OPTIMAL SCHEDULING SOLUTION FOR SAPIENZA OPTICAL NETWORK FOR SPACE DEBRIS MONITORING

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ABSTRACT

Sapienza S5Lab research group has developed a network of observatories completely dedicated to observations on space debris as part of the framework agreement between the Italian Space Agency (ASI) and the National Institute of Astrophysics (INAF) called "Support for IADC activities and pre-intervention validation for SST" (N.2015-028 -R.0). This network is composed by optical observatories. Moreover, S5Lab research team cooperate with Astronomy Department of University of Michigan and INAF (Italian National Institute of Astrophysics) and their observatories for monitoring space debris population.

The growing number of orbital debris to be observed caused the combinatorial explosion in the number of intervals to be scheduled. Therefore, a new planning approach to provide a solution to process the observing request has been developed. The presented scheduler is called NICO (Networked Instrument Coordinator for Observations on debris) and it has been developed specifically for the harmonization of individual user requests considering the meteorological and astronomical constraints. This paper outlines the benefits of the presented solution based on a modular architecture and microservices. The scheduler is composed by two main layers: he front-end is designed to allow external registered users to specify their observation requests and assign a specific scientific priority; the back-end is the change for the business logic determining the windows of visibility for each request and to resolve the conflict by using genetic algorithm approach. This document outlines the results of the application of the NICO scheduler to the recent IADC optical observation campaigns (Inter-Agency Space Debris Coordination Committee)..

1 INTRODUCTION

It is estimated that more than 700,000 dangerous debris objects are in Earth orbit and they all travel at speeds up to 7.9 km/s, fast enough for a relatively small piece of orbital debris to have the potential to damage or destroy operational satellites. This rising population increases the potential danger to all space vehicles [1]. Therefore, it is very important to improve the capabilities in terms of space surveillance of space debris [2]-[10].

Some recent event has proved the importance of an improvement of the space surveillance capability in terms of sensors involved and data analysis. Therefore, the European Parliament has started the Space Surveillance and Tracking (SST) program [11], aimed to develop a European surveillance network. The long-term objective is to support the development of space surveillance infrastructures to: i) prevent collisions between orbiting objects [11]; ii) limit the risks associated with the launch of new satellites; iii) reduce the proliferation of debris, iv) provide information to government services and civil protection in the event of uncontrolled return of objects in the Earth's atmosphere. The main idea of the SST program is to provide a reliable and timely response in case of contingencies.

The combinatorial explosion of more observatories in the number of intervals to be scheduled has been caused by the increasing number of space debris to be observed with optical ground station. Therefore, new scheduling approach are needed to provide a solution to the new requests.

Scheduling can be considered as the allocation of resources over time to perform collection of tasks. The scheduling model of orbital debris is composed by a set of optical ground station which move with the surface of the Earth, a set of space situation awareness centre which can be assumed connected to ground station, and orbital debris travelling through different kind of orbit generating visibility windows when the line of sight (LOS) to ground station exist.

The objective of the scheduler is to generate, from a set of requests, a schedule which is a subset of these requests selected for execution (Figure 1).

The length of the visibility windows strongly depends on the geometry of the problem. For GEO orbits, only a

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small section of the visibility windows might be needed depending on several observability constraints. Therefore, release time and due time should be detected to extract a section of the visibility windows in which the scheduler must operate to identify the task.

The finite time duration of the scheduler is normally defined as scheduling horizon in which all collected requests must be processed to obtain the schedule.

If time-overlaying requests associated either to the same satellite or ground station occurs, these are considered a conflict. For this case, a conflict solution approach must be applied. In fact, the scheduling problem requires finding a feasible schedule that maximize the sum of the priorities of the request included in the schedule, given the requests and the associated constraints ([12]-[17]). The problem can be complicated even more by considering more debris to be observed by a network of optical observatories.

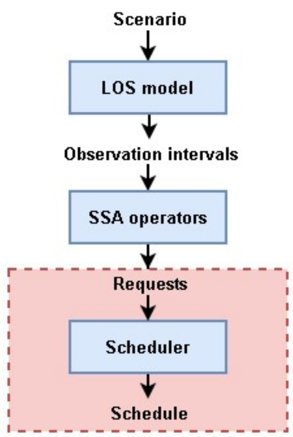

Figure 1. Request creation process

A set of requests can be represented as in Figure 2 where the start and end times of the visibility windows are indicated along with their associated priorities based on user preferences. A feasible schedule is then shown where all conflicts have been solved.

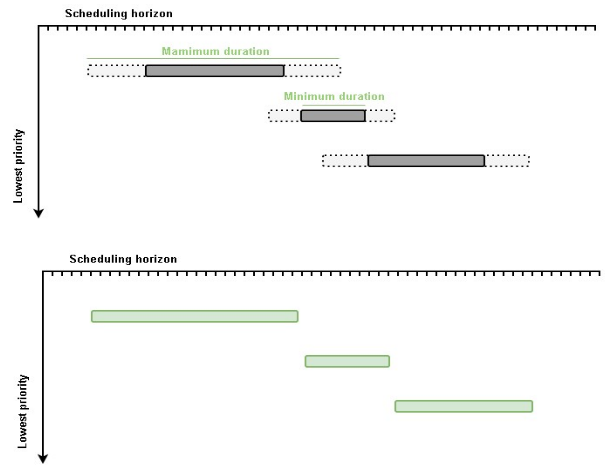

Figure 2. Visibility windows associated to the requests.

2 S5LAB NETWORK OF OBSERVATORIES

In the presented context, Sapienza Space System and Space Surveillance Laboratory (S5Lab) research group of Sapienza University of Rome, in 2015 started the refurbishing of their mid latitude observatory fully dedicated to space surveillance located in Rome to improve the Italian capabilities to monitoring the near-earth orbital environment. The observatory is called MITO (Mid-latitude ITalian Observatory) and the telescope has been in operative phase since early 2016. The total field of view is about 3.5 x 2.5 degrees. The huge FOV is particularly indicated to statistically survey the GEO region and to perform light-curve measurements of bright LEO object.

The project EQUO (EQUatorial Italian Observatory) [18]-[20] started in 2015 in the framework of the ASI-Sapienza Agreement (n. 2013-078-C.O). The goal is to develop and operate an observatory composed by two telescopes installed at Broglio Space Center in Malindi. The observatory consists of two telescopes located one at the base camp of BSC named EQUO-OG (EQUO-On Ground) while the other on the Santa Rita 2 off-shore platform 6 km from the coast in the Indian Ocean (EQUO-OS: EQUO-Off Shore) (Figure 3 and Figure 4).

Figure 3. S5Lab Network.

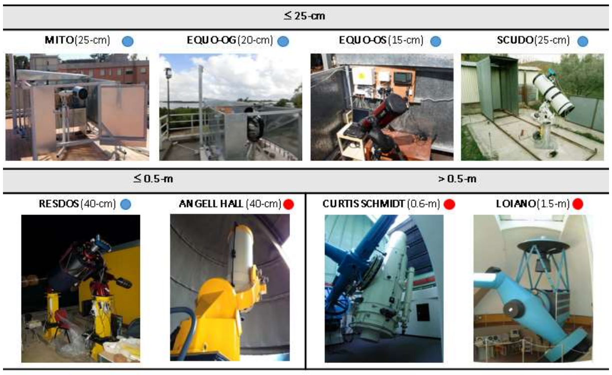

Figure 4. S5Lab optical network. Telescopes are divided into classes depending on the mirror size.

3 S5LAB SCHEDULER NICO

The increasing number of space debris has caused the combinatorial explosion in the number of intervals to be scheduled. Therefore, new scheduling approach are needed. In the framework of ASI/INAF Agreement (N.2015-028-R.0), NICO (Networked Instrument Coordinator for space debris Observations) scheduler has been developed to coordinate the whole network for optical observations of space debris. The main goal is the harmonization of the requests for optical observation by considering astronomical and weather conditions constraints and maximizing the operative time of the network by solving the conflicts (Figure 5).

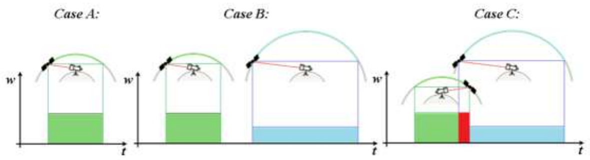

Figure 5. Three main chases that can occur: case A, a single task has been scheduled, case B two consecutive tasks have been scheduled and no conflict occurs; case C two consecutive tasks are requested but conflict occurs. Red outlines the conflict.

NICO ARCHITECTURE OVERVIEW

NICO is composed by two main layers:

Front-End Layer.

Only registered users can log in via WAN through their computers and enter requests into the request database. The Front-End (FE) layer is designed to allow external registered users such as SSA entities to specify their observing requests according to their needs and populate an external database (Figure 6).

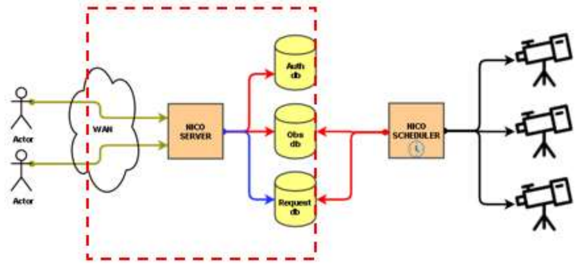

Figure 6. NICO Front-End layer flowchart.

Request database management is multi-transaction and hashing password algorithms (SHA256/HMAC) are implemented. The users can select different type of requests:

1. Survey in Medium Earth Orbit (MEO), in GEO or in Molniya orbit. The scheduler will identify the most convenient celestial coordinates region in terms of statistical analysis of the population of the specified orbit to perform acquisitions [21][22];

2. Light-curve by indicating the NORAD (North American Aerospace Defense Command) catalogue identification code of the target [23];

3. Follow-up analogous of the tracking mode, nevertheless once the target is scheduled it will be automatically scheduled for the next day too with the highest scientific priority to improve the orbit [6].

4. Specific celestial coordinates by indicating the right ascension (RA) and declination (DEC).

The users can select a specific priority for each of their request. Moreover, the user can set a preference for the observatory to be used for the specific request or let the system evaluate the one to schedule with.

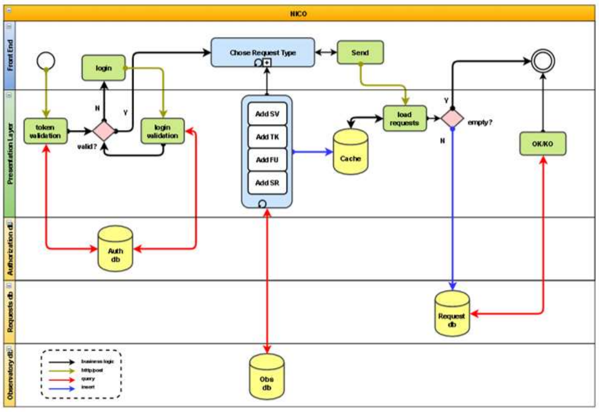

Figure 7. FE layer logical scheme.

Example of the layers are reported in Figure 8 to Figure 12.

Figure 8. NICO FE login.

Figure 9. NICO FE task selection.

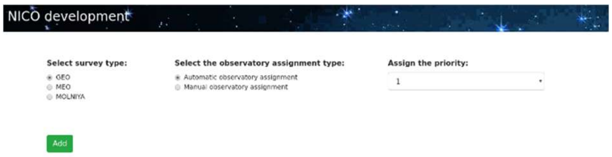

Figure 10. NICO FE survey.

Figure 11. NICO FE tracking.

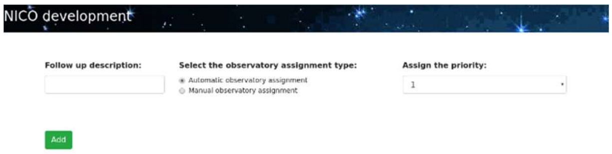

Figure 12. NICO FE follow-up.

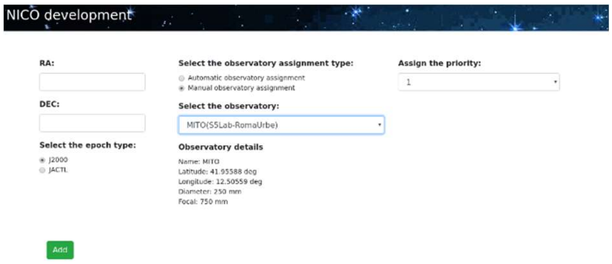

Figure 13. NICO FE sky region.

Back-End Layer.

The ack-End (BE) layer is the core of the presented NICO scheduling software (Figure 4). Cronetab is used to execute NICO scheduling process at specific time.

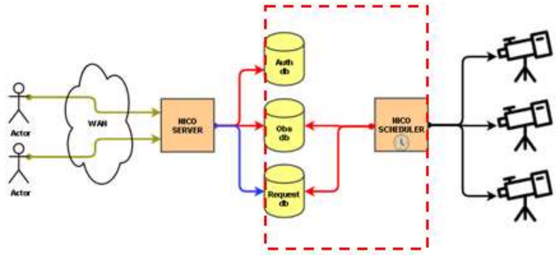

Figure 14. NICO Back-End layer flowchart.

Once all requested for the night have been collected into a database, the software automatically download and process them to obtain the schedules for each observatory of the network. Data are downloaded from the requests database and pre-processed. Alert for maintenance status and weather condition for the night are collected from each observatory of the network to exclude specific observatory from the scheduling process for specific hours or exclude them completely if not available for the whole night. The schedule is designed to resume observation from the previous day if it was not possible to include them in the final schedules due to conflict with another request or if are needed to be repeated.

One of the main task is the visibility window allocation process in which all requests are computed to allocate the time to be observed. Then, conflicts are solved using a developed implementation of genetic algorithms. During this phase, the duration of the requests is muted inside the parameters defined in the visibility windows and it is evolved to better solutions. The goal of the optimization process is to maximize the metric of the schedules of the whole network. Finally, once the new temporal slots are defined for each accepted request, a specific schedule generator process is applied. This module implements the observing strategies defined in IADC meetings especially for survey [22]. Moreover, the implemented strategies are compliant to IADC-WG1 standard observing strategies. The implemented strategies consider the different characteristics of the sensors and mount. The outputs are the schedule in a standard format to be transmitted to the observatories of the network. The whole process is monitored with a log to evaluate the performance of the software during the execution. Moreover, general and specific report for each observatory are generated and stored.

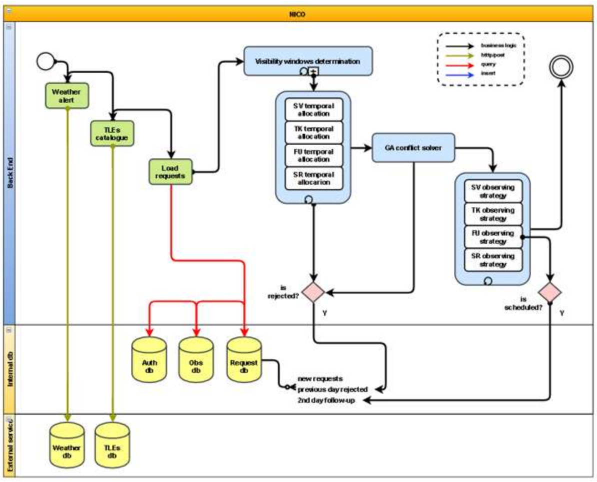

Figure 15. NICO BE architecture.

4 NICO BACK END LAYER

As presented in Figure 4, the internal architecture of the scheduler is designed to search at the beginning over the set of internal use database in which operative information are stored. In details, the main information needed from the scheduler to evaluate the operability of an observatory of the network are data contained in the maintenance alert log and the weather alert log. If ordinary or extra-ordinary maintenance procedures are scheduled at a specific observatory, it can be flagged as non-operative for the whole night or out of service only for specific hours of the night. If the sky is forecasted to be fully cloudy or if the seeing will be over a certain value NICO is designed to not schedule observations at all at for the specific observatory and all the observations will be scheduled on the other observatories of the network.

The output of the input phase is the population of database in which the request given by external users are stored. At defined UTC time, the scheduler is designed to automatic download the new request from the database. Once the new requests are loaded, the system is designed to look for the previous day requests that need to be rescheduled. In fact, if a user request is rejected, it is not discharged but it is stored into another databased ready to be rescheduled the next day with the highest user priority. Moreover, as previously mention, follow-up observations need to be observed for at least two consecutive nights to improve the orbit. Therefore, also these requests are loaded and appended to the NICO request dataset.

For data processing, the TLE are used to propagate the current population of orbital objects. Therefore, a API REST is used to connect to external database and automatically download the current TLE population available in the public catalogue. Starting from this database, three subsets are generated for the specific survey population (GEO, MEO, Molniya) basing on the mean motion, inclination and eccentricity values.

The main advantage of the presented NICO scheduler is the modular architecture and its adaptability to a possible evolution of the network which must manage and coordinate.

Each one of the described phases is surrounded by a logging phase that is crucial to evaluate not only the statistics of the NICO in terms of metrics of the scheduler, but mostly the correct behaviour of the code and allows the operators to estimate an optimization level for the different task.

As mentioned in Section 3.1, users can set a specific priority value. This is only one of the factor that compose the global priority weight. Depending on the contingency of the request users can perform, different weight can be associated. Furthermore, each kind of request have different priority cost. Metrics of the schedule is evaluated by multiplying the allocated time for the global priority value. The conflict solver loop is designed to accept the request with the higher value of metrics and rejects the one with the lower. Consequently, it is important to compensate the difference that non-homogeneous request might have in terms of temporal allocation.

The visibility windows definition process is one of the main module of NICO. Its function is to evaluate each request and allocate the optimal visibility windows to execute the requests. Each request is evaluated individually and different requirements are applied depending of the kind of the request. It is possible to classify them into shared constraints and custom constraints.

General constraints

- Minimum elevation of the target: for each observatory of the network it has been estimated performing an analysis on the full 360-degree azimuth range. The result is a median value of 20 degrees. This is needed to avoid any ground based obstacles that can disturb the observations and to avoid any possible light pollution.
- Maximum elevation of the sun: for astronomical purpose, the maximum elevation angle of the sun to be considered is -18 degrees (limit of the astronomical twilight).

Custom constrains

- Maximum phase angle: phase angle is the angle between the direction to the Sun and the direction to the observer, as seen at the object being observed. Phase angle disregards important illumination geometry, which has a dramatic effect on the irradiance measurements. By considering a body reference coordinate system centred in the orbiting object (Figure 5) it is possible to define the two angles needed to describe the position of the sun and the two angles for the position of the observer.

Therefore:

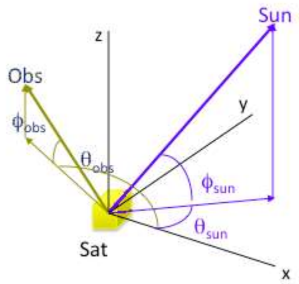

Figure 16. Solar phase angle.

$$\widehat{n_{\mathrm{Sun}}} = [\cos\theta_{\mathrm{Sun}}(\mathrm{t})\cos\phi_{\mathrm{Sun}}(\mathrm{t})]\hat{x} + [\sin\theta_{Sun}(t)\cos\phi_{Sun}(t)]\hat{y} + [\sin\phi_{Sun}(t)]\hat{z}$$

$$\widehat{n_{\mathrm{Obs}}} = [\cos\theta_{\mathrm{Obs}}(\mathrm{t})\cos\phi_{\mathrm{Obs}}(\mathrm{t})]\hat{x} + [\sin\theta_{Obs}(t)\cos\phi_{Obs}(t)]\hat{y} + [\sin\phi_{Obs}(t)]\hat{z}$$

$$SPA(t) = arccos[\widehat{n_{Sun}}(t) \cdot \widehat{n_{Obs}}(t)]$$

The imposed limit is equals to 80 degrees.

- Minimum distance to the moon: during night time, moon is the greatest source of non-artificial light pollution. The main effect on image quality consists into a sensible reduction of the signal to noise ratio (SNR) of the observed target on the sensor caused by a higher median value of the background sky.
- Minimum distance to Milky-Way: for light-curves analysis star contamination represents a huge source of noise for data measurements.

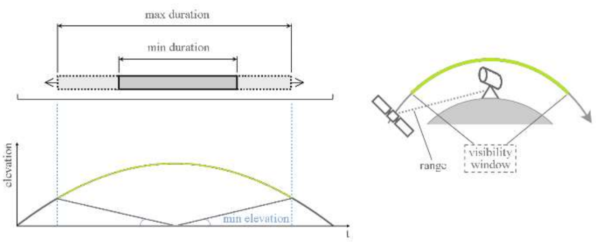

Figure 17. Visibility windows and minimum elevation.

Space debris scheduling problem means to schedule a multitude of request per day between a network of telescopes and the number of possible targets is increasing. The scheduling of the observations must take place in a time windows because the target is visible from the observatory only for limited time. The longer time window of the higher-altitude satellites makes scheduling them less difficult than scheduling the low-altitude satellites. As shown in Figure 6, the minimum duration required for LEO object to collected valuable data is defined as half the maximum visibility windows.

The scheduler is intended to define length and the required time windows for each observation relies on the goal of the observations itself, as well as which observatory can serve the requests if the user does not specify which observatory prefers to take observations [25]. Due to the need to maximize the metric of the schedule, the time windows may need to be restricted than the physical visibility limit. In this way two request that presents an overlapping in the allocation of a specific observatory may be scheduled consequently by reducing the observing intervals inside their visibility windows. The schedulers must also allow for a required turn-around time between observations to allow the mount to be reoriented (Figure 7). These constraints are solved implementing genetic algorithms [24]. Therefore, the result is the night-schedule.

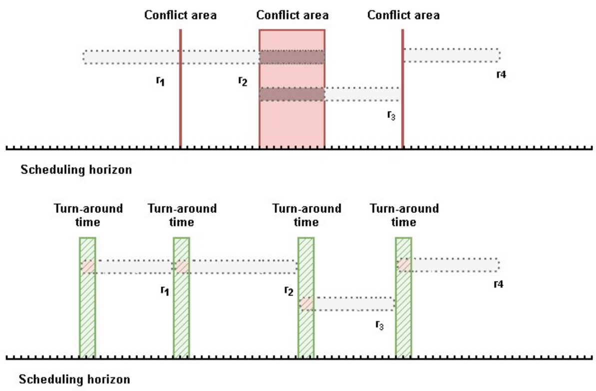

Figure 18. Conflict.

The conflict solver routine has been implemented with Genetic algorithms to maximize the metric of the schedule [25]. The main advantage is that the genetic algorithm can search the entire solution space, not just ordering the request. Therefore, no decoding procedure is necessary. It requires the construction of domain-specific recombination operators and it is problem-specific.

Managing a single observatory means to create a schedule with the objective to maximize the metric of the received requests. GA approach can be used to solve the problems and solve the conflict. When the observatory is part of a network, each schedule to be created has an individual objective to be satisfied. Moreover, these objectives under consideration can conflict with each

other, and optimizing a solution for an observatory with respect to a single objective can result in unacceptable results with respect to the other objectives. The pre-processed requests for each observatory are evaluated. The main information for each request are the starting time of the request, indicated with X, the total duration of the visibility windows, indicated with L and the weight associated W. These data are used to generate the first population of the chromosomes [24].
Several constrains are applied to chromosome population. The starting time X can mutate from the beginning of the temporal windows to the half of the temporal windows. min(X) = t0; max(X) = Δt/2 = (t1-t0)/2.
Consequently, the total duration L is limited from Δt/2 to Δt to never exceed the visibility windows. Figure 8 represents an example of the generation of a dataset.

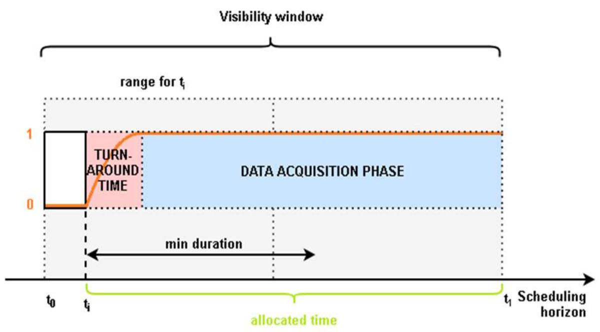

Figure 19. Dataset definition.

The start time for the allocation is inside the first half of the visibility window. A turn around phase is considered, then data can be taken for the whole duration of the slot. The orange line represents the readiness for operativity service of the single telescope over the single request. It goes from zero to one, with a transactional phased during the turn-around time. This can go to one minute to several minutes depending on the observatories.
Consequently, a fitness-function is implemented to calculate the metric of the schedule. The fitness is the metric of the schedule. The goal of the GA is to generate a population that maximize the metric within a certain amount of generations.
The fitness function is defined to work on each observatory of the network simultaneously as the core of the multi-objective approach of the scheduling problem [24]- [25]. Conflicts are solved as follows:

- If two consecutive request R1 and R2 are not in conflict (X2 · [X1; X1 + L1], (X2 + L2) · [X1; X1 + L1] and vice versa), the W1 and W2 are evaluated to calculate the metric Y = L1 * W1 + L2 * W2 = Y1 + Y2.
- On the contrary, if two requests are in conflict, a preliminary individual metric figure Y1 and Y2 are computed as previous described. If Y1 > Y2, then W2 is set to zero (request is rejected). Therefore, the total metric is evaluated as Y = Y1 + 0.

The GA set options are:

- Population size: indicating the number of individuals. As previously mentioned, with a large population size, the GA searches the solution space more thoroughly, thereby reducing the chance that the algorithm returns a local minimum that is not a global minimum [=200];
- Generations: indicating the maximum number of generations allowed [=200];
- Crossover fraction: indicating the fraction of genes swapped between individuals [=0.8];
- Migration direction: represent the direction that fittest individuals from the various sub-populations may migrate to other sub-populations [both directions. Therefore, the nth subpopulation migrates into both the $(n-1)_{th}$ and the $(n+1)_{th}$ subpopulation]
- Migration interval: specifies how many generation pass between migrations [=5];
- Migration fraction: specifies how many individuals move between subpopulations [=0.2];

After the run of NICO-GA implementation, the schedules are created. For each observatory, it is composed by a starting time, expressed in Julian Date rounded to closest starting minute, and duration time expressed in minute. Each observation is separated in time to allows the turn-around time for mount (and eventually dome) rotation for pointing. Then, a routine to implement the different observing strategy is needed according to the specific requirements of the requests.

5 NICO VALIDATION

To validate the code, several Monte Carlo (MC) simulation runs have been applied ([Buxey (1979)], [Spangelo (2013)]). MC simulation is a technique used to study how a model responds to randomly generated inputs. It typically involves a three-step process:

1. Randomly generate N inputs called scenarios.
2. Run a simulation for each of the N scenarios. Simulations are run on a computerized model of the system being analyzed.
3. Aggregate and assess the outputs from the simulations.

NICO performance has been evaluated using MC prior than the operative phases to evaluate its performance in terms of merit, number of rejected request, computation time [Cardona et al. (2017b)].

Five-hundred Monte-Carlo simulations have been run referred to a specific date. Each scenario was composed by a set of thirty single requests for each one of the four-different observatory involved in the simulation (MITO, EQUO-OG, EQUO-OS, SPADE). The set of requests was initialized as follows:

- 15 Light-curves requests.
- 5 First night follow-up requests.
- 5 Second night follow-up requests.
- 2 Survey requests.
- 3 Celestial coordinates requests.

Each request has been generated randomly using random probability for the user assignment and priority value. The SSN number for the light-curve and follow-up request have been selected randomly from a list of two-hundred LEO and MEO object already observed in past S5Lab observing campaigns. The coordinates for celestial coordinates pointing have been selected using coordinates of standard field visible from the different observatory locations.

Measurements are generated in terms of

- Number of selected request to be processed
- .Number of requested scheduled using GA approach for conflict solving.
- Merit of global schedule.
- Maximum weight assigned to the single request.
- Computational time.

For the analysis an Intel i5-5200 2.20 GHz with 8GB of RAM has been used. The median computation time value is 270 s. For each scenario the value the ratio between the number of processed requests versus the scheduled one is obtained. Then the global network merit is divided for the maximum weight of the single request. Finally, it is normalized to the maximum merit from all scenarios. The mean value for the schedule percentage of request is 80% with a normalized merit above 70% (Figure 20).

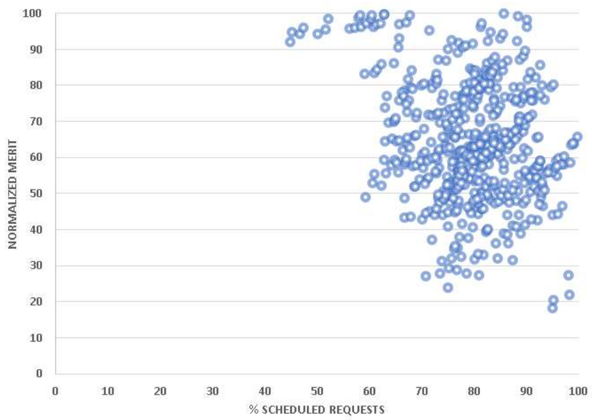

Figure 20. NICO Monte Carlo simulation results.

6 NICO APPLICATIONS

NICO has been successfully applied for the following observing campaigns

- IADC-WG1 – IT34.1 "Feasible options to study Molniya population of space debris"
- IADC-WG1 – AI32.1 "Reflected Signal Variations Measurements of Massive LEO Objects"
- Support to ILRS campaign for close encounters between Topex/Poseidon and the Jason satellites
- Tiangong-1 re-entry

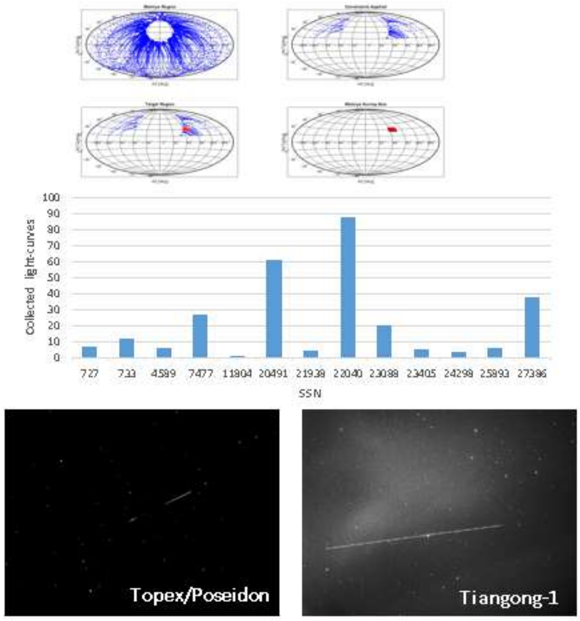

Figure 21. NICO applications.

7 CONCLUSIONS

The presented paper has described the scheduler called NICO developed by S5Lab (Sapienza Space Systems and Space Surveillance Laboratory) research group for the Italian network of optical telescopes fully dedicated to space debris monitoring. It has been developed in the framework of the agreement between ASI (Italian Space Agency) and INAF (Italian National Institute for Astrophysics) in support to IADC (Inter-Agency Space Debris Coordination Committee) activities. The input phase and main phase of NICO has been presented with special focus on the implemented observing strategies (i.e. tracking, beam-park and follow-up) and the genetic algorithms implemented for the harmonization of the different requests by taking care also of external limitations such as astronomical constraints and weather conditions.

8 ACKNOWLEDGEMENTS

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