Astronomy ESFRI & Research Infrastructure Cluster

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Multi-facility scheduling simulation and performance analysis software demonstration

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Abstract

The full context of an astrophysical source or a phenomenon can become clear and new science can be learned, when Multi-Wavelength (MW) observations are carried out. MW campaigns for Astronomical Transients (AT) or steady sources are costly, but have provided the most detailed astrophysical information we have on all source classes. In an ideal world, all astrophysical observations are multi-frequency.

Recently, the need for not only MW observations but also Multi-messenger (MM) observations have 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.

MW and MM observations should then become the norm rather than the exception.

For many types of transient events and steady sources, a common scheduling software for the involved facilities will have a high impact on the scientific output. We used the ASTERICS initiative to develop a new approach for maximizing simultaneous astrophysical observations, optimizing in a dynamical way the scheduling of one facility taking into account the constraints introduced by others. The aim is that multi-frequency observations are acquired by default in as many cases as possible. We provide details of the idea as well as a few worked-out examples, which already show the potential of the approach.

I. COPYRIGHT NOTICE

II. DELIVERY SLIP

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IV. APPLICATION 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. DOCUMENT AMENDMENT PROCEDURE

Amendments, comments and suggestions should be sent to the authors. The procedures documented in the ASTERICS "Document Management Procedure" will be followed: https://wiki.asterics2020.eu/wiki/Procedures

VI. TERMINOLOGY

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

A glossary of terms specific to this paper are given below:

- AGN - Active Galactic Nuclei.
- ALMA - The Atacama Large Millimeter Array.
- AMON - The Astrophysical Multimessenger Observatory Network. www.amon.psu.edu
- ASTERICS - Astronomy ESFRI and Research Infrastructure Cluster.
- AT – Astronomical Transient
- CARMENES - A dual spectrograph on the 3.5m telescope at Calar Alto Observatory.
- CLEOPATRA - Connecting Locations of ESFRI Observatories and Partners in Astronomy for Timing and Real-time Alerts. One of the five work packages in ASTERICS.
- CR - Cosmic Ray.
- CTA - The Cherenkov Telescope Array.
- EC – Evolutionary Computation
- ELT - ESO Extremely Large Telescope.
- EM - Electro-magnetic
- ESFRI - European Strategy Forum on Research Infrastructures.
- Fermi - γ-ray satellite.

- Gaia – astrometry satellite.
- GA – Genetic Algorithm
- GW - Gravity Wave.
- KM3NeT - neutrino detector.
- LIGO - The Laser Interferometer Gravitational-Wave Observatory.
- LT - The Liverpool Telescope. A 2m aperture robotic telescope operating on La Palma. telescope.livjm.ac.uk
- MeerKAT - A radio telescope array in South Africa. www.ska.ac.za.
- MM – Multi-Messenger
- MOEA – Multi-objective Evolutionary Algorithm
- MOP - Multi-objective Optimization Problem
- MW – Multi-Wavelength
- NTT - The ESO New Technology Telescope.
- PESSTO / ePESSTO - The Public ESO Spectroscopic Survey of Transient Objects was an ESO long-term project allocated time on the NTT telescope for the spectroscopy of transient targets allowing them to be classified. ePESSTO is a successor long-term allocation.
- SB - Scheduling Block, a generic description of a proposed observation.
- Scheduler - Process that selects the next SB to be executed by each facility.
- SKA - The Square Kilometer Array.
- TAT - Transient and Alert Team. A group within PESSTO tasked with triaging incoming alerts.
- TJO - Telescope Joan Oró, a 1m class robotic telescope operating at the Observatori Astronòmic del Montsec in Catalunya, Spain.
- ToO - Target of Opportunity.
- VOEvent - A standardized language for reporting astronomical events (http://www.ivoa.net/documents/VOEvent).

VII. PROJECT SUMMARY

The EU funds a number of astronomical facilities that are members of the `European Strategy Forum for Research Infrastructures', ESFRI. The `ASTronomy 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 maximize 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.

VIII. EXECUTIVE SUMMARY

The scope of this document is describing several demonstration tests to show how the efficient scheduling of multi-observatory coordinated programs can translate into a better performance to carry out MM programs. The analyzed indicators are also devoted to show that the single-observatory programs are not penalized, when this change of the scheduling paradigm is applied. This document is a continuation of the work presented in the ASTERICS deliverable 5.9, where the general concepts for telescope and observatory scheduling and the ingredients to promote the multi-messenger programs were given.

First, a description of the benefits of multi-facility scheduling for MM science is introduced. Next, the concept for such a proposal is given, together with the details of the technical implementation. The general design of different test cases is also described, in order to show the scenarios considered to prove the suitability of the coordinated scheduling solution, from the simplest to the more complex configurations. Therefore, the observation strategies and the facilities considered are introduced and, finally, the results obtained for this concept demonstration are presented and analyzed.

The STARS scheduling framework introduced in the deliverable 5.9 has been used to carry out the demonstration tests. The initial implementation of this framework was extended to cover also the simultaneous observation of MM programs and, in particular, the GW follow-up carried out by the CTA North and South observatories.

IX. TABLE OF CONTENTS

Introduction

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 (Acciari et al. 2009). 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 for not only MW observations but also Multi-messenger (MM) observations have 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 (ref AGNS) 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 types of transient events, a common scheduling software for the involved facilities 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 (see, e.g., Tavani et al. 2011, Abdo et al. 2011), and on the other hand, multifrequency observations of steady sources have proven key to develop and testing models. Multi-wavelength observations should then become the norm rather than the exception.

We used the ASTERICS initiative to develop a new approach for maximizing simultaneous astrophysical observations, optimizing in a dynamical way the scheduling of one facility taking into account the constraints introduced by others. The aim is that multi-frequency observations are acquired by default in as many cases as possible. We provide details of the idea as well as a few worked-out examples, which already show the potential of the approach.

Multi-facility Scheduling

Concept and technical implementation

We propose a solution to obtain efficient MW/MM coverage by using a cross-facility scheduling. Such scheduler should be able to fulfil simultaneously the scientific aims of each participating facility, maximizing the time in which an MW coverage of the source being observed is obtained, given knowledge of the other telescopes' schedules.

Scheduling together more than one astronomical facility will produce conflicting objectives (known as non-disjoint) that should be optimized, resulting in a Multi-objective Optimization Problem (MOP). This can be defined as the problem of finding a vector of decision variables satisfying constraints and optimizing a vector function whose elements represent the objective functions (Osyczka 1985). These functions form a mathematical description of performance criteria that are usually not disjoint (i.e., they are in conflict with each other). Hence, the term optimize refers to finding a solution that yields acceptable values for all objective functions (Coello Coello 1999). Usually, there is not a single point that simultaneously optimizes all the objective functions of a MOP. Therefore, in these problems, it is necessary to look for trade-offs, rather than single solutions. The concept of Pareto Optimality (Pareto 1897) defines that we can consider a Pareto optimal when no feasible vector of decision variables exists, that would decrease some criterion without causing a simultaneous increase in at least one another criterion. Multi-Objective Evolutionary Algorithms, MOEAs, (Coello Coello et al. 2007, Garcia-Piquer 2012) are recognized as one of the most valuable and promising approaches to addressing complex and diverse problems of multi-objective optimization. MOEAs are a particular case of Genetic Algorithms (GAs), which are Evolutionary Computation (EC) techniques (Holland 1975). EC is an Artificial Intelligence subfield focused on emulating natural evolution by means of combining potential solutions using selection, combination and mutation operators (Freitas 2002). MOEAs are well suited for complex optimization problems (Arias Montano et al. 2012) for several reasons: they can continuously improve the fitness function defined in the problem (improvement-driven); they allow the incorporation of a wide variety of extensions and constraints that cannot be provided in traditional methods; they are robust, balancing efficiency and efficacy; they are easily coupled to other optimization techniques.

Our proposed solution is based on using MOEAs inside an automated scheduler for obtaining the near-optimal schedule of tasks that maximizes simultaneity between facilities and, at the same time, optimizes the specific objectives of each facility. This approach is innovative and new in the astronomical context. Solving the challenges posed can be useful not only for astronomy, but for other disciplines and/or industrial processes as well.

Currently, our first prototype of scheduler for CTA is based on GAs that optimizes a single objective (this objective summarizes several disjoint objectives). Actually, we developed a scheduler software based on a similar approach for the CARMENES instrument (Garcia-Piquer et al. 2017), and it has demonstrated the expected optimization performance after 18 months of continuous operation. To expand it to a multi-facilities application, we complement the optimization process with the ability of working with objectives that are not disjoint.

We explore the possibility of scheduling a network of facilities (e.g., CTA, SKA or single optical telescopes) as a single global entity, obtaining a schedule of tasks to be performed in each facility for a period of time that can range from a night (mid-term schedule) to several months (long-term schedule). The telescope will, for the purpose of this approach, be in fact consisting at once of multiple, multi-site facilities operating each at different frequencies, each having their own constraints. Those constraints are classified as hard and soft. The hard constraints have to be fulfilled to accept an available solution, whereas the second ones are optimized depending on the goals defined. The **hard constraints** include limits related to visibility constraints and to resources ones. For instance, the target has to be visible from each location and the conditions of the particular observation fulfilled, that is, fulfilling limits related to solar or moonlight, minimum altitude, etc. The **soft constraints** are defined rather as the conditions the scheduler should optimize to achieve the scientific case proposed. For instance, they include the maximization of the observatory working time or the completeness of proposals or prioritization of targets to increase the scientific efficiency. For our particular case, we also include the maximization of the simultaneity of observations between the facilities described below.

The STARS scheduling framework (see ASTERICS deliverable 5.9 for a detailed description) has been extended to cover the multi-observatory coordinated scheduling and to include the aforementioned constraints and objectives. Figure 1 illustrates the multi-facility model used to manage the possible configurations, when more than one observatory is considered.

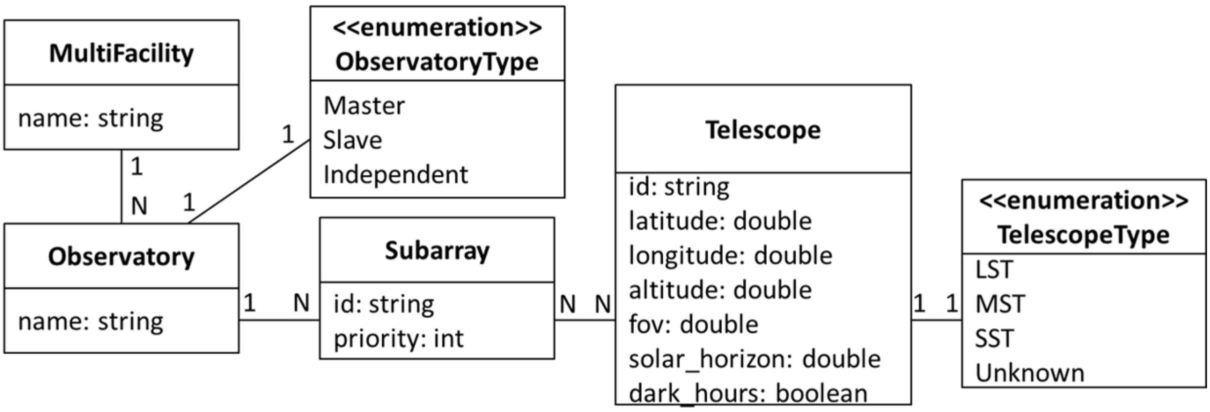

Figure 1: Multi-facility model describing the possible configurations, when more than one observatory is considered.

Observation strategy and facilities

To test the multi-facility scheduler, we quantitatively estimate, via simulations, how many simultaneous observations we would gain if we are able to subsidiary schedule one facility with respect to other or optimized all the schedules simultaneously. We test the performance applied to the three different installations with different particularities, namely, a gamma-ray observatory (the Cherenkov Telescope Array - CTA), a radio large-scale array (the Square Kilometer array - SKA) and a 4.2m optical telescope (the William Herschel Telescope). To test the MM scenario, we simulated the response of CTA to follow-up a Gravitational Wave alert along the North and South hemisphere.

In the following, we describe the characteristics of each instrument and the tests performed:

The Cherenkov Telescope Array (CTA) will be a high energy observatory working in the TeV domain, aiming to cover the energy range from 20 GeV up to more than 300 TeV. CTA will be fully operative in a few years and will be located at two sites (Acharya et al. 2017). In the North hemisphere, 19 telescopes, focused on the lowest part of the high energy spectrum and spread out over ~1 km2, will be located in La Palma, whereas in the South hemisphere, a larger area will be covered with 99 telescopes spread out over ~5 km2 (70 SSTs, 25 MSTs, 4 LSTs) in Paranal, Chile, increasing the sensitivity by a factor 10 when compared with current instruments at the central energy band around 1 TeV and enlarging the energy range to the highest energies. The CTA observatory will significantly boost detection area, improving detection capability (x25000) with respect to current instruments (Fermi-LAT, Abdo et al. 2009) for < 100 GeV phenomena lasting < 1 hr. Also, it will substantially improve angular resolution (x2-3) and field of view (x2), and hence the ability to image extended sources and their energy-dependent morphology, providing at sensitivity in the inner 3 out of the 8 degrees coverage per pointing.

CTA will dramatically enhance current surveying capabilities (x400), allowing simultaneous observations of multiple fields. Groundbreaking observations are expected in the following years.

The Square Kilometer Array (SKA) main instruments will include dishes and low-frequency antennas, and also potentially mid-frequency aperture arrays in a subsequent phase (e.g., Taylor 2012). Australia will host the low-frequency instrument with more than 500 stations, each containing around 250 individual antennas, whilst South Africa will host an array of 200 dishes, incorporating the 64-m dish MeerKAT precursor. Phase 2 will complete the telescope arrays at both sites, and become fully operational in the late 2020s, by which time the SKA will count with some 2000 high and mid-frequency dishes and aperture arrays and up to a million low-frequency antennas. SKA's angular resolution and survey speed capability will exceed current survey speeds by thousands of times; and even before SKA, radio continuum surveys planned (or on-going) with advanced radio telescopes operating just prior to SKA, like APERTIF (The Netherlands), ASKAP (Australia), eMERLIN (UK), VLA (USA), e-EVN (based in Europe), LOFAR (The Netherlands and other places in Europe), Meerkat (South Africa), and the Murchison Wide-field Array (Australia) will substantially change the radio data availability.

The William Herschell Telescope (WHT) was used to test subsidiary observations approach, assuming a punctual field-of-view (FoV), when comparing with the large FoV sub-tended by the CTA and SKA Arrays.

To ensure a realistic simulation, we used the planned observation projects described in Acharya et al. 2017 for CTA and the one described in Dickey et al 2013, proposing a survey of the low and intermediate latitude disk on the Galactic plane for SKA (see Figure 2). For the simulations including the WHT, we used the observation program followed in 2014 (http://www.ing.iac.es/Astronomy/observing/inglogs.php).

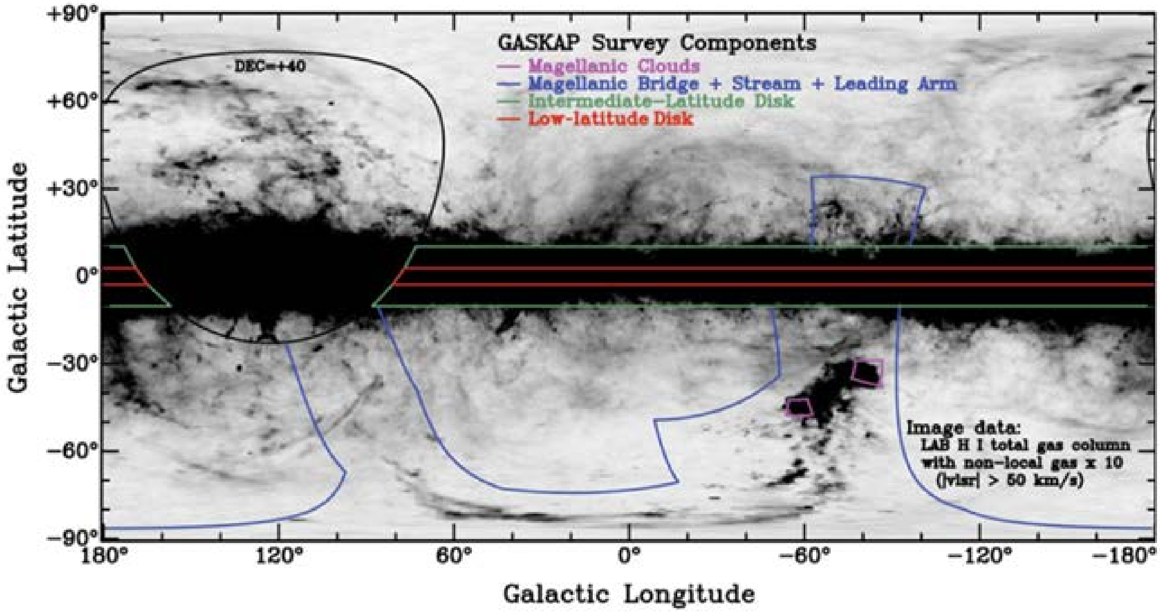

Figure 2: The GASKAP survey areas in Galactic coordinates (Dickey et al 2013)

The most powerful ever TeV and radio observatories, CTA and SKA will soon start taking data, and will do so essentially at the same time. However, even for large field of view instruments like SKA and CTA, simultaneity of astrophysical observations will not come by chance. If CTA (with ~8 degrees of field of view) and SKA (with ~20 degrees) are pointing at a random direction along the Galactic plane, the probability for a random coincidence of both field of views is of the order of 1%. And this number does not take into account precise location of observatories, random occurrence of bad weather or instrumental breakdowns, nor any other complexities alike. If one considers the whole sky beyond the Galaxy, this number is significantly reduced.

We considered different observation strategy approaches to test the efficiency of our multi-facility scheduler:

- Subsidiary observations approach

  We obtained the performance of the three different installations with different particularities, when one of them follows the observation strategy defined by the leader. First, we defined CTA as a leader followed by the optical telescopes WHT. Secondly, we designated SKA as leader, followed by CTA. In all cases, we established the optimizing goals to minimize slew time and maximize the observation time and the time when the follower abides by the leader.

- Interactive approach

  In a second more sophisticated approach, we optimized the programs of the two facilities simultaneously, keeping the minimizing slew time and maximizing observation time goals, but adding an additional constraint to prime the simultaneously of the observations. The observation programs proposed for CTA and SKA are used in this case.

- Multi-messenger approach

  As a final test, we simulate a number of randomly-generated alerts to the CTA observatory, where the simultaneous observations of the North and South sites are primed to follow-up a putative GW.

Results

We consider several situations as a test.

We shall consider that independent subarrays are optimized individually so that the aims are to:

- Minimize slew time
- Maximize the observation time

Within the functions of leader and follower (or master and slave) regarding scheduling, we shall consider two strategies:

Strategy 1

As explained above, in the Strategy 1 the leader and follower subarrays are optimized simultaneously so that the aims are:

- Minimize slew time
- Maximize the observation time
- Maximize the simultaneity of the observations

Strategy 2

In the Strategy 2 the leader telescope is optimized individually, and the follower tries to adapt to it, so that the aims are:

- Minimize slew time
- Maximize the observation time
- Maximize the time when followers do follow-up

Within these general strategies, we consider several scenarios.

Scenario 1

First, in what we call our Scenario 1 (which will act as a control case) we shall consider two telescopes, with defined roles of Master and Slave, in regards to scheduling.

The control case is defined by assuming that the Master & Slave are the same telescope: CTA North, which is in turn doing a North survey example. We considered that the maximum Zenith Angle of the observations is 55º.

The table below shows our results.

	MF Strategy 1		MF Strategy 2 (follow-up)	
	CTA North	CTA North	CTA North	CTA North
Required Time (h)	2861.30	2861.30	2861.30	2861.30
Targets in the survey	389	389	389	389
Available Time (h)	1455.30	1455.30	1373.84	1373.84
Working Time (h)	1261	1209.33	1225.67	1223.33
Slew (% of WT)	81.17	79.66	32.34	32.21
#Observations	3783	3628	3677	3670
Targets observed (#Planned (#Completed))	372 (41)	370 (29)	364 (229)	362 (224)
Survey completion (%)	44.07	42.27	42.84	42.75
Coinciding targets observation (h)	-	1179.53 (41.22% of RT)	-	1220.52 (42.66% of RT)
Coinciding time from coinciding targets (%)	-	97.54	-	99.77

Some clarifications are given hereafter:

- In this table, the available time is different because the weather is stochastically assumed.
- Coinciding targets are targets from the slave that should be observed at the same time in the master
- Coinciding targets observation is the time observed from the targets that should be observed at the same time.
- Thus, it could include observations of these targets that are no coinciding with the master.
- The 'Coinciding time from Coinciding targets (%)' indicates the real coincidence of the observed time of the coinciding targets

The fact that this exercise provides a very high (almost perfect) 'Coinciding time from Coinciding targets' proves that at least the algorithm is not fooled at a basic level.

Scenario 2

With this reassurance, we consider the Scenario 2 in which CTA and an optical facility intervene. For instance, we considered that the Master is CTA North, doing a North survey example, with a FOV having a diameter of 2 degrees, and that the Slave is the optical telescope

WHT, doing the real observations done in 2014 (translated in time for the sake of exercise). WHT has a FOV having an effective diameter of essentially 0 degrees (only exact pointing), a crude but quite good approximation in comparison with the FOV of CTA.

The results can be seen in the following table:

	MF Strategy 1		MF Strategy 2 (follow-up)	
	CTA North	WHT	CTA North	WHT
Required Time (h)	2861.30	191.77	2861.30	191.77
Targets in the survey	1840	462	1840	462
Available Time (h)	1558.33	1558.33	1564.97	1564.97
Working Time (h)	1459.33	1287.33	1457.67	1283.67
Slew (% of WT)	34.83	81.93	37.70	76.06
#Observations	4378	3862	4373	3851
Targets observed (#Planned (#Completed))	227 (161)	1949 (1906)	179 (139)	1927 (1907)
Survey completion (%)	51	62.12	51	58.74
Coinciding targets observation (h)	-	112.38 (58.6% of RT)	-	102.59 (53.5% of RT)
Coinciding time from coinciding targets (%)	-	92.62	-	99.28

Here, differences between the two approaches start to be obvious, with the strategy in which the leader and follower subarrays are optimized simultaneously is slightly preferred.

Scenario 3

Finally, we consider the case so-called, Scenario 3, in which we make correlations of possible schedules between CTA and SKA. In this scenario, we consider that the master telescope is the Australian-SKA, while it is doing the GASKAP survey (covering a Low/Intermediate-Latitude disk) with a FOV having a diameter of 5 degrees. The slave in this case is considered to be CTA South, doing a CTA, south survey example, with a FOV having a diameter of 8 degrees.

We note in this case that there are no targets defined that can be observed simultaneously in CTA South and SKA because of the maximum ZA (55º) constraint; thus, the optimization reduces the time distance between observations. The following plot (Figure 3) is useful to explain better the aim of this optimization: we require to do the CTA observations as soon as possible after (or before) the SKA coverage of the same field. Figure 4 illustrates also the coordinated planned observations and the FOV for the CTA South and the SKA observatories.

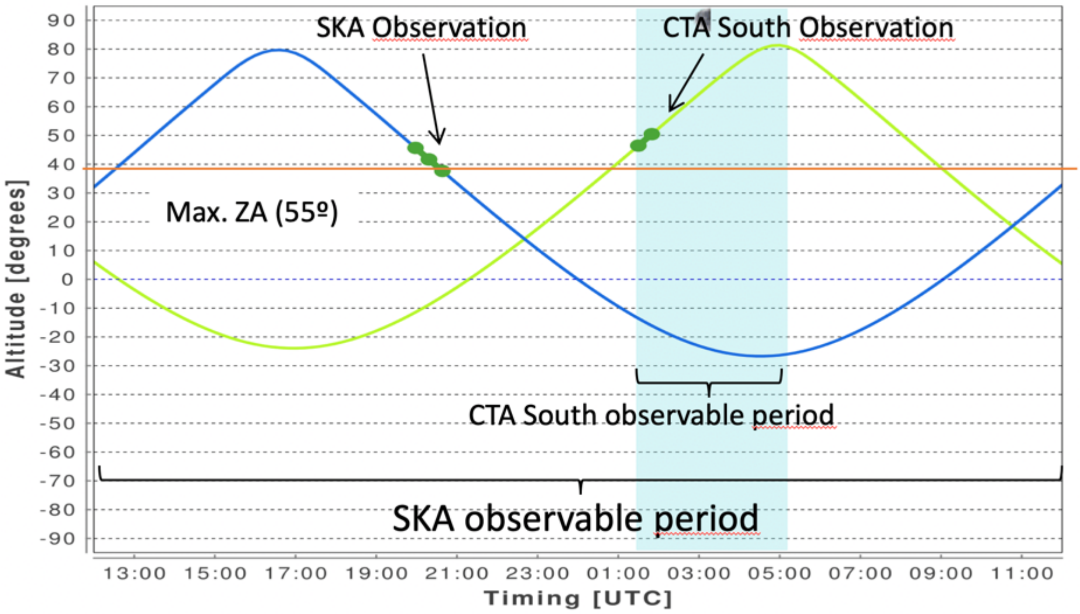

Figure 3: Target coordinated observations for SKA and CTA South

The results are included in the following table.

	MF Strategy 1		Individually	
	SKA	CTA South	SKA	CTA South
Required Time (h)	13300	2062.25	13300	2062.25
Targets in the survey	275	1356	275	1356
Available Time (h)	6132	1149.78	6359.34	1193.52
Observing Time (h)	3968.67	713.33	3984.67	720.67
Slew Time (h)	255.64	72.02	88.75	27.3
#Observations	11906	2140	11954	2162
Targets observed (#Planned (#Completed))	235 (19)	652 (212)	236 (43)	483 (373)
Survey completion (%)	29.84	34.59	29.96	34.95

The exercise shows in this case that the individual optimization with the requirement of reducing as much as possible to time separation of the observations provides a better solution.

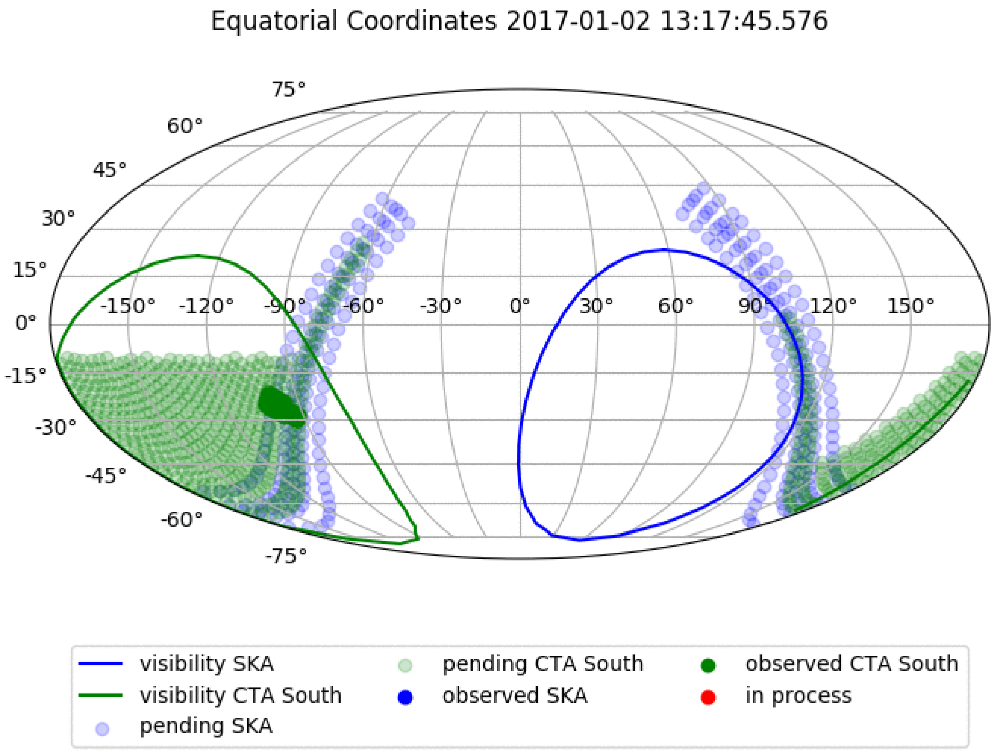

Figure 4: Snapshot of planned observations where both CTAS and SKA sites pointed coordinately. The FoV of each one is marked in green and blue. The observation planned pending and observed are marked in light green and blue bullets respectively.

Multi-Messenger approach

We simulate one year of CTA observations, following the observation program described in the CTA Key Project document. We defined a randomly-generated number of events, simulating transients to be followed by the two observatories simultaneously, as the real case of a GW alert. Those 'transient events' are defined by their RA and DEC position, and are included in the general planning of the CTA proposed KSP discussed in Archaya et al 2017. We simulate two sites, one located in the North hemisphere (La Palma, Spain) and one in the South (Paranal, Chile) (see Figure 5).

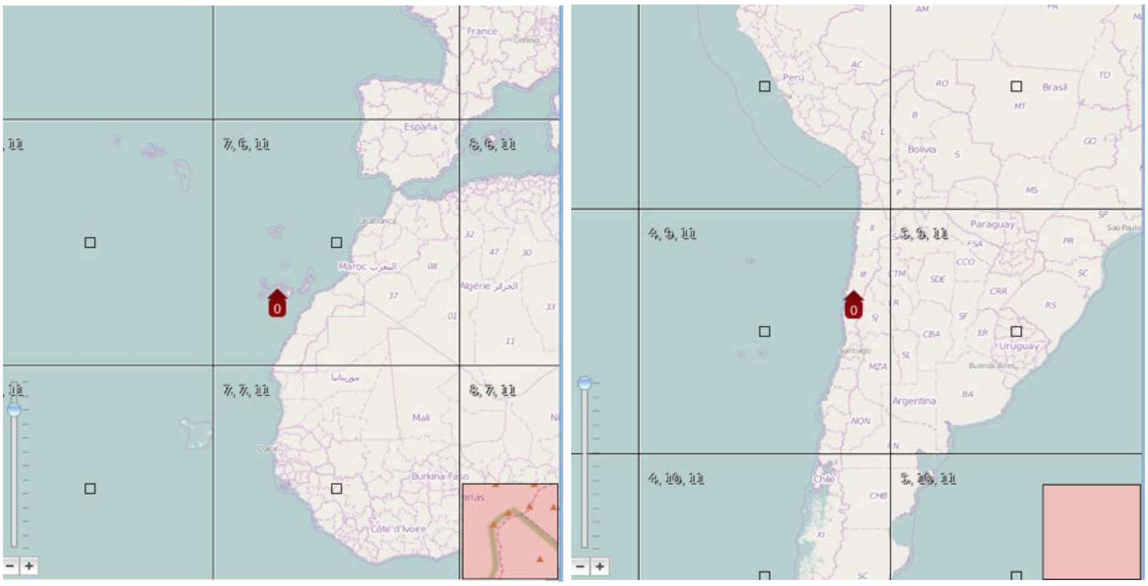

Figure 5: Simulated sites for simultaneous observations of GW transients

The scheduler was run by defining the following *soft* criterium:

- Minimize the slew time
- Maximize the simultaneous observation between the North and the South observatory.

The initial plan to schedule consists of 854 targets with a total required time of 7200 hours, from which 2000 hours corresponds to Transient events. The available time in one year is 2536.25 hours after considering realistic weather conditions (obtained from real weather conditions based on archival data using 2 years observations of CHILE_ATMOSCOPE database and Spain Weather historical database. The conditions to allow observations are the following:

- wind speed < 36 km/h
- humidity between 4% and 95%
- cloudless
- temperature between -10 and 25 C

Periods with no Moon are only allowed and dark nights when the sun is -18 degree below the horizon are considered.

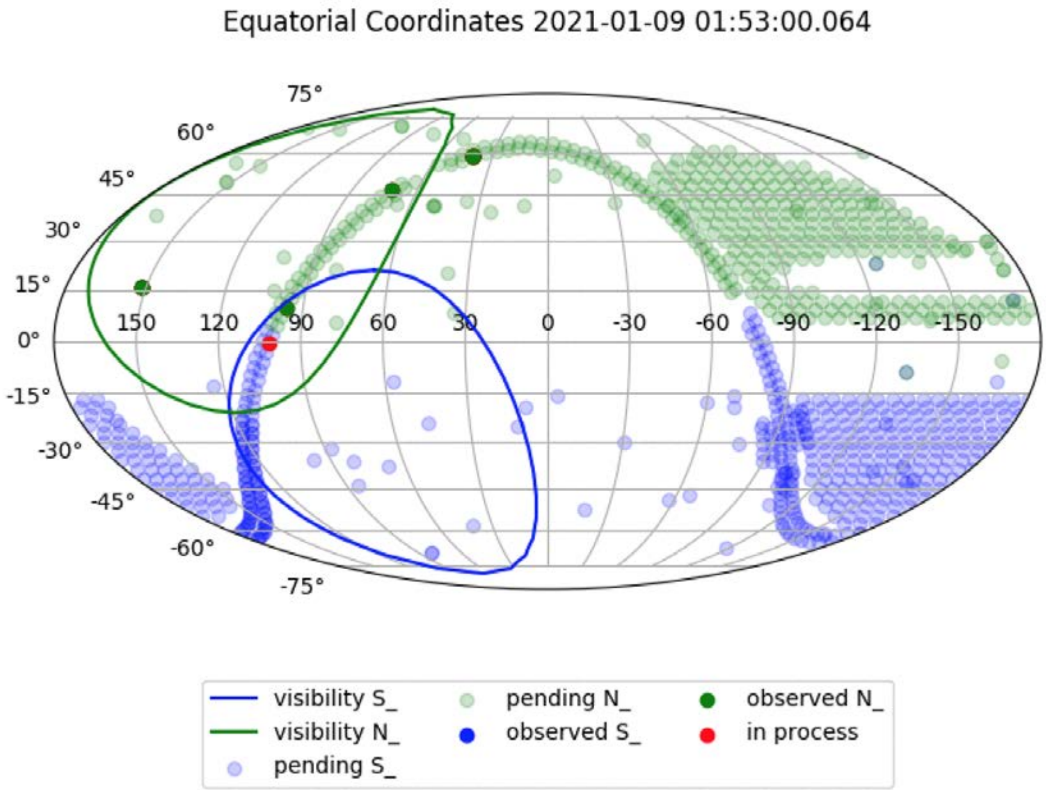

Figure 6: Snapshot of a planned observation (in red) where both CTA sites pointed simultaneously. The FoV of each one is marked in green and blue. The observation planned pending and observed are marked in light green and blue bullets respectively.

The software was modified to derive statistical results referring to the Multi-site observations. A similar simulation was done without prioritizing the simultaneous North-South observations. Figure 6 illustrates a planned observation, where both CTA sites point simultaneously to the same position to observe a transient GW event.

The first result to notice is a similar efficiency in the available time planning: the working time on the North site reaches 79% of the available observation time whereas the South site reaches 95% of the available time, similar to the time when no constraints on the simultaneity are present. The time devoted to observe transients which are observable from the two sites is 28.62 hours, which represent 12% of the required time. Even if this number does not seem to be too large, it should be considered that the scheduler is designed, in this first attempt to optimize GW follow-ups, to also optimize the scheduler of the two sites, without causing major disruption in the main observation plan. The observation completeness according to the general plan reaches 86.25%. Given the large time assigned to Transients follow-up (for ten years) and the available time in 1 year, 12% seems a fair number to complete the program in 10 years. Figure 7 shows the target completeness according to the multi-facility observations. The y-axis shows the transients names (defined as ExGPS_# and Gal#).

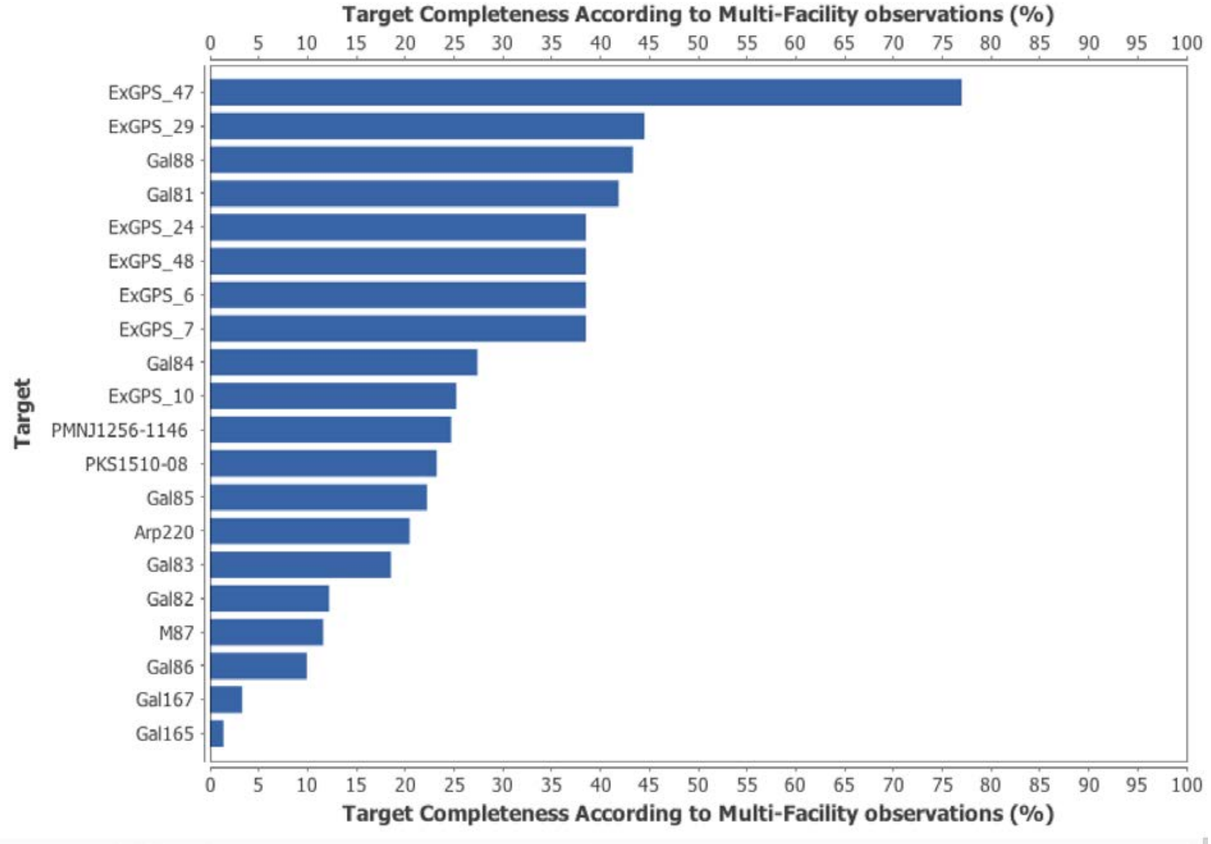

Figure 7: Completeness for sources for which North and South simultaneous observations are required.

Figure 8 shows the positions of the objects planned. The different color scheme marks the completed, uncompleted, unplanned and not visible targets.

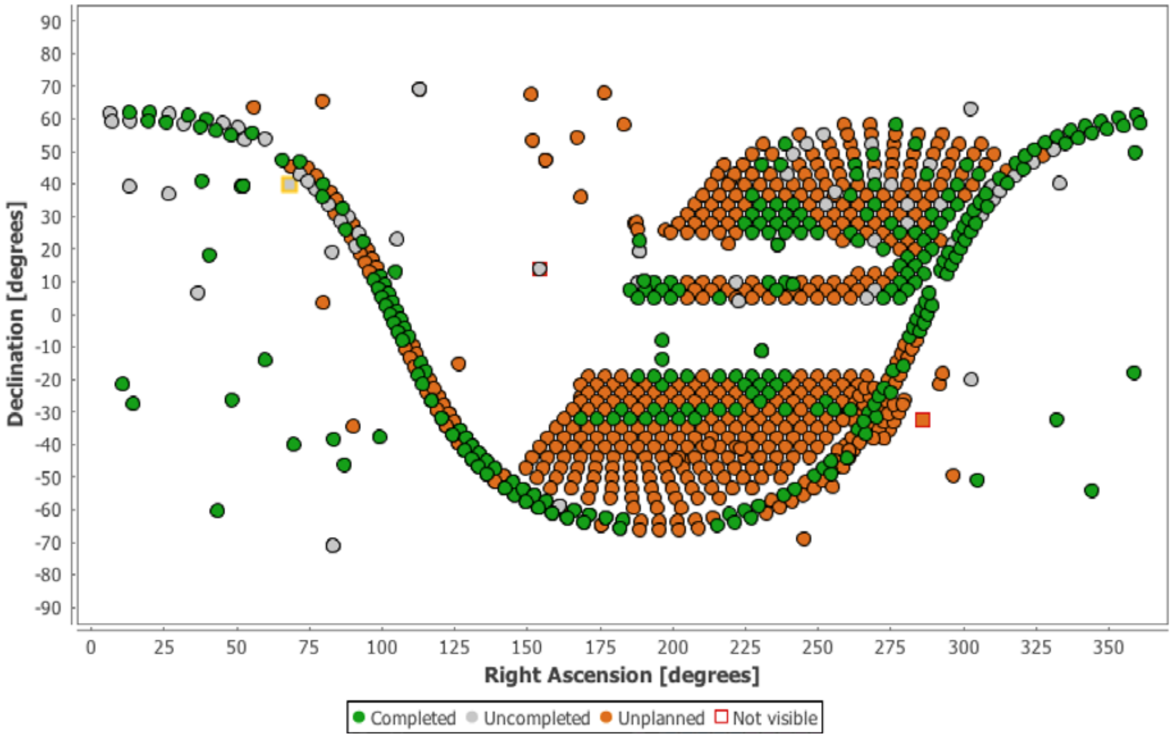

Figure 8: RA and DEC of the planned sources after 1 year of favouring simultaneous North and South observations to follow Gravitational Waves Transient Events.

We demonstrate the potential of scheduling automatically transient alerts to be followed by the North and South observatory. The scheduler also allows changing the prioritization of certain events, given the different alerts that one would expect to arrive at the observatory.

As next steps, we will include more realistic GW alerts with maximum priority and repointing as the precision of the position in the sky improves with information provided from better angular resolution instruments following-up the electromagnetic counterpart.

X. CONCLUSIONS

There is an inexpensive new approach for maximizing simultaneous observations before everything happen to obtain efficient MW/MM coverage. An approach that 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.

We propose a scheduling solution devoted to fulfil simultaneously the scientific aims of each participating facility, maximizing the time in which an MW/MM coverage of the source being observed is obtained, and using the given knowledge of the other telescopes' schedules.

The features of the STARS framework (see ASTERICS deliverable 5.9) for telescope time scheduling have been extended to cover the multi-observatory coordinated scheduling. The algorithms have been improved for this purpose and have proven good performance for the testing cases considered.

We have demonstrated the suitability of such an operational solution to promote MW and MM science programs by using different strategies, scenarios and observatory configurations. Special focus has been put on the CTA and GASKAP (SKA precursor) observatories and the key scientific survey programs, as they were published and are well known by the researchers at the IEEC. We have also checked the lack of any penalization to the programs that are not executed or do not require multi-observatory coordination.

A particular case on MM science has been evaluated for GW alert follow-up observations scheduled at the CTA North and South, which required some extension of the software framework features. Results also show good performance in this case, although further analysis is required to consolidate them by considering more realistic alerts with maximum priority and repointing as the precision of the position in the sky improves with information provided from better angular resolution instruments following-up the electromagnetic counterpart.

LESSONS LEARNED

Task 5.4 is led by J. Colome (IEEC) and involves teams at ATC/STFC, IEEC and GTD. The task's activities carried out for this particular deliverable were mainly done by the IEEC team that take advantage of the expertise on scheduling tools and the role in CTA and SKA played by some of the researchers involved in the ASTERICS project. Scheduling solutions were explored and applied to different test cases in order to extract conclusions that would help extend their applicability to other ground and space-based facilities for space science research (e.g. LIGO, E-ELT, ALMA, ESA missions) and, especially, for those that would be intended to run MM programs.

Several lessons have been learned so far and are listed hereafter:

- *Sharing plans and observation blocks*: The presented simulations were designed and carried out thanks to the available publications, where the planned surveys for different facilities were shared and, in particular, thanks to those publications describing the CTA and GASKAP key science projects. The role of IEEC researchers in these projects contributed also to a better understanding of the observational strategies to apply and their translation into a sample of observation blocks to schedule. The WHT case was approached differently and the public available schedule in the telescope web site was used as a reference input. We experienced the difficulties in accessing and interpreting the schedules and samples from the observatories, which is the necessary step for a suitable multi-observatory coordinated scheduling. This lack of openness from the observatories should be addressed to promote the benefits that such a coordinated scheduling would provide. The proposal to build a Multi-Messenger coordination Platform within the ASTERICS project (see ASTERICS deliverable 5.16) was partially focused on addressing this situation and should be promoted beyond the project if multi-observatory scheduling solutions are prioritized by the community.
- *Networking*: The results obtained with the simulations described in this document have been presented in different forums. In particular, they were presented in the SPIE meeting on Astronomical Telescopes and Instrumentation in Austin in July 2018

(García-Piquer et al. 2018), and in "The New Era of Multi-Messenger Astrophysics Conference" organized by the ASTERICS consortium in Groningen in March 2019. These two events represented a good opportunity to share the results obtained with the community of large facilities and a confirmation of the positive interest from them. Partnerships are mandatory for this solution to be extended and, therefore, we expect that the new contacts made will translate into future collaborations to make the multi-observatory coordination a reality for the benefit of the MM science.

- *Overlapping interests with task 5.2 and the VO community*: Multi-messenger science including transient alerts is a key topic for multi-observatory scheduling. The important synergies with task 5.2 have been confirmed again in the preparation of this deliverable, as we stated in the ASTERICS deliverable 5.9. A closer work with the participation of all actors should continue in the future to achieve the aforementioned benefits. This is also true for the VO community that has produced many tools for observatory data sharing, which could be a building block to make the multi-observatory scheduling a reality in the near future. The latter applies to VO Events for Transient Alert publication, but it also applies to new protocols that are being proposed to share the visibility of tasks from different observatories and space missions (see ASTERICS deliverable 5.16 for more references).

FUTURE WORK

Particular actions are proposed for the near future in order to promote the multi-observatory scheduling for the benefit of the MM science case. Some of them are aligned with the list of tasks mentioned in ASTERICS deliverable 5.9. In particular, we will work on:

- We need to know/let others know what we are observing for the achievement of a competitive solution for MM science based on coordinated scheduling. It is then mandatory to construct the necessary tools to share the existing programs and plans and promote the coordinated observations. In this sense, we will put special emphasis to work on the proposed MM Coordination Platform that was carried out in the last phase of the project ASTERICS (see deliverable 5.16). This should persist beyond the end of ASTERICS.
- Help collaborations plan efficient observation sequences by providing components for the construction of coordinating web apps.
- Gauge interest in holding meetings beyond the ASTERICS project to bring together people with experience, e.g. PESSTO, SMARTNet, AMON, to chart the way forward in developing useful tools for coordinated observing.
- Participate in the coming conferences like the SCIOPS workshop in 2019 that is devoted to "Cross facilities collaboration in the multi-messenger era". This kind of forum can be the right place to disseminate the results obtained and described in this report, in order to obtain the necessary support to engage research facilities and scientific teams in fostering the application of multi-observatory scheduling software.
- Continue developing the STARS scheduling framework and its library of algorithms so that they are useful in optimizing schedules across the complexity scales of ground and space-based observatories.
- Develop metrics to evaluate the optimal operation of cases, in particular for the coordination of multiple-observatories.
- Contribute to the creation of a protocol to share the schedules that are obtained to benefit the coordinated observation. This will require extending the existing solutions

given by the VO community and is being evaluated in the framework of the MM coordination platform (see ASTERICS deliverable 5.16).

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