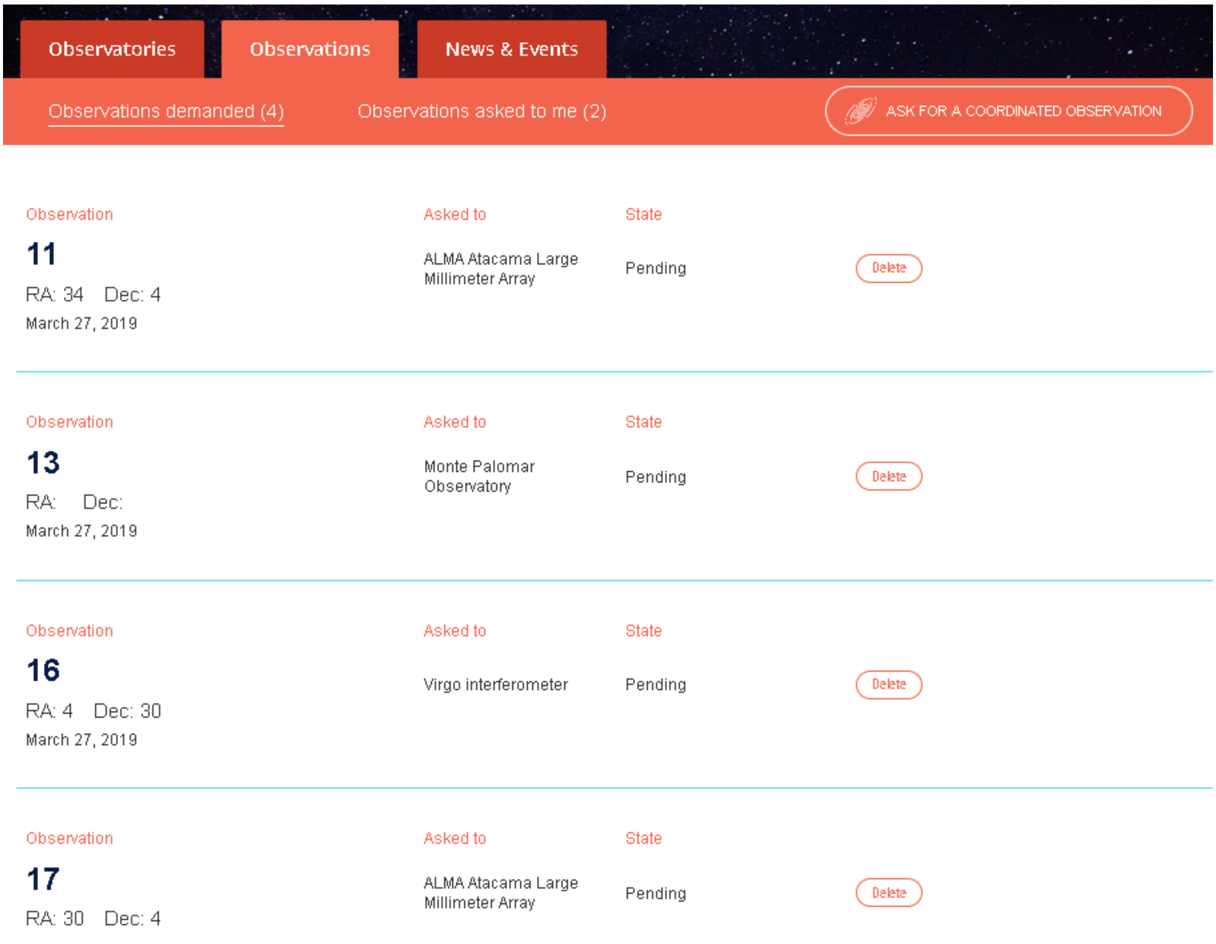
- in the x-axis the timeline between initial and end time configured in the search
- in the y-axis the list of infrastructures presenting visibility periods with or without events in such visibility periods, for the sky position and the timeline selected
- the diagram shows a past and future sides
  - The past events lead to the Sky map ALADIN
  - The future events lead to a coordinated observation form



The figure below shows the coordinated observation form. The form includes a "EXPORT TO SCHEDULE". This function enables in the future to export to scheduling/planning tools the coordinated observation parameters ***[TOOLS-06].***



The user MY ZONE main function "OBSERVATIONS" is devoted to centralized all alerts, subscriptions and coordinated observations petitions. The images below show: first, the list of coordinated observations sent to other infrastructures. Secondly, the list of coordinated information received ***[COM-02]:***

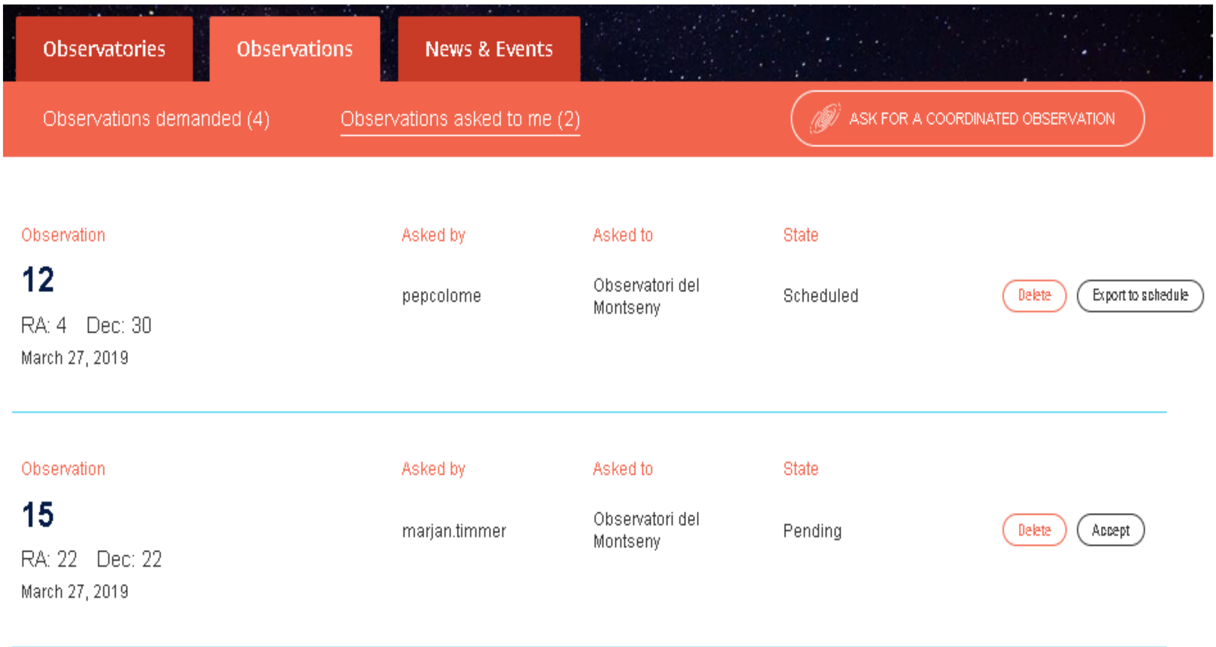


All coordinated observations are tagged unequivocally to ease future traceability of the multi-messenger interactions and the data in a multi-messenger database.

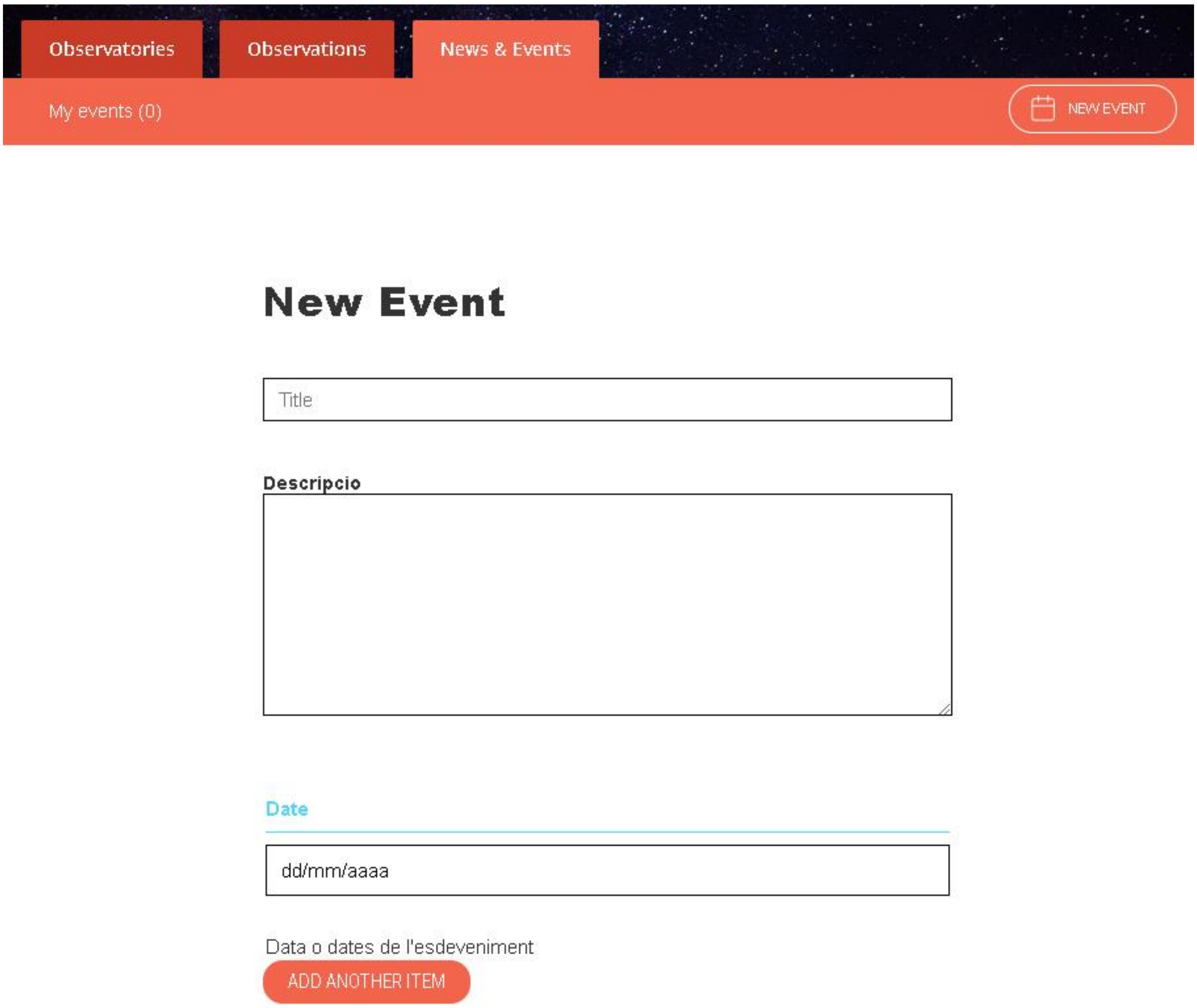
The list of coordinated observations sent allows to delete the petition and shows the status of the petition (accepted/pending).

The list of coordinated observations received allows to accept/delete the petition.

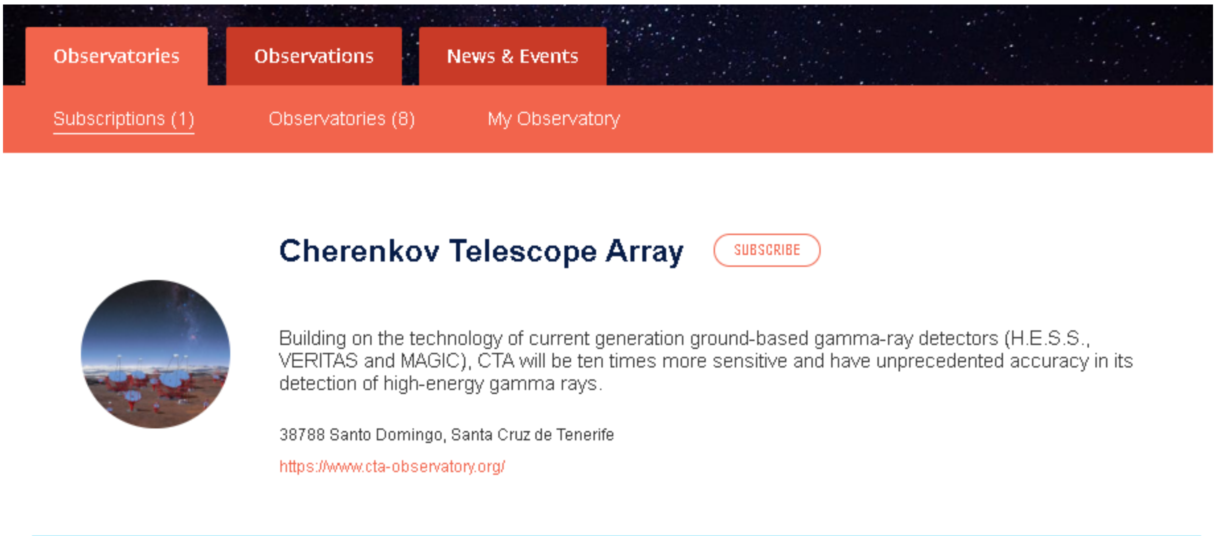
In both cases, once the petition has been accepted for both parties, the platform allows to "EXPORT TO SCHEDULE" the multi-messenger observation ***[TOOLS-06].***



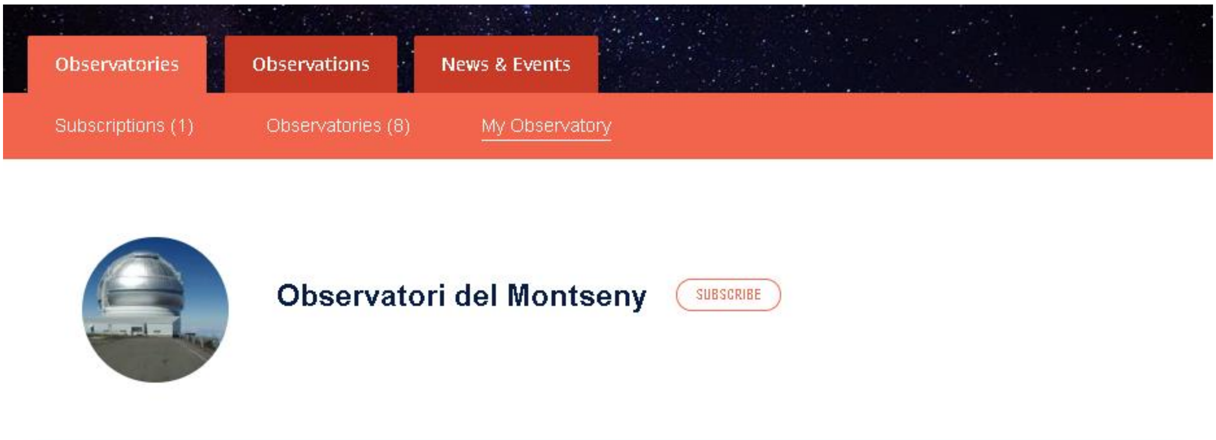
The MY ZONE presents a second functionality that allows as well to create NEWS&EVENTS, that will appear posted in the front-end. That section is available for the manager of the infrastructure with permits to change and edit the news related to that infrastructure.



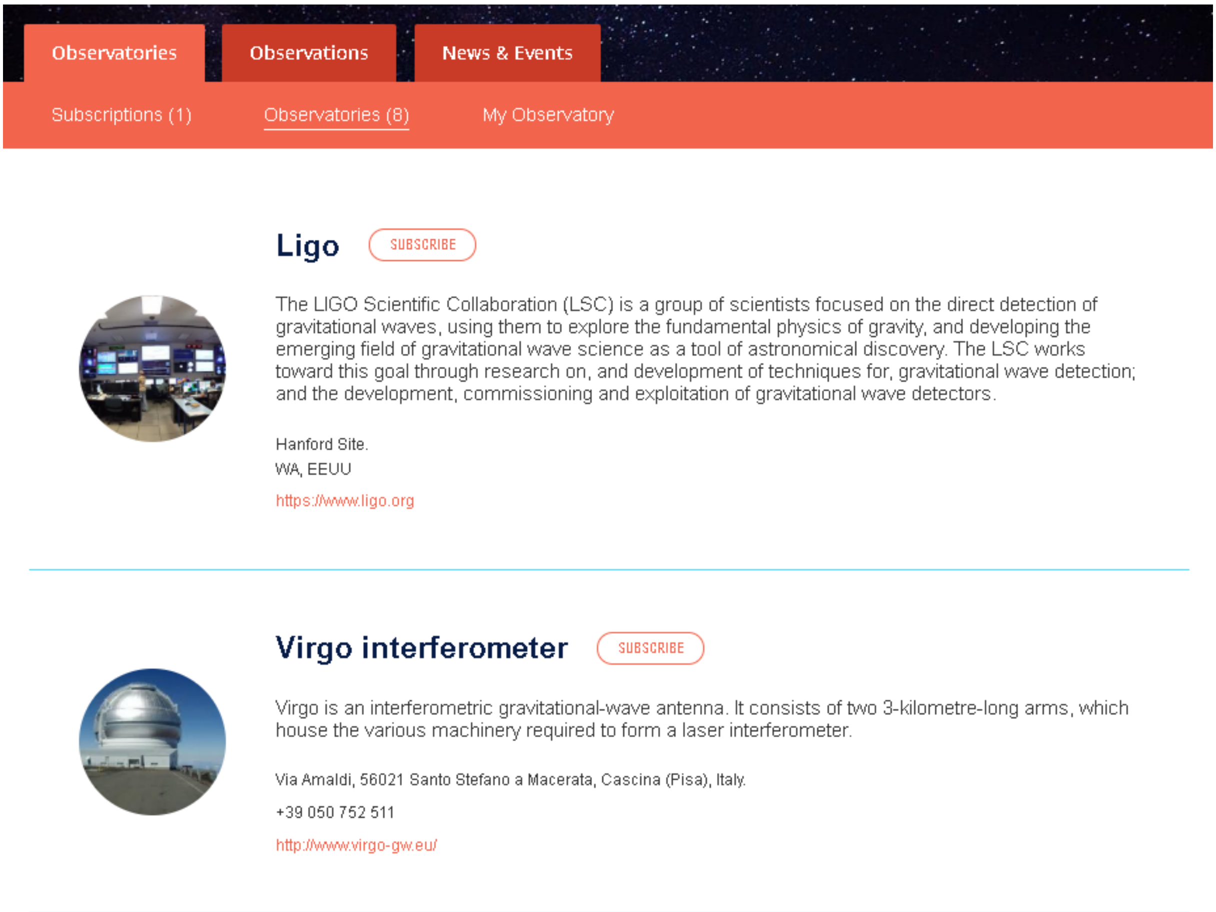
The MY ZONE presents a third functionality "OBSERVATORIES", which is the subscription and follow of infrastructures.



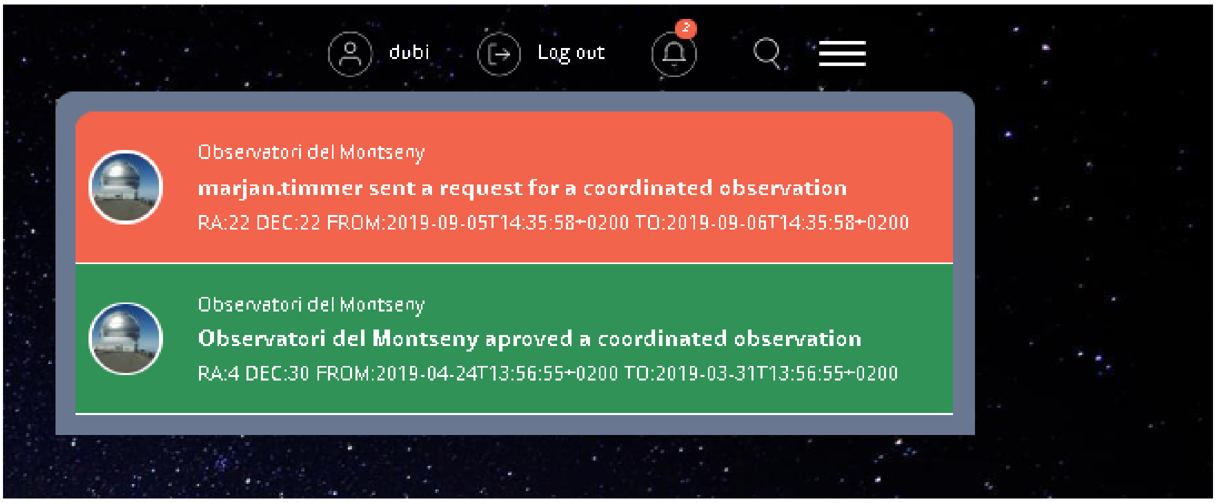
In case the user is the manager of an infrastructure, it would be allowed to create a NEW OBSERVATORY, and it appears as "MY OBSERVATORY"

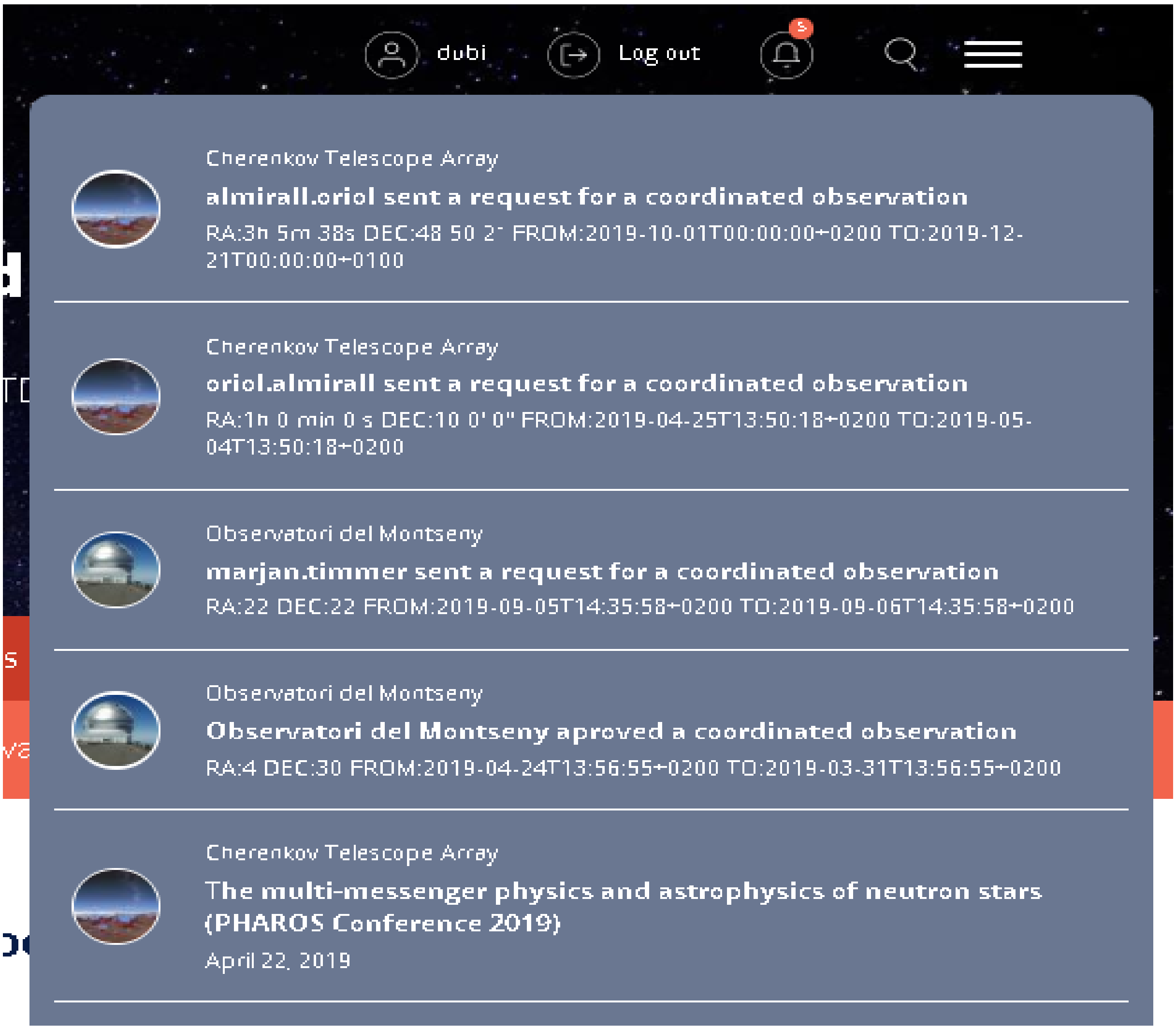


In the same tag, the users are allowed to manage subscriptions to infrastructures with shared interests. The subscriptions allow the user to follow the observatory activity through alerts in the platform and emails.



The images below show the alerts received in MY ZONE. The alerts are also sent to user email.


dubi
Log out
2
Observatori del Montseny
marjan.timmer sent a request for a coordinated observation
RA:22 DEC:22 FROM:2019-09-05T14:35:58+0200 TO:2019-09-06T14:35:58+0200
Observatori del Montseny
Observatori del Montseny aproved a coordinated observation
RA:4 DEC:30 FROM:2019-04-24T13:56:55+0200 TO:2019-03-31T13:56:55+0200


dubi
Log out
5
Cherenkov Telescope Array
almirall.oriol sent a request for a coordinated observation
RA:3h 5m 38s DEC:48 50 2' FROM:2019-10-01T00:00:00+0200 TO:2019-12-21T00:00:00+0100
Cherenkov Telescope Array
oriol.almirall sent a request for a coordinated observation
RA:1h 0 min 0 s DEC:10 0' 0" FROM:2019-04-25T13:50:18+0200 TO:2019-05-04T13:50:18+0200
Observatori del Montseny
marjan.timmer sent a request for a coordinated observation
RA:22 DEC:22 FROM:2019-09-05T14:35:58+0200 TO:2019-09-06T14:35:58+0200
Observatori del Montseny
Observatori del Montseny aproved a coordinated observation
RA:4 DEC:30 FROM:2019-04-24T13:56:55+0200 TO:2019-03-31T13:56:55+0200
Cherenkov Telescope Array
The multi-messenger physics and astrophysics of neutron stars (PHAROS Conference 2019)
April 22, 2019

Datasets for Testing

Several datasets were collected to test the MM platform performance. The datasets were intended to provide schedules that could be used to gather the sky pointing directions of different facilities: this is one of the ingredients needed for the user story devoted to multi-observatory coordination and scheduling, as described in a previous section.

- ALMA executed blocks were provided by ESO: the data set includes 2 random days in January 2019. A file with all the entries of the activities that are done during shifts were given. Some clarifications of data format were given.
- ARIEL Space mission (ESA-M4): 3.5 yr simulation data set following IEEC-defined protocol (based on RTML and other similar solutions). The dataset considers a target sample for the mission that was provided by the IEEC.
- CHANDRA X-ray Observatory: data retrieved from the mission website.
    - "CHANDRA Long-term Schedule": http://cxc.harvard.edu/target_lists/longsched.html
    - "CHANDRA Short-term Schedule": http://cxc.harvard.edu/target_lists/stscheds/index.html
- CTA Observatory data set for simulated surveys: data set provided by the IEEC.

These datasets were useful to check also different formats to describe the same information. However, they were finally not used in the prototype back-end for the lack of time to work on the homogenization of data parameters.

The datasets were not shared to other partners than those involved in the activity and for any other purpose than the one of the activity.

Prototyping Language

The platform is implemented in the PHP programming language and is based on Drupal, an open-source content management framework. Drupal/PHP is ideal for those aspects of the proposed platform that require user management, logins, private spaces, etc. On the other hand, the Python language has become very popular with the astronomical community and many libraries that will be useful for the platform are implemented in it.

Trade-off: PHP vs Python

Front-end platforms can be fully developed in PHP or Python. It is important to come up with a plan during the design phase that will ensure smooth development and a homogeneous result. Here are some factors to consider:

- PHP and Python are equally well considered as front-end development languages.
- Development using a single programming language would be simpler.
- PHP/Drupal is used for many social networking sites.
- Python is a language of choice for most astronomers working today, and libraries that implement many essential algorithms are written in it (e.g. AstroPy).
- While using a single programming language is desirable for the sake of simplicity, it is perfectly feasible to develop the platform using two languages, if it is found that specific functionalities

require it; for example, PHP for design and user interface and Python for scientific algorithms. There are two ways to achieve this:

- Service oriented architecture (SoA). In this scheme, the website is assembled from a set of components. Each component is implemented as a standalone microservice, and communicates with the others via HTTP requests. Each component presents a simple interface that conceals internal complexity. Theoretically, each component could be written in a different language.
- Less elegant, but effective, would be to write the top level of the platform in PHP but use Python for selected functions. This could be done by using shell_exec() or a similar PHP function to run a Python script and use its output. Running a child process has a high overhead but this is not a problem unless the process working in real-time.

A first conclusion is to recommend that we use Python in the future MM platform project, based on the current prototype. If it turns out that other development constraints or requirements demand PHP, we will do this using one of the methods described above.

Github Repository

The prototype platform is publicly available in the following repository, under GNU General Public License:

https://github.com/mm-astro/astericsh2020-multimessenger_platform

Conclusions

What and Why: the MM Platform for the MM Science Era

Coordinated observations are crucial in obtaining a more complete picture of several cosmic processes from different messengers and wavelengths.

The coordinated follow up of alerts triggered by gravitational waves (GWs) and by high-energy neutrinos has provided important insights. Moreover, many astrophysical events that are expected to produce high-frequency GWs but which have yet to be observed, are likely to drive relativistic outflows emitting high-energy (GeV-PeV) neutrinos; e.g. gamma-ray bursts resulting from merging compact objects, core-collapse supernovae with rapidly rotating cores, flares from soft gamma repeaters.

Currently, the mechanisms for coordinating observations are cumbersome and inefficient - no longer fit for purpose as the number of triggers grows. The need for improvement was theoretical but is now becoming urgent, as illustrated by the beginning of the third observing run (O3) of the LIGO/Virgo consortium, which has recorded five events in the first weeks, some requiring large follow-up efforts to localize and characterize the EM counterpart. In 2022, the scale of the number of alerts will increase even more, with the advent of the LSST unleashing a flood of several million transient alerts per night to be handled.

In addition, efficient multi-messenger (MM) and multi-wavelength (MW) observation of steady sources is important as well. Indeed multi-frequency observations have proven key to developing and testing models of many of these steady sources.

Collaborative operation of large astronomical facilities and space missions is key to promote MM science. Several use cases and tools must be considered for a significant change in the current paradigm in order to go for a grid and cooperative global infrastructure. The MM platform is an example of such a tool that is devoted to facilitate collaboration between different communities in astronomy and astroparticle physics.

Who: an ASTERICS Key Initiative

The main aim of the ASTERICS project has been to promote collaboration between previously separated communities in astronomy and astroparticle physics. Instead of developing tools separately for each research infrastructure, the goal was to encourage joint working so that they move forward together. The environment for knowledge sharing provided by ASTERICS is key to collaborative innovation in science and, in particular, creates fertile conditions for multi-messenger astrophysics.

In early 2018, ASTERICS identified the need for a MM platform to promote efficient MM science, whose development could take advantage of the project community of 26 European partners and external stakeholders, and the tools developed by it.

Two work packages in particular, CLEOPATRA and DADI, have strong synergies and experience relevant to the platform. Groups involved in these work packages have expertise on: the scientific use-cases for MM observation, IVOA standard protocols, tools for collaborative observation of targets, how proposals are defined and submitted to observatories, and finally how to optimize multi-observatory coordinated plans.

The team working on this project, and the network of stakeholders that participated in the design discussions, have connections to many facilities potentially interested in the MM platform. These are: the Cherenkov Telescope Array (CTA); the European Space Agency (ESA), the European Southern Observatory (ESO), in particular ALMA; the European VLBI Network (EVN); the International LOFAR Telescope (ILT); the Cubic Kilometre Neutrino Telescope (KM3NeT); the Laser Interferometer Gravitational-Wave Observatory (LIGO); the Square Kilometre Array (SKA), and Virgo.

At the final ASTERICS event, the 'New Era of Multi-Messenger Astrophysics' conference held in Groningen in March 2019, several talks dealt with the topic of transient follow-up and observing coordination, each showing similar diagrams with event brokers and facilities linked by some process in between. The fact that many people are looking urgently at this area is a confirmation of its importance.

How: Key Points for the MM Platform

The analysis of the MM platform in this document presents an overview of the current situation and describes what is missing. An important design theme is that we avoid building from scratch, but instead reuse and combine existing tools to match the community's needs. Instead of focusing either on individuals or on facilities, we aim to cover both.

Coordinating and Connecting Development

Our analysis shows that many of the initiatives undertaken by the MM community are important, but uncoordinated. Different groups tackle different parts of the problem. AMON, for example, seeks to correlate trigger events and collate follow-up events. SmartNet aims to facilitate collaborative observing of selected targets. Brokers such as Lasair add value to events, then filter them and deliver them to the community. ESASky gives easy public access to ESA satellite data archives. TOM toolkit provides components that can be assembled in various ways to facilitate observation planning and scheduling.

The main objective of the MM platform is to connect together various components being developed around the world, providing a path from target selection through follow-up observation planning and reduction, to archiving. The idea is that in this case ‘the whole can be more than the sum of the parts’. An important part of this work is to identify any gaps that need to be filled, and fill them. Equally important is to make and maintain contact with fellow stakeholders, to do the human ‘networking’ required to identify opportunities and build collaborations taking the work forward.

The Facility View

This will show the capabilities of facilities, ranging from a basic description to details of instrument performance, target visibility, and instrument footprint on Aladin Lite (Figure 8). It will be possible to filter the facilities according to messenger type and instrument capability. It will also be possible to view the observing schedules of those facilities that make them public.

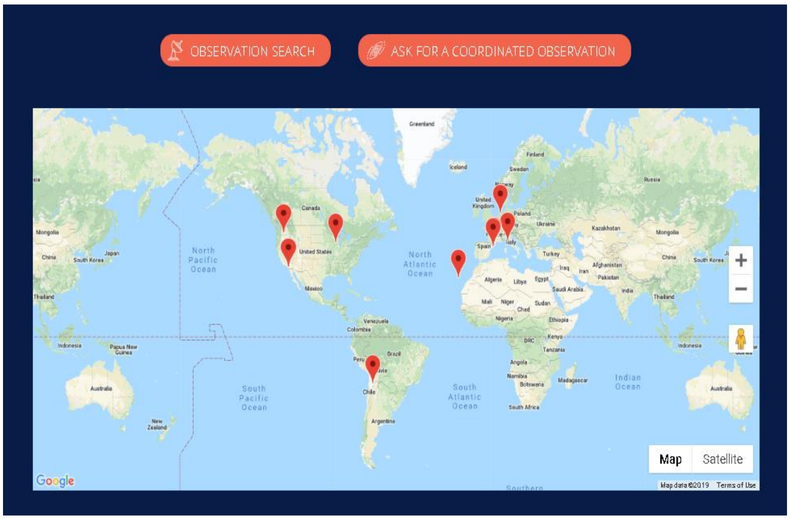


Figure 8. The facility view in the MM platform prototype, showing the location of facilities, and offering the possibility to retrieve additional information ranging from a basic description to details of instrument performance, target visibility and instrument footprint.

Integrated Visibility/Observing Schedule Display

For any target, knowledge of its visibility from facilities and of any known scheduled observations, are essential in planning observations. Ideally, this information should be presented in one display such as that shown below (Figure 9).

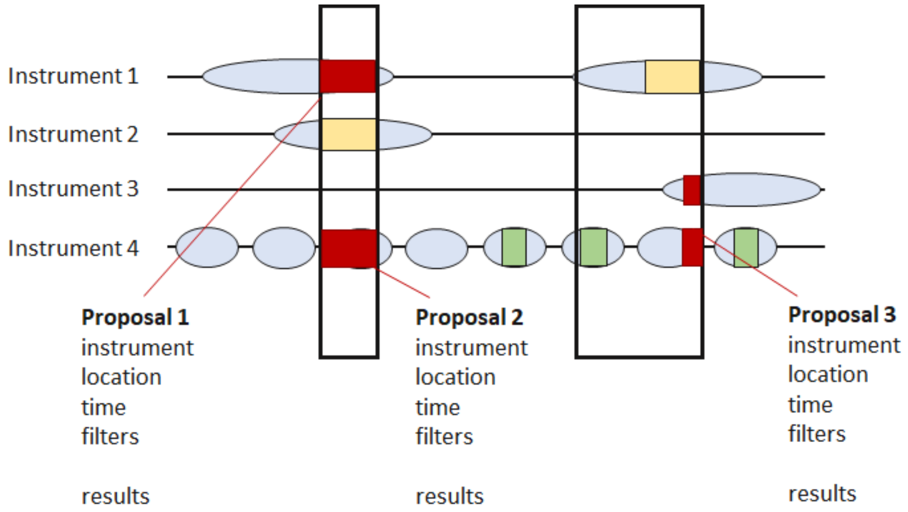


Figure 9. An example of how the MM platform might present an optimal observing schedule for multiple observatories.

There was not enough time to implement a prototype version, though we have contacted those at ESA who are working on making their satellite target visibility, and schedule information available through the ObjLocTAP and ObsVisSAP IVOA protocols. They are keen that such a tool be developed that can display their satellite information to the public.

Broker Hook-up

There was not enough time to link the prototype to external event brokers. The next development cycle should establish a complete chain from target selection, through follow-up, to archive - connecting to the brokers is the first link in this chain. AMON is specialised broker, with a particular set of skills developed for correlating trigger events, and for collating events that are secondary to a trigger. Connecting the platform to AMON would add an important set of capabilities not available elsewhere.

Integrated Scheduling Optimization

A key aim of the MM platform is to provide tools that facilitate the organization, scheduling and analysis of collaborative observations.

Scheduling software is under development for obtaining a plan that can fulfil simultaneously the scientific aims of different participating facilities, maximizing the time for which MW/MM coverage of a source is obtained. The software uses the target visibility, the shared schedules from the telescopes, and other operational and observational constraints, in order to obtain a common optimization (Figure

10 and 11). A further objective, to promote the simultaneity of the observations for MM science programmes, is also adopted. The latter is achieved by maximizing coincident observations among the involved facilities or by minimizing the distance between them.

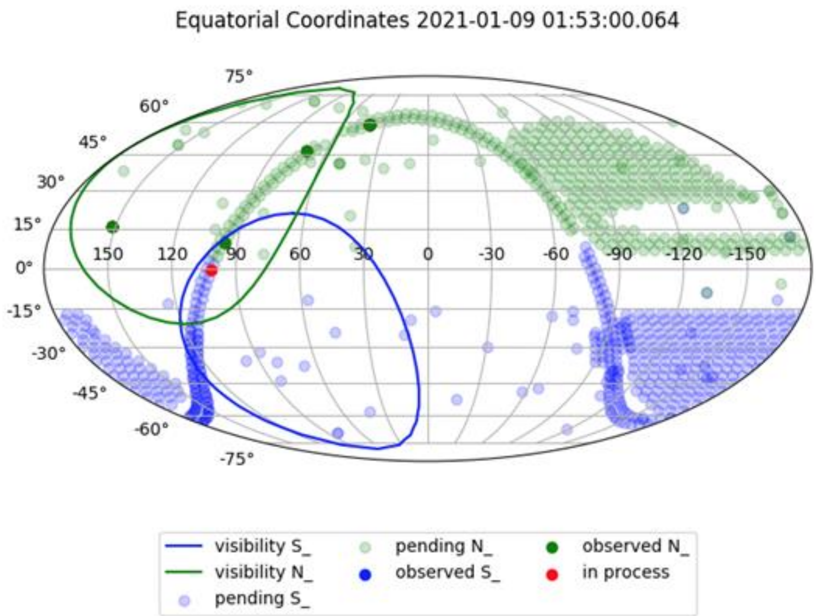


Figure 10. Snapshot of a planned observation (in red) where both CTA sites pointed simultaneously. The field of view of each one is marked in green and blue. The observation planned pending and observed are marked in light green and blue bullets respectively.

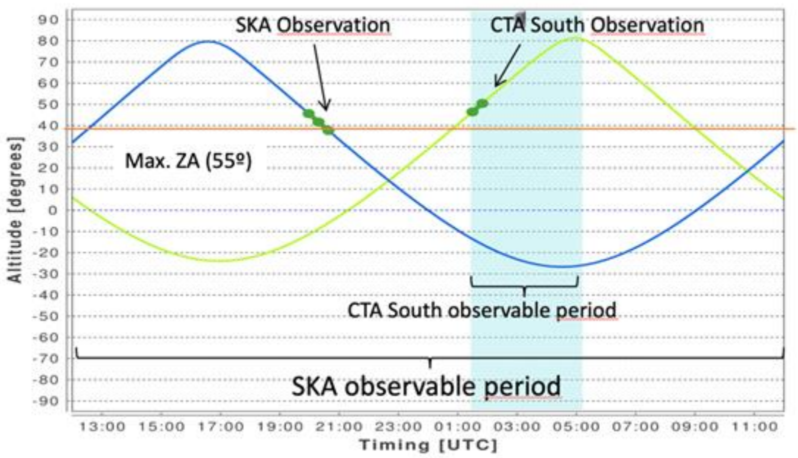


Figure 11. Target coordinated observations for SKA and CTA South.

The Coordinated Observing Story

The MM platform needs a structure that can store the component observations of an observing campaign. The basis for such a thing has already been developed as the IVOA ObsLocTAP protocol, lacking only the ability to store observations from more than one Observatory.

In addition to adding an 'Observatory' column to the ObsLocTAP table, the MM platform will also investigate ways to store ancillary information, ideally notes and comments that might illuminate the story of how and why the observing campaign developed as it did - this we would call the 'observation story'. Such metadata could be useful in future when the observing campaign is retrieved from archive.

Technology

At the time the prototype was specified and construction begun, we were focused on the collaborative 'SmartNet' aspects of the platform, and on high-level views of ground and space-based facilities. The prototype contractor identified the best match to these tasks as the Drupal framework, programmed in PHP. While a good choice for the capability subset, it immediately raised an important question. Python is the dominant scripting language in astronomy today - should we not be using it and a framework such as Django for development? Or is a hybrid scheme possible, where components written in the language best suited to them can be combined?

Standalone Services

Assembling the MM platform from an array of components offers the chance that many of the components will be useful in other systems, some perhaps able to exist as a standalone service, as the brokers do today.

Next Steps

We believe we have made a good start to developing the MM platform and would like to carry on many of the things that we have begun.

In future work, we will continue to follow good practice, namely reusing pluggable components where possible and developing them only where necessary to add new capability - we will avoid reinventing stuff. Much of the work of the MM platform involves communication between components and we will use IVOA standards for this wherever we can.

By sharing news of the project and its development, we will continue to build relationships with industry and facility stakeholders, helping form a community of people interested in coordinated, collaborative observing.

Core Platform

In the short term (timescale of 1 year), we will work towards these overall aims by concentrating on the 'core' aspects of the MM platform. At the end of this time, we would hope to have a working version. Particular goals include:

- ***Re-focus the core design*** The 'core' design must be compact yet retain the most essential features. There was not enough time to link together in the prototype all the components needed to run through a complete triggered observing campaign, from target selection, through follow-up, to completion. This is one of the most important, general use-cases for the MM platform, and we will focus sharply on that.
- ***Choice of technology*** As noted earlier, the capability subset driving the prototype, requiring users, logins, private spaces, seemed an ideal 'fit' for Drupal/PHP. However, this conflicts with the widespread adoption of Python by the astronomical community. Since one of the main goals of the platform is to integrate community tools, now and in the future, it is important that we look for the best way to combine PHP and Python in the platform. Do we need both?
- ***Broker hook-up*** Possibly the most important part missing from the prototype was the link to event brokers. They will be the main generators of targets for follow-up and will implement the sophisticated filters essential for target selection.
  We are in contact with the Lasair development team so it makes sense to adopt this broker as representative of the class of object. To connect to the platform brokers will have to export, in machine-readable form, data on targets selected. Lasair would be willing to add an 'export' button to each target on a Lasair event page to write the data in JSON to a pop-up window, which could be cut and pasted to the MM platform input. This is sufficient to make the connection; in time, the process would be streamlined.
- ***TOM toolkit*** is a box of components, written in Python/Django, that can be used to build a Target and Observation Manager (TOM) for the purpose of organizing follow-up observations. It uses Django and Python. We will use TOM toolkit components to plan and schedule follow-up observations on the facilities it can currently handle; the LCOGT, SOAR and Gemini. Unless there is a good reason not to, we will aim to make any new components we develop compatible with TOM toolkit. This will ensure that any new capabilities developed by us will be re-useable by the community. We have already made contact with the LCO team developing the TOM toolkit.
- ***Integrated visibility/schedule-observation display*** It is important for efficient follow-up planning that observers know what has been done, what is already scheduled to be done, and what it is possible to do in the future. The advent of the IVOA interfaces ObsLocTAP and ObjVisSAP (described above) make this possible, and services providing this information for some ESA and NASA satellites are beginning to come on stream - we are in contact with the ESAC team working on this. We will construct a tool to display this information, able to combine data from a selectable range of facilities so that coordinated or even quasi-simultaneous observations can be planned.
- ***Centralised News Facility and Registry*** Many groups working in the field of collaborative observing seem unaware of each other's existence. We would develop a 'news' component for the TOM tools package that could be incorporated into any TOM to repeat news items from a central 'place'. In addition, it might be useful if operational TOMs could sign up to a central registry, which could be listed as part of the 'news'. Such advertisement would help stop unknowing duplication.
- ***AMON*** is a specialised event broker with an unusual but important set of abilities. Its main function is to watch for correlations between alerts from different messengers/wavelengths. A secondary aim is to issue alerts that report follow-up observations for a triggering alert. As it is important that the MM platform incorporate alert updates, correlations and follow-ups into a target's observation story, so it makes sense to include AMON as a target selection

broker for the core platform. At the AMON workshop in Japan in May 2019, contact was made with an AMON collaborator with the aim of exploring future synergies with the MM platform.

Moving towards a Full Platform

During this stage (2-3 years from now), we would aim to expand the 'core' platform to be able to function as a collaborative tool that provides services in a reliable way. This will involve the addition of further capabilities, in particular those that enable group working: data display, communication within the group, display and editing of multi-facility observing schedules. In particular:

- ***The Observatory View*** There are many more facilities out there than most of us realise. This display will filter instruments by capability and show what is available on the ground or in space. Clicking on a facility will give access to public information about instrumentation, application procedures, observing schedules, etc. A first version of this view was developed for the prototype platform.
- ***Tools for Collaborative Observing*** One thorny issue for follow-up observing with multiple facilities is how to get observing time on them all. One solution is to follow ENGRAVE and simply apply for an amount of 'blanket' ToO time covering many instruments, in their case all the ESO telescopes at Paranal. Obviously, this works, but not everyone can do it. As an alternative we will develop the idea, begun by SmartNet, that people join the collaboration on a target by contributing data from one facility, presumably one they are experienced using and either already have time for or can obtain it quickly.

  For this, we would need to develop a software object that describes a multi-facility schedule, with space for facility keys so that collaboration members can retain control of their time until ready to commit. Also needed would be tools to show and edit such an object.

MM Platform Goals in a Global Context

The MM platform is aligned with several global initiatives for the optimization of the existing and future research infrastructures on astronomy to foster MM science.

Towards an EU Umbrella Initiative (ASTERICS-like) to attract Communities or Coordinate with other Initiatives around the World

The long-term goal is to have a functioning MM platform that is used by large facilities and consortiums. For this, it is important to build on the community of stakeholders involved in the initial part of the work, and to engage new facilities and groups.

The community formed as part of the development process will have a voice that can be used to promote ideas that are more generally important to the success of MM astronomy, notably the Open Universe Initiative (www.openuniverse.asi.it), which encourages open access for all to space science data, and the EU Open Access initiative.

In time, the community may development into a more official collaboration, perhaps mirroring the SCiMMA organization in the U.S. An EU initiative could engage large communities in Europe that are contributing to the construction of facilities (i.e., SKA, E-ELT, ESA-LISA) that will be operative in the next decade and will produce massive data that will certainly contribute to MM science.

Collaborative Operation built on Data Connection

The MM platform is built on a new paradigm that pursues the grid and collaborative operation of large astronomical facilities and space missions. Open sharing of processed data products is the key ingredient for the success of such a goal.

New paradigm **Grid and collaborative operation of large astronomical facilities and space missions driven by:**		
MM Science	**Link Users**	**Link Infrastructures (Ground & ESFRIs & ESAs)**

The set of data tools identified connects the MM platform with the Open Access global EU initiative, in particular the Open Data & Open Science parts. These actions are building blocks for the Responsible Research and Innovation strategy defined by the EU. The MM platform is fully aligned with and will contribute to this global strategy for the ultimate benefit of the scientific community and the society.

The Platform as VO app

The MM platform is built on foundations provided by the IVOA, the largest initiative in the world promoting data sharing among astronomical observatories and space missions. IVOA products of particular interest include:

- All those developed since the IVOA's inception in 2002 that are now embedded invisibly in services around the world enabling interoperability: the table exchange format, specification for simple catalogue and image query services, the definition of metadata describing resources, the Table Access Protocol allowing software to send flexible queries to a wide variety of databases, etc.
- Draft protocols such VOEvent for reporting transients. ObsLocTAP for sharing observing schedules, ObjVisSAP for reporting target visibility.
- The pluggable and extensible visualization tool, Aladin Lite.

Any data protocols that arise as part of platform development, such as one for describing a coordinated observation plan, we will endeavour to develop in collaboration with the IVOA or in an IVOA-sympathetic style.

References

Aladin Lite: https://aladin.u-strasbg.fr/AladinLite/

Astrophysical Multimessenger Observatory Network (AMON): https://www.amon.psu.edu/

ENGRAVE collaboration: http://www.engrave-eso.org/

ESASky: https://sky.esa.int/

IVOA draft protocols: http://www.ivoa.net/documents/ObjVisSAP/20180713/index.html and http://www.ivoa.net/documents/ObsLocTAP/index.html

Lasair: https://lasair.roe.ac.uk

Open Universe Initiative: www.openuniverse.asi.it

SmartNet: http://www.isdc.unige.ch/smartnet/

SCiMMA: https://scimma.org/

TOM Toolkit: https://lco.global/tomtoolkit/