CARMENES Instrument Control System and Operational Scheduler

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ABSTRACT

The main goal of the CARMENES instrument is to perform high-accuracy measurements of stellar radial velocities (1 m/s) with long-term stability. CARMENES will be installed in 2015 at the 3.5 m telescope in the Calar Alto Observatory (Spain) and it will be equipped with two spectrographs covering from the visible to the near-infrared. It will make use of its near-IR capabilities to observe late-type stars, whose peak of the spectral energy distribution falls in the relevant wavelength interval. The technology needed to develop this instrument represents a challenge at all levels. We present two software packages that play a key role in the control layer for an efficient operation of the instrument: the Instrument Control System (ICS) and the Operational Scheduler. The coordination and management of CARMENES is handled by the ICS, which is responsible for carrying out the operations of the different subsystems providing a tool to operate the instrument in an integrated manner from low to high user interaction level. The ICS interacts with the following subsystems: the near-IR and visible channels, composed by the detectors and exposure meters; the calibration units; the environment sensors; the front-end electronics; the acquisition and guiding module; the interfaces with telescope and dome; and, finally, the software subsystems for operational scheduling of tasks, data processing, and data archiving. We describe the ICS software design, which implements the CARMENES operational design and is planned to be integrated in the instrument by the end of 2014. The CARMENES operational scheduler is the second key element in the control layer described in this contribution. It is the main actor in the translation of the survey strategy into a detailed schedule for the achievement of the optimization goals. The scheduler is based on Artificial Intelligence techniques and computes the survey planning by combining the static constraints that are known a priori (i.e., target visibility, sky background, required time sampling coverage) and the dynamic change of the system conditions (i.e., weather, system conditions). Off-line and on-line strategies are integrated into a single tool for a suitable transfer of the target prioritization made by the science team to the real-time schedule that will be used by the instrument operators. A suitable solution will be expected to increase the efficiency of telescope operations, which will represent an important benefit in terms of scientific return and operational costs. We present the operational scheduling tool designed for CARMENES, which is based on two algorithms combining a global and a local search: Genetic Algorithms and Hill Climbing astronomy-based heuristics, respectively. The algorithm explores a large amount of potential solutions from the vast search space and is able to identify the most efficient ones. A planning solution is considered efficient when it optimizes the objectives defined, which, in our case, are related to the reduction of the time that the telescope is not in use and the maximization of the scientific return, measured in terms of the time coverage of each target in the survey. We present the results obtained using different test cases.

Keywords: Instrument Operation, Control System, Constraint-Based Reasoning, Scheduling, Artificial Intelligence, Genetic Algorithms, Spectrograph, CARMENES.

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1. INTRODUCTION

CARMENES (Calar Alto high-Resolution search for M dwarfs with Exo-earths with Near-infrared and optical Échelle Spectrographs) will perform high-precision measurements of stellar radial velocities with long-term stability.[1,2] To carry out its purpose, CARMENES is based on two spectroscopic channels, optimized in the near-infrared (NIR) and visible (VIS) windows, and multiple subsystems that have to work in a coordinated manner: the front-end, calibration units and exposure meters of each spectroscopic channel, acquisition and guiding module, interfaces with the telescope and the dome, and, finally, the software subsystems for task scheduling, data processing and data archiving. The two key software components related to the management of CARMENES are the CArmenes Scheduling Tool (CAST) and the Instrument Control System (ICS).

The CAST is a standalone scheduler focused on translating the survey strategy into a detailed schedule for the achievement of the optimization goals. Specifically, CAST has to schedule thousands of observations related to the targets according to several constraints. Some of these restrictions can be calculated in advance, but there are others that can only be computed in real-time. For this reason, CAST combines two scheduling strategies: off-line and on-line.[3] The off-line strategy provides a schedule of the observations without considering the constraints that cannot be predicted, and the on-line strategy repairs the off-line schedule in consonance with the constraints that must be calculated on the fly.[4] To fulfil this behaviour, scheduling based on Artificial Intelligence techniques[5] is used in CAST to increase the efficiency of telescope operations, which will represent an important benefit in terms of scientific return and operational costs.

On the other hand, the ICS is the main software component of the system in charge of coordinating and managing the subsystems, providing completely automatic control and high level of reliability and performance. Its primary purpose is to allow scientists to operate the instrument without having to interact directly with the low-level Application Programming Interfaces (APIs) that manage each subsystem and to provide an integrated control of the entire instrument. Scientists should only define astronomical observations and the ICS will setup and manage all subsystems to perform the observations. This approach is intended to maximize the system operation time and efficiency. These aspects and the instrument operational design compose the high level requirements that drive the design of the ICS.

In this contribution, we describe the CAST, we present the progress made in the ICS according to the system presented in Ref. 6, and we discuss the scheduling results obtained, which show that the proposed scheduler technology is robust and offers a competitive performance in the CARMENES survey.

The paper is organized as follows. Section 2 explains the operational design of CARMENES. Section 3 defines the CARMENES scheduling constraints and the details on CAST. Section 4 describes the ICS and defines how it is integrated with CAST. Section 5 presents the experimentation done and the discussion of the results. Finally, Section 6 ends with conclusions and further work.

2. CARMENES OPERATIONAL DESIGN

The strategy to complete the CARMENES survey can be described with a list of targets and their observation patterns aimed at carrying out intensive monitoring to achieve the envisioned scientific goals. The instrument will have to execute the tasks involved in the data acquisition process. Complementary tasks will also be necessary for the instrument commissioning, its routine calibration and maintenance. All these tasks are supported and managed by the ICS, which handles the operation of the CARMENES instrument by taking into account several control, operation and scheduling modes.

2.1 Operation Modes

The channels NIR and VIS can act as master or slave when they work together. When a channel acts as master, it decides when the operation ends and forces the slave to stop. Three different operation cases are considered in science to provide higher flexibility during the instrument commissioning and maximum efficiency during the nominal operation:

- Single channel: one channel (NIR or VIS) is used to perform any of the operational tasks under any of the ICS control modes (see Section 4.3).
- Multiple channels: both NIR and VIS channels are used, but none of them takes the role of master. The observation and data processing execution work flows run independently.

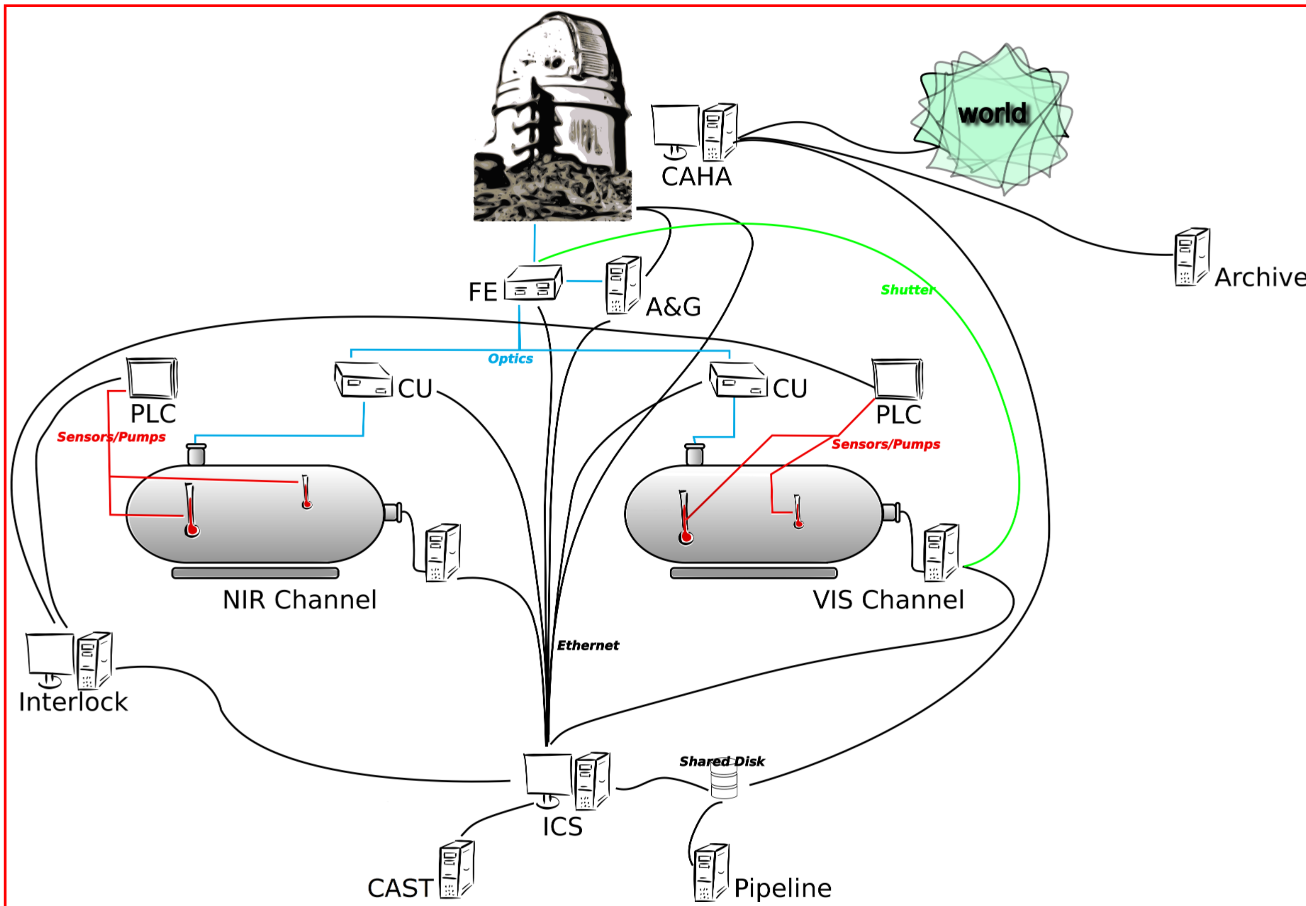

Figure 1: CARMENES System architecture. CU, A&G and FE stand for calibration unit (one for each channel), acquisition and guiding (A&G), and front-end electronics. The PLCs, one set for each channel, are programmable logic controllers.

- Multiple channels, one of them acting as master: both NIR and VIS channels are used and one of them acts as a master regarding observation and data processing control.

The standard operation mode (or CARMENES mode) for the instrument is defined using both channels with the NIR working as master. The VIS channel operation is subordinated to the execution time and overheads of the NIR channel that leads the work flow.

2.2 Architecture

The CARMENES instrument is formed by a set of hardware and software components in both instrument channels: VIS and NIR. In addition, the nominal operation of the instrument requires a fully synchronized control of the telescope and dome structure. An auxiliary set of instrumentation for environment monitoring (weather station, cloud sensor, seeing monitor, etc.) is also necessary for a suitable and efficient operation. The system is completed by the computer resources and network.

The global control system of the CARMENES instrument is organized in individual functional units called subsystems. Subsystems can just have a software entity (i.e., data pipeline) or can involve the operation of hardware. The subsystems in the CARMENES instrument are briefly described in Table 1.

Fig. 1 depicts the scheme of logical and physical connections between all main CARMENES subsystems. In terms of connectivity and control, the ICS will have access to the monitored data of all subsystems and provided by computers controlling NIR and VIS channels, NIR and VIS CUs, FE, A&G, Interlocks, and the scheduler (CAST).

Table 1: Subsystems of the CARMENES instrument.

Subsystem	Description
Telescope and Dome Control System	This subsystem controls the telescope and dome of the Zeiss 3.5 m Calar Alto Telescope (3.5 m CA), and reports the status of several sensors such as weather conditions, sky quality and cloud sensor monitors.
Front-end (FE)	It is the subsystem in charge of providing the hardware interface with the 3.5 m telescope, as well as, a guiding subsystem to position the telescope with the required precision. This subsystem includes the telescope interfaces, the optics and optomechanics components that collect the light from the telescope, the atmospheric dispersion corrector, the guiding camera and the control software to coordinate and manage all these components. The optical fibres are not include in this subsystem.
Acquisition and Guiding (A&G)	This subsystem is in charge of guiding the telescope with the precision required by the instrument. It is composed by the optics and optomechanics components, together with the detector, the control electronics and its own software.
NIR Channel	It is the subsystem in charge of obtaining stellar spectra in the near infrared wavelength region, from 950 to 1700 nm, to achieve a long-term radial velocity precision of 1 m/s. This subsystem includes from the optical fibres, which carry the optical beam to the spectrograph, to the supports of the vacuum tank on the floor of the coudé room of the 3.5 m telescope, and the control computer and its own software.
VIS Channel	It is the subsystem in charge of obtaining stellar spectra in the visible wavelength region, from 550 to 1050 nm, to achieve a long-term radial velocity precision of 1 m/s. This subsystem includes from the optical fibres, which carry the optical beam to the spectrograph, to the supports of the vacuum tank on the floor of the coudé room of the 3.5 m telescope, and the control computer and its own software.
Calibration Unit (CU)	There are two CUs, one for NIR and another one for VIS. This subsystem provides a simultaneous calibration, using a reference wavelength, to the NIR and VIS spectrographs. This subsystem includes all the components for this subsystem to work as a whole (optics, optomechanics and embedded control software), from the fibre feed, which holds the optical fibre head, to the lamps, including all the components necessary for its correct work.
Interlock	This subsystem monitors and controls all the CARMENES subsystems that could lead to a hazardous situation for persons or the instrument. For instance, it monitors the coudé, NIR and VIS room conditions, the cooling and vacuum systems, etc. It works independently of the ICS, but all data gathered by the Interlock is sent to the ICS to react (e.g., to stop current observation).
Scheduling Tool (CAST)	It is the subsystem that schedules target observations to be executed each night. It works as a sort of brain that computes the most suitable observation at a given point in time according to all the constraints of the project. This subsystem includes the CAST Archive, which stores the survey database and the observations executed during CARMENES life.
Data Pipeline	This subsystem is in charge of carrying out automatically after each exposure the full analysis of the data obtained by the instrument. This includes tools and software scripts to perform the data reduction and the radial velocity measurements.
Data Archive	This subsystem is in charge of archiving the raw and processed data following virtual observatory protocols. It provides a tool for easy data distribution among the consortium members during guaranteed time and and among the whole international astronomical community afterwards.

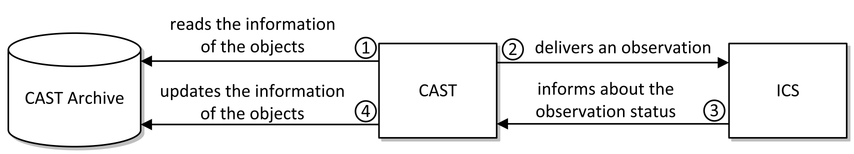

Figure 2: Work flow of CARMENES when the ICS requests CAST a new object observation. The origin of the arrow indicates the element that prompts the action. The numbers indicate the logical order of the operations.

2.3 Work Flow

The main work flow of CARMENES is triggered by the ICS when it requests CAST a new object observation. Then, CAST retrieves the information of the objects (objects of the CARMENES survey and the observations executed successfully) from the CAST Archive. With this information, CAST computes the scheduling of a new observation and sends to the ICS the data necessary to execute the observation. At this point, the data-taking of the observation execution will be handled by the ICS. Data-taking control will include the monitoring and control capabilities for different subsystems: telescope, NIR and VIS channel, front-end, acquisition and guiding and calibration units. The ICS will receive the images from each channel computer just after data collection is complete. Finally, the ICS performs a quick quality check and reports CAST the final status of the observation (completed, stopped, invalid), then CAST will update its archive. In parallel, the successful images will be stored on a shared folder to be processed by the pipeline. The results of this process will be automatically stored in a dedicated computer.

Figure 2 depicts the process described above. CAST acts as a sort of brain that communicates to the ICS the next observation to be executed, and this decision determines the remaining actions of the ICS.

3. CARMENES SCHEDULING TOOL

To achieve its purpose, CARMENES has to execute thousands of observations of different objects by fulfilling several constraints. Some of these constraints can be known a priori, such as the visibility and altitude of the object, or the sky brightness. However, there are constraints related to unexpected situations such as environment or system conditions that must also be considered. For instance, the resulting quality for an observation (measured in terms of signal-to-noise ratio) is strongly dependent on the environment conditions, because it is dynamically calculated with an exposure meter during the execution of the observation. Thus, the selection of the next object to be observed depends directly on the end time of the execution of the previous observation. This is an important limitation that makes it difficult to respect a previously calculated schedule of target observations. Moreover, the CARMENES scheduling of observations has to optimize the scientific return, reduce downtimes and invest less than five seconds in selecting the next target, which is a science requirement. For this reason, this process becomes unaffordable for human planners due to the complexity in computing the enormous amount of possible combinations in search for a near-optimal solution. In this sense, there are many mathematical tools to solve automatic planning and scheduling problems: from simple heuristics to more complex Artificial Intelligence (AI) approaches.[5,7]

CAST is focused on planning and scheduling the CARMENES survey according to all the problem conditions. CAST combines two scheduling strategies, off-line and on-line.[3] The first one obtains a plan of objects to be observed in a period of time according to the CARMENES constraints that can be computed beforehand. This strategy contains two different types of planning: (1) long-term to schedule object observations with a time scope of several months, and (2) mid-term to schedule object observations for a specific night. On the other hand, the on-line strategy contains a short-term scheduler that reacts to unexpected situations by adapting the previously computed mid-term plan.[4] It must be emphasized that CAST will be used only during the guaranteed time of the CARMENES consortium.

Fig. 3 shows the activity diagram of CAST when it is executed:

1. Load the information of the objects and their executed observations.
2. Compute the visibility of the objects in the current night.
3. If the use of a long-term plan is not required, go to Step 6.
4. If a previously calculated long-term plan is stored, load it and go to Step 6.
5. Execute the long-term scheduler.
6. If a mid-term plan of the current night is stored, load it and go to Step 8.
7. Execute the mid-term scheduler.
8. Execute the short-term scheduler each time an observation is required until the end of the night.

The three schedulers consider in their computation the objects that have been properly observed during the survey.

3.1 CARMENES Constraints

CARMENES can be considered as a constraint-satisfaction problem, which is a mathematical problem defined as a set of objects whose state must satisfy a number of constraints or limitations. Specifically, two kinds of constraints are identified: hard constraints and soft constraints, which are described in Table 2. The first ones have to be necessarily satisfied, and the other ones express a preference of some solutions over others. Thus, the final scheduling solution must fulfil all the hard constraints and it should optimize the soft ones. The optimization of the soft constraints is a key factor for obtaining a suitable mission plan with an adequate exploitation of the resources and with a high scientific return.

3.2 Off-Line Optimization Strategy

The long-term and mid-term schedulers are not time-critical, for this reason, they are based on Genetic Algorithms (GAs),[8] which are a computationally expensive AI approach focused on emulating natural evolution by means of combining potential solutions using selection, combination and mutation operators.[9] The solution obtained with these algorithms highly optimizes the objectives defined in the problem. In CARMENES, these objectives are related to fulfil the constraints, maximize the scientific return and to reduce the downtimes between observations. It is important to highlight that GAs must be adapted according to the particularities of the problem to be solved in order to obtain suitable results.[10]

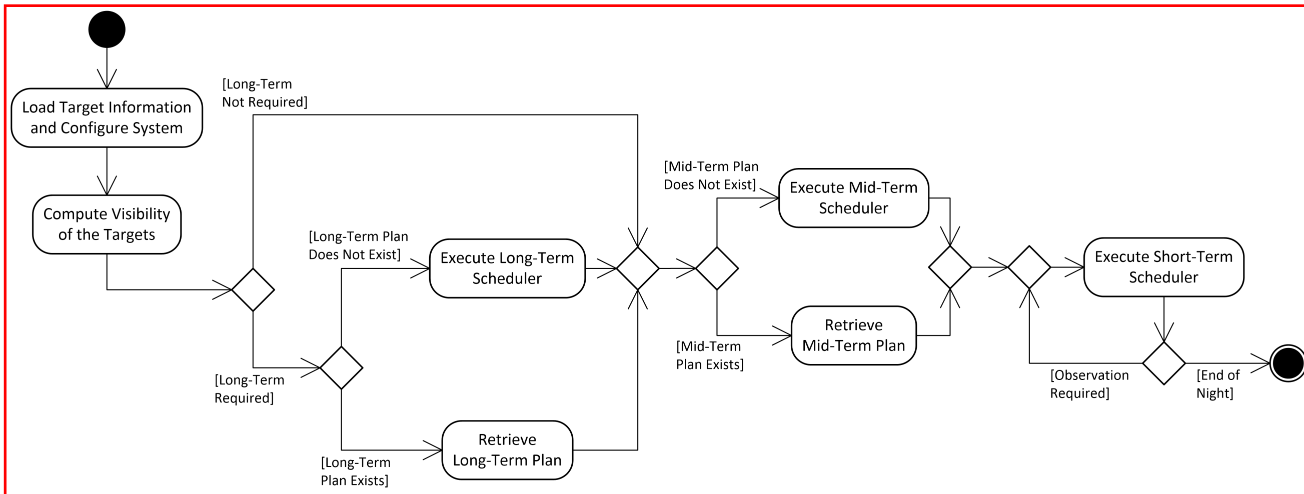

Figure 3: Activity diagram of CAST.

Table 2: Constraint description.

Type	Computation	Constraint	Description	Scope
Hard	In Advance	Night	Objects must be observed during the night.	Long-Term, Mid-Term, Short-Term
Hard	In Advance	Altitude	Objects must be observed if they exceed a specific elevation during a given time.	Long-Term, Mid-Term, Short-Term
Hard	In Advance	Moon Influence	Objects must be observed when the Moon is below the horizon or its illumination does not contaminate the observation.	Long-Term, Mid-Term, Short-Term
Hard	In Advance	Pointing	The object can be pointed during its observation without changing the dome hatch position. The dome of the telescope has a sliding hatch that allows observing a specific angle range at each position, in terms of operation, the hatch cannot be moved during a target observation.	Long-Term, Mid-Term, Short-Term
Hard	In Advance	Overlapping	The telescope can only do one task at a time, so observations must be scheduled by avoiding overlaps, including the time to reconfigure the system (i.e., slew time).	Mid-Term, Short-Term
Hard	On the Fly	Slewing	Pointing to a particular object requires a specific configuration. Thus, time to transfer to a new configuration must be taken into account when scheduling an observation.	Short-Term
Hard	On the Fly	Environment Conditions	The telescope can only observe objects if the weather is correct according to Calar Alto observation conditions for the 3.5 m telescope operation.	Short-Term
Hard	On the Fly	System Conditions	The telescope can only observe objects if the system conditions (e.g., ICS, observatory...) are correct.	Short-Term
Soft	In Advance	Periodogram Completeness	The phase variance between observations of the same target. It should be minimized.	Long-Term
Soft	In Advance / On the Fly	Observing Time	Time that the telescope is observing objects. It should be maximized.	Mid-Term, Short-Term
Soft	In Advance	Observation Deviation	The deviation between the number of times that all objects of the same priority have been observed in the complete survey. It should be minimized.	Mid-Term

3.2.1 Long-Term Scheduler

The long-term scheduler follows the process described in Fig. 4:

1. Define the long-term period p_{lt} according to the current time and the scope defined in the configuration.
2. Compute the visibility of all the objects in period p_{lt}.
3. For each one of the visible objects in the period, find the best days to observe the object using a GA.
4. Build and save a long-term plan, which is a list of potential observing days for each object.

The GA used in Step 3 is executed for each one of the objects. Thus, the GA plans target observations on the days that maximize the scientific return in terms of periodogram completeness. Specifically, the periodogram fitness function

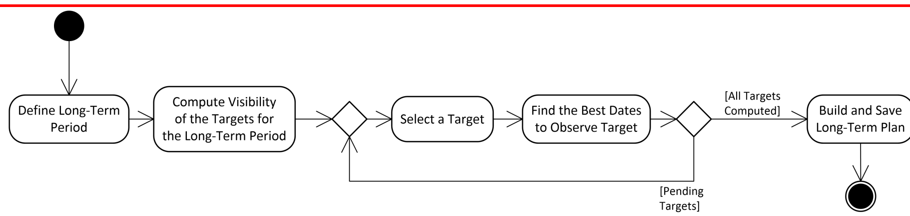

Figure 4: Activity diagram of the long-term scheduler.

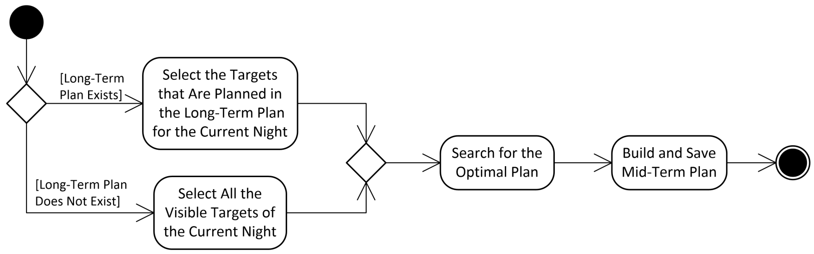

Figure 5: Activity diagram of the mid-term scheduler.

would be based on the orbital phase coverage of potential exoplanets.[11] A well-sampled window function of the observations ensures the best possible detectability of all orbital periods within the relevant range for CARMENES. The optimal sequence of measurements is determined using a phase variance parameter. At the end of the long-term scheduler, the resulting long-term plan fulfils the night, altitude and Moon influence constraints.

3.2.2 Mid-Term Scheduler

The mid-term scheduler follows the process described in Fig. 4:

1. Depending on conditions, select the objects to be observed from the long-term plan or from all the visible objects in the current night.
2. Search for the optimal plan of all the selected objects using a GA.
3. Build and save the mid-term plan, which is a timetable of observations that should be executed during the night.

The optimization goal of the GA is to schedule the selected objects in the current night by minimizing two objectives: (1) the idle time (time during the night in which the instrument is not acquiring scientific data), and (2) the deviation between the number of times that all objects of the same priority have been observed in the complete survey, to avoid scheduling every night the objects that require larger observation time. Thus, the fitness function used in the GA is an average of these two objectives. At the end of the mid-term scheduler, the resulting mid-term plan fulfils all the hard constraints that are predictable (night, altitude, Moon influence, pointing and overlapping constraints). The priority of the objects can be modified by the scientists during the development of the survey.

3.3 On-Line Optimization Strategy (Short-Term Scheduler)

The on-line optimization strategy consists of a short-term scheduler that reacts to unexpected situations such as environment or system conditions. Unlike the long-term and mid-term schedulers, the short-term scheduler is time critical because it has to schedule an observation in small time (less than 5 s). For this reason, with the aim of avoiding intensive calculations, it uses astronomy-based heuristics[12] with the aim of repairing the night schedule obtained by the mid-term scheduler.[13] The short-term scheduler follows the process described in Fig. 6:

1. All the planned observations in the mid-term plan whose assigned observation periods end before the current time of the observatory are removed from the mid-term plan, as Fig. 7 shows.
2. Select from the mid-term plan the planned observation whose observation period contains the current time of the observatory, and remove it from the mid-term plan. If there is no planned observation that matches this, no observation is returned and go to Step 4. An example is shown in Fig. 7.

3. Adjust the selected object observation according to the current time and estimate the slew time needed to change the telescope orientation from its current position to the object position, with the aim of predicting if the overall observation of the selected object will be in its visibility period. The result is a scheduled observation. However, if it is predicted that the observation will end after the visibility period of the object, it cannot be returned as solution and go to Step 5 to select another object, otherwise go to Step 6. Fig. 8 presents an example of this process.

4. Select the first observation of the list of objects that are visible between the current time and the start time of the first object in the mid-term plan. The list of objects is sorted in ascending order according to the number of times that they are executed in the full survey. Moreover, at this point of the process the first object in the mid-term plan is an object planned after the current time because all the previous ones have been removed from the plan. Go to Step 2.

5. Send the adjusted observation (scheduled observation) to the ICS.

6. Save the observation status when the ICS returns a response.

Fig. 6 also shows that if the object observation cannot be adjusted in Step 2, the selection process of Step 4 is repeated until a scheduled observation is obtained, the computation time (5 s) is exceeded, or no object can be observed. The observation scheduled by the short-term scheduler fulfils with all the hard constraints defined in Table 2.

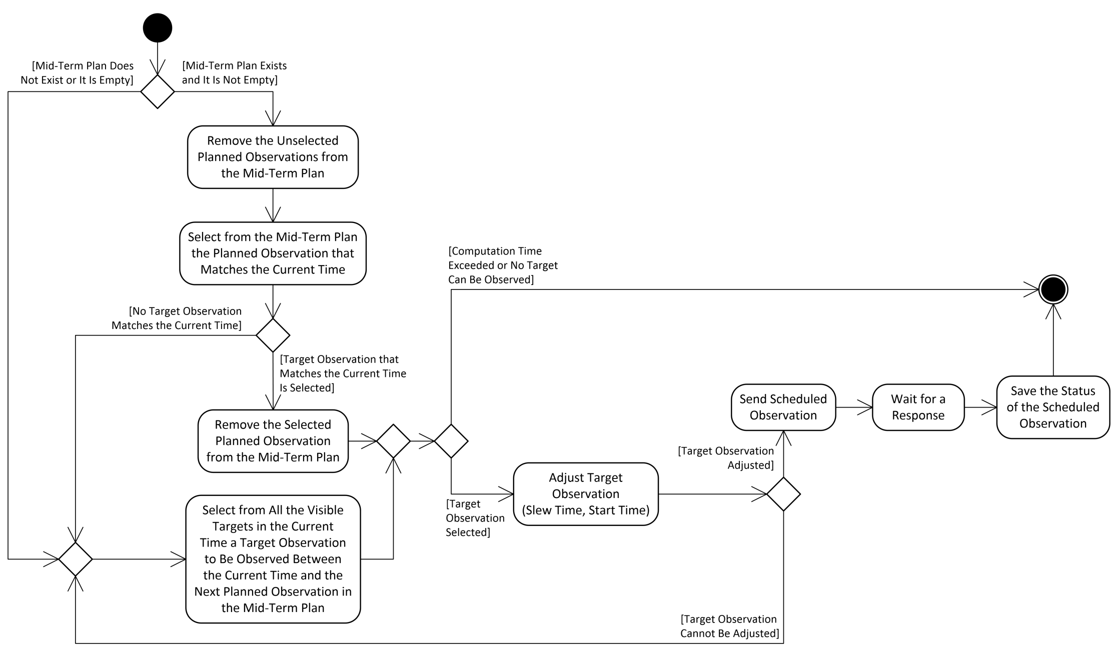

Figure 6: Activity diagram of the short-term scheduler.

4. INSTRUMENT CONTROL SYSTEM

Fig. 1 shows that the ICS is the central software application in the CARMENES control layer. It is based on a modular architecture and a high level of abstraction design motivated by the heterogeneity of the different subsystems. A master/slave model architecture is used to build the control layer, where the ICS acts as a master and almost every other subsystem is a slave. The ICS acts as a slave only for the User Interface subsystem, which controls and monitors the ICS functionalities.

4.1 Subsystem Integration

The subsystems managed by the ICS are seen as "black boxes" and there is no dependence with their internal architecture thanks to the high abstraction level used. A well-defined API, providing a connection bus and a protocol, is the basis to intercommunicate the subsystems. This approach ensures the separation in functionality and increases the modularity of the full system. The subsystem data (e.g., temperatures, encoder positions) are periodically reported to (or monitored by)

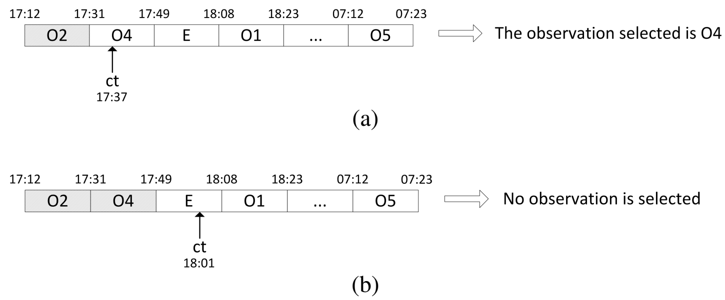

Figure 7: Example of an observation selection according to the current time (*ct*), where O_t indicates an observation of target *t*, *E* indicates an empty gap (no observation planned), and the numbers indicate the time. In (a) O_2 is discarded and O_4 is selected, in (b) O_2 and O_4 are discarded, and no observation is selected.

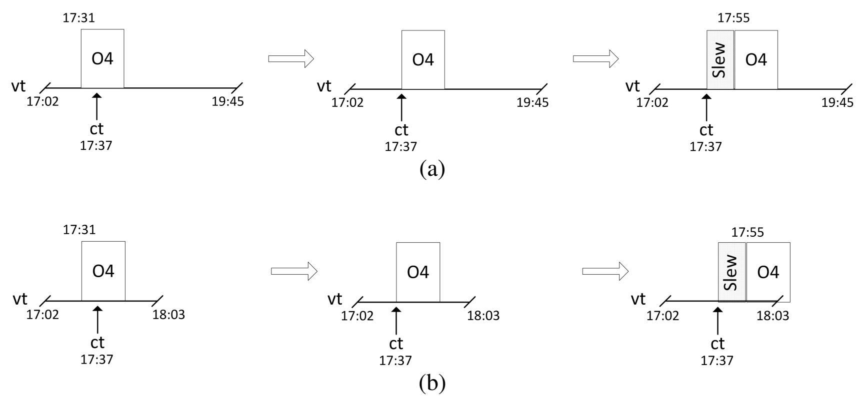

Figure 8: Example of an observation adjustment to the current time (*ct*) and the required slew time. The timeline (*vt*) indicates the time range when the target is visible and the numbers indicate the time. In (a) the observation of target 4 (O_4) is shifted and it is predicted that it can be executed in the visibility of the corresponding target. On the other hand, (b) shows that O_4 cannot be executed according to the current time because it will be completed after the end of the visibility of the target, thus O_4 must be discarded.

the ICS using its communication protocol and are stored into a central database that conforms a pool of updated data for all the parameters of the system (like a snapshot). Events (or contingencies) can arise during a nominal subsystem execution. An event is something that happens to the subsystem that generates a notification to the user or the execution of actions.

The designed actions are encapsulated in a common API and the ICS can trigger them using a common interface and without any dependence with the communication protocol. Actions can be stored in an action manager and executed when necessary following a predefined sequence. The system status is checked previous to the action execution to prevent possible erroneous commands.

The overall system operation is, finally, handled by procedures that execute predefined actions. These actions change the status of one or more components to reach the required configuration or response. Actions can be also triggered by an operator using any of the interface options (graphical or simple scripting) when the system is not running in the automatic control mode. The heterogeneity of the CARMENES subsystems imposes different interaction methods and protocols. For more details about the ICS design and the protocols used, the reader is referred to Ref. 6.

4.2 Operation Tasks

Three kinds of tasks can be executed by the ICS:

- Maintenance: ICS configures the subsystems to run maintenance tasks.
- Calibration: ICS configures the subsystems to run calibration tasks.
- Science: ICS configures the subsystems to run science tasks.

4.3 Control Modes

The ICS can be operated in two different control modes:

- Interactive: in this mode, the logged user has total control over the ICS and, according to its role, is able to carry out different actions.
- Automatic: on this mode, the ICS takes control of the instrument and will automatically execute the observations computed by CAST. If there is any error, the ICS will return to interactive mode and handover the control to the user.

4.4 Roles

Different roles are defined for controlling the ICS:

- Administrator: is able to manage users. ICS system administrator is done through the ICS computer's operating system and its levels shall be managed by regular Operating System User Management.
- Engineer: is able to execute engineering commands (to command any subsystem or to configure the ICS). Also, an Engineer is allowed to do the same operations than an Observer.
- Observer: is able to execute CAST and start the automatic mode (see Section 4.3). Also, an Observer is allowed to do the same operations than a Visitor.
- Visitor: can configure a custom observation and start it using a basic ICS interface. A Visitor is not allowed to use CAST and operate in automatic mode.

4.5 Integration with the CARMENES Scheduling Tool

Fig. 9 illustrates the main interactions between the ICS and CAST. It can be seen that CAST consists of the off-line module that contains the long-term and mid-term schedulers, the on-line module that corresponds to the short-term scheduler, and the CAST Archive. The CAST Archive stores the CARMENES survey[2] (CARMENCITA, CARMENes Cool star Information and daTa Archive), and the information of the observations done to each object (e.g., date and time, status).

Each one of the schedulers in CAST can be executed through the ICS or automatically. In the automatic mode, the mid-term scheduler is executed before the night, and the short-term scheduler is executed when a new observation is required in a specific point in time. On the other hand, the long-term scheduler has a more flexible configuration and its execution frequency and temporal scope can be parameterized.

It terms of communications, ICS interacts with CAST by means of four operations:

- Informs about housekeeping: the ICS sends information about the housekeeping to CAST. This information will contain the environment conditions (e.g., weather) and the system conditions. This message is sent every minute.
- Requests a long or mid-term plan: the ICS requests the computation of a new long-term or mid-term plan to CAST (off-line module). The new plan will replace the previous plan. Thus, the on-line module of CAST will use the new one in the execution of the short-term scheduler.
- Requests an observation: a new observation is required from CAST (on-line module) by the ICS. The short-term scheduler will consider the last housekeeping information received for computing the new observation.
- Informs about the observation status: the ICS sends the status of the last observation executed by CARMENES. The status will indicate the observation duration and if it has been completed or stopped.

On the other hand, CAST communicates with the ICS via three operations:

- Delivers a long or mid-term plan: CAST (off-line module) sends the computed long-term or mid-term plan to the ICS.
- Delivers an observation: CAST (on-line module) sends a new observation to be observed to the ICS.

- Informs about the CAST status: CAST sends a message to the ICS every minute with information about its status (e.g., running long-term scheduler, running mid-term scheduler, waiting for a new observation request...).

Inside CAST, three modules communicate with each other:

- Reads the information of the objects: the three schedulers of CAST access the information of the objects in the CAST Archive.
- Updates the information of the objects: when the ICS sends to CAST the status of the last observation executed, the on-line module of CAST modifies the object data in the CAST Archive database with the status of the observation.

All the communications between the ICS and CAST are done by means of the Internet Communication Engine (ICE) protocol.[14]

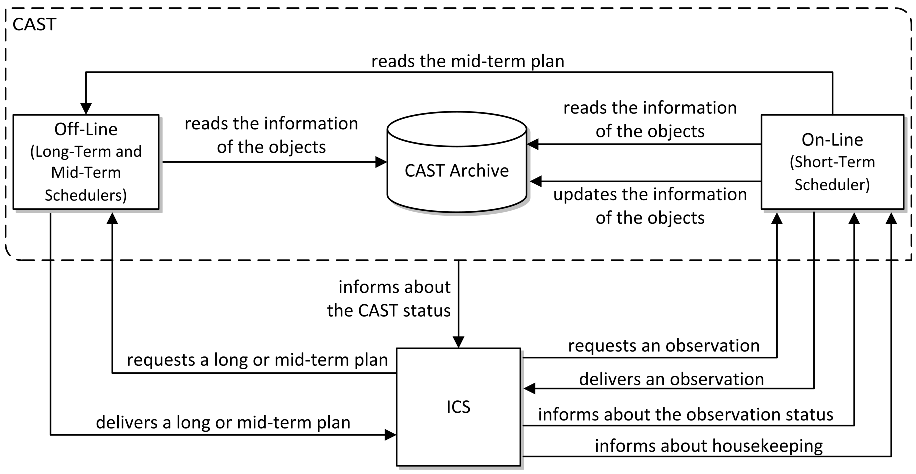

Figure 9: Interactions between CAST and the ICS. The origin of the arrow indicates the element that prompts the action.

5. EXPERIMENTS, RESULTS AND DISCUSSION

This section empirically analyses the performance of CAST to show the suitability of the obtained schedules in CARMENES. To do this analysis, CAST has been executed using an ICS simulator, which considers the environment and system conditions.

5.1 Experimental Methodology

This section describes the test sample used in the experimentation, the optimization approaches and configuration of the three schedulers and the comparison metrics applied in the evaluation.

CARMENES Survey. Given the expected performance of the two spectrographs, the current sample selected for intensive monitoring has 300 objects and it is composed of three sub-samples:[2]

- *S1*: 100 stars with $M < 0.25M_{\odot}$ (spectral type M4 and later).
- *S2*: 100 stars with $0.25M_{\odot} < M < 0.30M_{\odot}$ (spectral type M3-M4).
- *S3*: 100 stars with $0.30M_{\odot} < M < 0.60M_{\odot}$ (spectral type M0-M2), relatively bright.

Sample *S1* is designed to cover the spectral type domain that can only be studied by CARMENES. Sample *S2* is selected to address a pool of targets for which CARMENES is very efficient but comparable to visible spectrographs and will provide a cross-check with other surveys. Sample *S3* will have the highest fraction of bright targets and will therefore be best suited as a "poor weather" sample. The brightest stars of all three samples have the potential of providing a sub-sample for the most frequently observed stars for which the detection of low-mass planets should be clearly enhanced. All three samples will necessarily contain a certain fraction (~20–30 %) of moderately active stars. This sub-sample of moderately active stars is defined to exploit best the capabilities of CARMENES (i.e., simultaneous coverage of the visible and near-IR), which should allow to disentangle in these stars the effects of activity and exoplanets. For more details about the CARMENES survey, the reader is referred to Ref. 2.

The CARMENES survey is programmed with a duration of around three years. In the experiments presented, the scenario was planned in one year in order to allow extrapolating the results to different durations of the survey.

General Test Bench Configuration. Some global assumptions for the problem constraints have to be specified when defining the test bench configuration:

- Tests cover 1 year (2015).
- All the objects in the CARMENES survey have the same priority.
- The simulator has considered the weather history of years 2004 to 2006.
- The weather model is based on Calar Alto observation conditions for the telescope operation, which are listed as follows: (1) dome should be closed above 98% relative humidity, and shall be closed until it is at 95% or below for at least twenty minutes, (2) observing cannot happen if the outside temperature is below -15 °C, and (3) no observation can be executed when the wind speed is higher than 24 m/s.
- Each target requires a specific observation time for obtaining results with the required signal-to-noise ratio. The simulator increases this time up to 20% according to the weather conditions of the night.
- The long-term plan is executed each three months and plans the next six months of the survey.
- The mid-term plan is executed each night.
- Overhead duration of 2 m and slew modelling according to the telescope.
- Read-out duration of 40 s.
- The minimum acceptable altitude for an object is 20°.
- The minimum acceptable distance to the Moon is 20°.

Comparison Metrics. Several metrics have been defined to evaluate and compare the performance of the schedule obtained by CAST in the aforementioned experiments. The first metrics are related to the use of resources:

- Observation Time: it is computed as a percentage of the total available observable time.
- Slew Time: it is calculated as a percentage of the total available observable time.

The next ones are related to the scientific return:

- Observations Done: it is the number of object observations that have been correctly executed.
- Periodogram Completeness: it is calculated as the average of the percentage of completeness of the periodogram of each object. As exposed in Section 3.2.1, the periodogram is based on the orbital phase coverage of potential exoplanets.[11]

Table 3: Results obtained (mean and deviation) for the defined metrics after 10 trials.

Observation Time	Slew Time	Observations Done	Periodogram Completeness
81.40±0.14 %	16.49±0.06 %	10209±26	99.75±0.01 %

5.2 Analysis of the Experimentation Results

This section presents the results obtained with CAST, which has been run several times using 10 different random seeds for each scenario. Each of these executions is referred hereafter as trial.

Table 3 describes the results obtained in terms of the four defined metrics (observation time, slew time, observations done and periodogram completeness). The mean and deviation values of each metric for the 10 trials are given. There is a small deviation in each measure, so it seems that CAST is able to obtain similar results in different executions.

Use of Resource Analysis. The available observation time is calculated according to the total theoretical observable time (4309.88 hours) and the environment and system conditions. Thus, only the time intervals of the nights that have the conditions to observe objects are considered (e.g., observable time windows with favourable weather). This results in an available time of 3088.97 hours during 2015 (i.e., 71.67% of the theoretical observable time). The telescope is observing during 81.4% of the total available time, which means that the telescope is observing for 2514.38 hours. Moreover, the telescope is working (observing or slewing) the 97.9% of the available time (3024.07 hours). Therefore, the use of resources is very high and, consequently, the idle time is negligible, which is one of the goals of the automatic scheduler.

Scientific Return Analysis. Table 3 shows that in one year the average periodogram completeness of all the targets is almost 100%. This means that the observations of the targets are well distributed over time. However, to increase the efficiency of the survey, it is necessary to execute a high number of observations to each target. Figure 10 shows that there is a significant difference between the most observed targets and the least observed; consequently, the priority of the targets in the rest of the survey will be modified with the aim of increasing the number of observations of the less observed objects or of objects that deserve an extra monitoring because of scientific reasons (e.g., presence of a promising signal of an exoearth candidate).

Computational Cost. Finally, with a CPU Intel Xeon E5-2430 v2 2.50GHz with 8GB of RAM, the planning results of the full simulation (one year) of a single trial are obtained in approximately 24 hours. Specifically, each long-term execution spends 3 hours and each mid-term execution around 3.5 minutes. Moreover, the average time used by the short-term scheduler in obtaining a new observation is 56 milliseconds, so it comfortably satisfies the requirement to provide a response in less than 5 seconds.

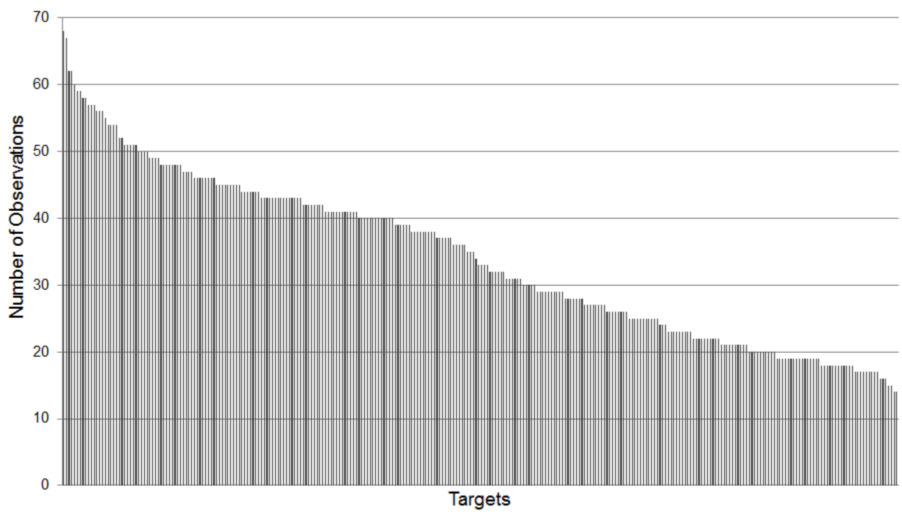

Figure 10: Histogram that represents the number of observations done to each target for one year in a single trial of CAST.

6. CONCLUSIONS AND FURTHER WORK

CARMENES is a new generation instrument that will provide stellar radial velocities of unprecedented accuracy (1 m/s). It will be installed at the Zeiss 3.5 m Calar Alto Telescope and will start operations in late 2015. It will be equipped with two channels for spectroscopic data collection in the NIR and VIS windows. The scientific requirements specified impose stringent conditions on stability and performance of the instrument so that the technology used in the development represents a challenge at all levels. The efficient and reliable operation is also specified as a requirement to maximize the scientific return. Such operational requirements result into strong constraints to define the control layer at the level of hardware and software, and all the subsystems that compose it. In this sense, the Instrument Control System (ICS) is focused on fulfilling the operation requirements and handle a heterogeneous group of subsystems in a coordinated manner. Moreover, one of the essential elements for the success of astronomical projects is the efficient planning and scheduling of tasks. In this direction, the CArmenes Scheduling Tool (CAST) is responsible for obtaining an efficient mission plan that respects the CARMENES constraints and maximize the ultimate scientific performance.

In the first part of the document we have described the operational design of CARMENES, showing the critical role of CAST and the ICS. In the second part of the document we have proposed a process to be followed for the automatic planning of the survey. Specifically, CAST consists of two scheduler strategies: off-line and on-line. The first one is used to obtain schedules that only consider the constraints that can be computed in advance, and it uses two kinds of tools: the long-term and the mid-term schedulers. On the other hand, the on-line strategy uses a short-term scheduler to schedule observations considering constraints that must be computed on the fly. The aim of this process is to use the off-line strategy, which is not time critical, to obtain the desired schedule of a night, and to use the on-line strategy to react to unexpected situations that may occur during the night. Next, we have presented the modular architecture and the high level of abstraction of the ICS, as well as how CAST is integrated in it.

In the experimentation analysis, we have simulated the work flow of the ICS and CAST for a year in order to analyse the scheduling performance of the system. The results show that the schedules obtained take full advantage of the available time, highly optimize the scientific return and can react to unexpected situations in less than one second. In short, CAST has obtained promising results and has demonstrated that it is able to obtain efficient results in different situations. Further work will focus on considering other measures for modelling the scientific return more accurately, and on adding a more intuitive interface for operators.

7. ACKNOWLEDGEMENTS

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