ARIEL Consortium Phase A Payload Study

ARIEL Long Term planning

ARIEL-ICE-GS-TN-001

Issue 1.0

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Date: 15/02/2017
# DOCUMENT CHANGE DETAILS

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Other Engineering Team

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1 PREAMBLE

1.1 SCOPE
This document is focused on the Long Term Mission Planning Tools proposed for the scheduling of the observations of the ARIEL mission. Two different approaches are presented, one based on Artificial Intelligence in the form of Genetic Algorithms, developed in Institute of Space Science (ICE-CSIC, Barcelona); and the other based on the tools developed by the Centre National d'Études Spatiales (CNES, Toulouse).

1.2 PURPOSE
The purpose of this document is to present the design and implementation of the proposed Planning Tool and the algorithms used with this purpose. We also present the results of the different planning tools applied to a sample of ARIEL targets [RD1] and we analyse 1) the efficiency of the tools scheduling the mission, and 2) the fulfilment of ARIEL science goals as a function of mission lifetime.

1.3 ACRONYMS

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1.4 APPLICABLE DOCUMENTS

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2 INTRODUCTION

The Atmospheric Remote-Sensing Infrared Exoplanet Large-Survey (ARIEL) is one of the ESA M4 mission candidates currently in assessment for potential launch in 2026. If selected, ARIEL will be the first dedicated mission to investigate the physics and chemistry of exoplanetary atmospheres. The primary objective is to study a representative sample of at least 500 exoplanets around nearby stars, with sizes from Jupiter to a few Earths, and determine the spectrum of the planetary atmosphere. This can be achieved by using high-precision spectrophotometric observations of two types of events: 1) transits (transmission spectra) and 2) eclipses (emission spectra), which implies observing at specific times when those events, known from previous studies, will occur, and which introduces an important constraint on the mission planning. In addition, the variation of a planet's spectrum during its orbit can also yield information on the planet's atmosphere. Among the criteria considered for the observations of each exoplanet are: target visibility, time and duration of event, number of events to be observed to achieve the needed SNR, and target priority.

An inevitable result of planning observations that must occur at specific times and of a pre-determined duration, and after accounting for the slew and settling time between targets is that there will be a lag between any two observations which is initially unused. We will discuss the statistics of these unscheduled blocks of time, and show that since the vast majority of them are short, they can be incorporated into the observations of the next target by beginning that observation a little earlier, thus also giving extra time to the detectors to stabilise. When this is accounted for, the efficiency of observations of science targets reaches ~92%, well above the requirement of 85%, with the remaining time going to observations of calibration sources (~4%), and slewing, settling and other HK activities (~4%).

A suitable mission plan will maximise the efficiency of mission, while fulfilling the constraints that must be respected to fulfil the mission objectives. Thus, the process of combining all this information becomes unfeasible for human planners due to the complexity in computing the huge amount of possible combinations in search for an optimum solution. There are several mathematical tools to solve the planning/scheduling issue: from simple heuristics to more complex Artificial Intelligence (AI) approaches.

In this document we present two mission planning tools for ARIEL, one based on the algorithms developed by the CNES, and the other one based on Evolutionary Algorithms (EAs), which are an AI approach focused on emulating natural evolution by means of combining potential solutions using selection, combination and mutation operators. This kind of algorithm attempts to generate solutions to optimization problems by exploring a large amount of potential solutions, including the most efficient ones. A solution is considered efficient when it highly optimizes the objectives defined in the problem that, in our case, correspond to maximizing the planning efficiency and the scientific return, measured in terms of the completeness of the observation of the mission reference sample within the allowable mission duration.

The remainder of the document is organized as follows. In Section 3 we describe the observations that ARIEL is expected to carry out, the sample of targets and the satellite operations that are considered in the mission planning. In Section 4, we present the tool based on Artificial Intelligence, we discuss the constraints that the mission plan must fulfil, we present the ARIEL mission planning optimization problem, we briefly describe the implementation of genetic algorithms for the mission planning, and we show the results of the simulations and the impact of key constraints in the mission planning. In Section 5 we present the tool approach developed at CNES, mission constraints used in this case, the resulting mission plan and its efficiency. Finally, the overall conclusions, which are similar for the two tools, are summarized in Section 6.
3 ARIEL MISSION OPERATIONS

The aim of this section is to present the main aspects that have to be considered for the Long Term Mission Planning Tool (hereafter, LT-MPT) design.

The main purpose of a mission planning tool is the allocation of tasks to a particular time, while optimizing different objectives like minimizing operation time overheads or maximizing the mission scientific return. This planning tool is a key element in the control layer for the observatory time optimization. The large complexity of the process to handle the observing constraints (e.g., visibility windows) for every target in the mission survey raises a big challenge concerning the scheduling of observations. This process must be carried out taking into account, for instance, the spacecraft configuration (e.g., attitude, modes), the operation tasks and the state of the housekeeping variables. Suitable planning algorithms are needed to achieve the project goals and make optimum use of the observatory. Artificial Intelligence (hereafter, AI) techniques based on optimization, such as Genetic Algorithms (hereafter, GAs), Ant Colony Optimization or Multi-Objective Evolutionary Algorithms, can be useful to solve this kind of problems of high mathematical and computational complexity. The algorithm selection process must consider the scheduling/planning problem that best fits the observatory characteristics (e.g., job-shop problem).

In addition to the algorithm used to plan the observations, the scheduling time-cycle is a critical ingredient to determine the best design approach. During the mission, the Science Operation Centre (hereafter, SOC), the Mission Operation Centre (hereafter, MOC), and the Instrument Operations and Science Data Centre (hereafter, IOSDC) should be in coordination to carry out the ARIEL science observations. IOSDC provides the SOC with required observations and a schedule, which are then communicated and executed by MOC. After the downlink process SOC send the observations to the ARIEL archive, and IOSDC can check which observations are successfully executed and can re-optimize the mission plan for next periods if required. The LT-MPT can be designed in such a way that can be run periodically (with an agreed time scope) and re-optimize the remaining mission plan taking into account all observations previously done. Therefore, the planning of the mission is not static but will be dynamically updated to account for the realities of operations.

3.1 OPERATION TASKS

During the mission, the ARIEL satellite will have to run different kinds of operations: from science observations, to calibration observations, data downlink, and station keeping operations. An efficient long-term mission planner will have to schedule each of these operations during the mission lifetime in order to optimize the survey. Therefore, the requirements of these operations need to be defined in advance. Different operation tasks may have to be done in fixed slots of time; thus, any possible overlapping with the observation of targets must be solved.

- **Science observations** correspond to actual observations of exoplanet transit events. A target event is defined as a time period when the exoplanet is transiting its host star or it is eclipsed. The duration of an event, \( T_{14} \), is the time between first and fourth transit/eclipse contacts. Additional time is included in order to observe the flux variation before and after the planet transit or eclipse, and to precisely measure the transit depth (see Figure 1). The ephemerides and \( T_{14} \) are provided as an input parameter in the target list (see Subsection 3.2 and [RD1]). As a basic assumption (and as per the requirements of the MRD [AD1]), it is assumed that each planetary event is observed over 2.5 times \( T_{14} \) with the transit in the centre of the overall observation time; however, the impact of different values of the multiplier of \( T_{14} \) in the survey efficiency have been analysed in this work.
Figure 1. Transit event of an exoplanet. Blue horizontal line indicates the duration of the transit from first to fourth contacts, and red lines, the fraction of time before the ingress and after the egress of the exoplanet that is used to measure the depth of the transit.

- **Calibration tasks** are associated to science observations, they are defined in the same execution pattern and they are established by the ARIEL Consortium. Specifically, several instrumental responses (e.g., instrument noise, instrument absolute wavelength or instrument pointing) will be monitored at intervals defined by the IOSDC. For the present exercise, the calibration scheme defined in [RD2] is assumed. A set of short and long calibrations is defined, consisting in observations of stable G-type stars during 1h or 6h respectively in order to monitor the instrumental response on the typical timescales of transits. The rate of these calibrations is assumed to be:
  
  - Short calibration (1h): every 36±12 hours.
  - Long calibration (6h): every 15±5 days.

A list of 536 G-type stable stars (and their location on the sky) is provided in order to take into account the slew between targets and calibration targets. On average, the closest distance between a calibration star and a target is about 5 deg. Priority is given to long calibrations, i.e., short calibrations closer than 36±12 hours to a long calibration are removed from the plan. With this scheme, about 370 hours are used for calibrations every year, which correspond to about 4.2% of the available time.

- **Downlink communication** periods will be established by ESA for transferring data from the spacecraft to stations on Earth. The design solution for nominal communications during science operations requires a link of 14 hours per week split in three contacts (excluding weekends) [AD1, R-OGS-080/085]. However, due to the requirements of the MRD, science observations can be done simultaneously to downlinks, and therefore we assume that they will not impose a constraint on the mission planning tool. A constraint is added that the downlinks can not run between observations due to the need to then slew the communications antenna during a downlink.

- **Station keeping operations** are determined by ESA MOC and they are defined to keep the spacecraft in the assigned orbit. The sequence of these operations cannot be established precisely in advance. As a conservative approach, we assume that these operations will be carried out every 28±3 days with a duration of 8 hours; this requires about 100 hours per year, 1.2% of the mission time. Simultaneous observations are not possible.

### 3.2 ARIEL SAMPLE

Given the number of ongoing projects and next generation instruments in development aiming at discovering exoplanets around bright stars, the number of available exoplanets at the time of ARIEL lunch will be much larger than now. Particularly interesting will be exoplanets orbiting bright stars, which
will require only one or few observations to reach the needed signal-to-noise ratio (hereafter, SNR) to characterize their atmospheres. ARIEL technical note [RD1] describes the targets included in the ARIEL Mission Reference Sample (hereafter, MRS), which considers both already known exoplanets and those expected to be discovered in the coming years by current and future ground based surveys (NGTS, CARMENES, SPIROU, WASP, HAT, etc.) and space missions (TESS, K2, etc.). The simulated planets are necessary at present to have a large input list to properly fill the ARIEL mission; but the goal is not to observe all the targets in the list, but to have sufficient targets to span over the diversity of planets to reach the science objectives of the mission.

A total of 1102 targets are included in the sample at the time of writing, 122 known planets and 980 that are simulated assuming conservative assumptions on the discovery rate for exoplanets and the upcoming facilities and missions. The MRS gives (among other information) the number of transit and occultation observations necessary for each target in three tiers (see below), i.e. six values for each target. These values, and also the choice of transit or occultation, are determined from the stellar type, the planet type, and the instrumental characteristics, and reflect the amount of observations needed to achieve a certain signal-to-noise ratio (hereafter SNR, see [RD1] for further details). Three different categories of targets are defined according to the resolution (R) and the SNR of the final spectra that will be obtained.

- **Tier 1, Survey.** Few transits or occultations will be observed for each planet in order to get low-resolution spectra with SNR = 7. For the scheduling purposes, the number of events that need to be observed for each target ranges between 1 and 4, and add up to a total of 1352, slightly more than 1 event per target on average. The mean value of the transit duration ($T_{14}$) is about 3.7 hours, thus the average monitoring time is about 9.25 hours.

- **Tier 2, Deep Survey.** A subsample of the Tier 1 planets will be observed further to get higher spectral resolution, at SNR = 7 or greater. Some of the planets will reach this level of precision even in Tier 1. For the scheduling purposes, the sample used in this exercise contains the number of observations that would be required for 480 out of the 1102 targets included. The number of additional events required for each target in this subsample is between 1 and 18, adding 1879 events, with an average of about 4 events per target.

- **Tier 3, Benchmark Planets.** Few tens of interesting planets orbiting bright stars will be observed at the maximum spectral resolution of ARIEL. For the current exercise, the sample includes the number of events required in this subsample for 66 targets, which require between 1 and 45 observations per target to reach a SNR of 7 or more, adding 485 additional events (about 7 observations per target on average).

Finally, the list of targets ranks all planets with a priority according to their properties. This is a value between 1 (high-priority) and 0 that can be used to optimize the scheduling of interesting planets. In the sample used here a total of 459 planets have priority=1, 126 are in Tier 2, and 66 in Tier 3.
4 ARIEL LONG-TERM MISSION PLANNING TOOL BASED ON ARTIFICIAL INTELLIGENCE

Planning of astronomical observations is an example of the classical task allocation problem known as job-shop problem, where several tasks are assigned to identical resources while minimizing the total execution time. The planning and scheduling problem that we want to face up is considered as NP-hard (Non-deterministic Polynomial acceptable problems, van Leeuwen 1998\(^1\)) because it is impossible to solve in polynomial time (i.e., feasible time) due to the complexity in computing the large amount of possible combinations in search for an optimum solution, and it is necessary to use strategies to guide the exploration in the search space of all feasible solutions with the aim of finding a close to optimal solution in reasonable time. There are many mathematical tools to solve this kind of optimization problems: from simple heuristics to more complex AI approaches (Donati et al. 2012\(^2\)). In this section we present a LT-MPT approach based on GAs (Holland 1975\(^3\)), which are an AI approach focused on emulating natural evolution by means of combining potential solutions using selection, combination and mutation operators, with the goal of obtaining a solution that highly optimizes the objectives defined (Freitas 2002\(^4\)). GAs are theoretically and empirically proven to provide a robust search in complex spaces, thereby offering a valid approach to problems requiring efficient and effective searches (Goldberg 1989\(^5\)). Nevertheless, we propose a standard process to be followed for building an automatic LT-MPT for the ARIEL mission independently of the technique used for solving the optimization problem.

4.1 SCHEDULING CONSTRAINTS

A scheduling process can be considered 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. Two kinds of constraints are identified: hard constraints and soft constraints. The first ones have to be necessarily satisfied, and the other ones express a preference of some solutions over other ones. Thus, the final scheduling solution, the suggested Long-Term Mission Plan (hereafter, LTMP) must fulfill all the hard constraints and it should optimize the soft ones.

The following subsections define the hard and soft constraints identified in the ARIEL mission, which are summarized in Table 1. The LT-MPT should schedule the operations defined in Section 3.1 taking into account these constraints.

4.1.1 Hard constraints

Five hard constraints are identified in the ARIEL mission, mainly related with the visibility of targets and the ephemerides of the events to be observed. Each constraint is explained in the next items:

- **Orbital constraint.** The satellite orbit and attitude constrain the visibility of targets. Thus, it must be considered by the LT-MPT when computing the visibility of targets during the mission. For the present exercise, we have assumed an L2 orbit and a maximum wobble angle of ±25° maximum wobble angle [AD1, R(OBS(020\)] around S/C Y axis.

- **Transit constraint.** As mentioned before, the strategy to execute the science observations depends on exoplanet transit or occultation events and their duration. This is included in the planning tool as a constraint. The exact time of target events can be computed in advance given the ephemerides of the time of eclipse or occultation and the properties of the planet. The

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duration of an event \((T_{\text{obs}})\) is defined as a multiple of the transit time \((T_{14})\). For this work, we have assumed that the total monitoring of each event last \(2.5 \cdot T_{14}\), but we have also estimated what is the impact of using \(2 \cdot T_{14}\) and \(3 \cdot T_{14}\).

- **Target Completeness constraint.** This constraint is related to science observations. In terms of scientific interest, only the observations of completed targets are useful. For this study, we have defined that a target is completed when it is observed 100% of the required number of times to reach the necessary resolution and SNR according to each tier. Therefore, if for a given mission plan there are targets that do not reach this threshold, they are discarded and the schedule is recomputed again filling the released time with other targets. On the other hand, when a target reaches 100% of required observations, it is not scheduled any more. These threshold values can be relaxed if spectra with lower SNR could also be interesting, or if additional observations of interesting targets are needed. Moreover, different limits could be defined according to each target class. These are additional items that will be considered in the continuation of this work in the next phase.

- **Slewing constraint.** Pointing to a particular target and acquiring data requires a specific configuration. Thus, time to transfer the satellite to a new configuration must be taken into account when computing the mission planning. This reconfiguration time mainly depends on the slewing speed of the satellite. Following ARIEL requirements, we assume a satellite slew speed of 4.5 deg/min and we add an additional stabilization time of 5 minutes [AD1, R-SYS-070].

- **Overlapping constraint.** A key constraint in the ARIEL mission is that some of the operations defined in Section 3.1 cannot be done simultaneously. The assumption is that only Downlink operations can be done at the same time as Science or Calibration observations longer than 4h. Thus, the LT-MPT must plan the operation tasks avoiding overlapping between targets observations, calibrations and station keeping operations, including the slew time to point to a new target.

For the present exercise, we only use the scheduler to plan science, calibration and station keeping operations (including slews). The distribution of science operations and gaps between observations are later studied in order to schedule downlink contacts with ground stations (in case there is a desire to remove the capability for simultaneous observation and downlink) and further target observations.

### 4.1.2 Soft constraints

Soft constraints are defined in order to promote some solutions over the others. In this case, although these constraints are not required to be fulfilled in order to obtain a valid plan, they are key factors for obtaining a close to optimal plan. For this study, in the case of the ARIEL mission, we have defined the next soft constraints:

- **Observing time.** The time in the plan during which the telescope is observing objects should be maximized. Also, there is a requirement that the overall efficiency must be \(\geq 85\%\) (R-OBS-040 in MRD [AD1]).

- **Number of targets completed.** The plan should promote the number of targets completed in order to obtain a high scientific return. The priority and the criticality of the targets (i.e. the fraction between the required number of events and the total number of windows available for each target) are taken into account.

The optimization of these soft constraints allows obtaining a LTMP with a large number of observations as well as a large number of completed targets. Nevertheless, the soft constraints used can be modified according to the characteristics of the optimization method used in order to provide more flexibility to the planning tool.
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<td>Transit constraint</td>
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<td>Slewing constraints</td>
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<td>Slew rate of 4.5 deg/min (+ 5 min stabilization time)</td>
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<td>Target and calibration observations (+ slew time) and stations keepings cannot be simultaneous</td>
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<td>Targets completed</td>
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Table 1. Hard and soft constraints of the ARIEL Long-Term Mission Planning Tool.

4.2 SCHEDULING ALGORITHM

In the process of scheduling the ARIEL survey, we can identify two main aspects based on the problem conditions described in previous section: 1) the optimization of the positioning of satellite operations such as calibrations, downlinks or station keepings focused on restricting less priority targets, and 2) the optimization of the observation scheduling of each target event avoiding overlapping and optimizing specific objectives.

Taking into account these considerations, we propose different steps for the LT-MPT described in the following subsections. The optimization phases (Step 2 and Step 3) can be done by using several mathematical tools such as simple heuristics or AI techniques. We propose to apply GAs, a well-known AI technique of the EAs family, which are able to solve optimization problems and have the ability to be adapted to new environments and constraints. Other approaches based on the EAs family, were analysed during the phase study of the EChO mission but proved to be less competitive.

4.2.1 Target event time windows (Step 0)

In this initial phase of the scheduling the goal is to obtain the windows of time where the targets can be scheduled, which correspond to the times where transit or eclipse events occur for each target. These are calculated using the target ephemerides together with the restrictions coming from the spacecraft sky visibility. The resulting information is a list of time windows for each target, each of which correspond to the duration of an event given by 2.5·T_{14} as defined for science observations.

4.2.2 Target clean-up (Step 1)

Once the visibility windows of each target are defined, we can compare the number of possible times in which each target can be observed with the number of required observations given in the target list. It is possible to configure the LT-MPT so that any target that cannot be observed a certain fraction of the requested times, is removed from the schedule from the very beginning. In the exercise presented here, we assume that at least 100% of the total requested times have to be schedulable in order to consider each target in the subsequent steps.

4.2.3 Satellite operations optimization (Step 2)

The satellite operations not related with exoplanet observations have usually time restrictions defined by the MOC, SOC and IOSDC. This is for example the case of downlinks, calibrations and station keeping manoeuvres. The goal of this step is to plan these operations minimizing the potential overlapping with science targets. Thus, this process is only aimed to identify the optimal time slots for these operations. In the present exercise, we assume that only calibration and station keeping operations need to be taken into account, since downlink observations can be done simultaneous to observations.

We assume that, although the rate of calibrations and house keeping operations could be fixed by default, there is some flexibility to allocate time slots to these operations. This flexibility is devoted to
find an optimal shifting to the default position for each calibration avoiding overlapping with exoplanet observations as much as possible.

The GA applied in this phase follows the next steps:

- First, a set of initial solutions is generated randomly. Each solution corresponds to a vector with the time position of each calibration operation and its duration, with a random time shift within a given agreed range $[-\delta, \delta]$ (here we assume $\pm 12$ hours for short calibrations, $\pm 5$ days for long calibrations, and $\pm 3$ days for station keeping operations).
- Crossover, mutation and replacement GAs are applied to this set of random solutions in order to produce a new generation of solutions.
- For each possible solution, an objective function is evaluated. In this step, the objective is to avoid as much as possible overlaps between calibrations and exoplanets targets. Therefore, taking into account the targets visibilities computed in Steps 0 and 1, these function is defined so that it is optimized when the overlap between calibrations and exoplanet targets is as small as possible, considering also the priority and criticality of each target. The best solutions are kept in the new population of solutions and used to get a new generation.
- Finally, the optimized solution after a parameterized number of generations is the final mission plan of calibration operations.

4.2.4 Observation planning optimization (Step 3)

This step of the LT-MPT is devoted to the allocation of exoplanet observations, avoiding again as much as possible overlapping between different targets, and maximizing the number of completed targets. In this step, the slew time of the telescope must be taken into account. The GA applied follows similar steps as described in the former subsection:

- First, an initial set of random solutions is generated. Each individual solution corresponds to a vector for each target indicating the time windows when each object is planned, selected randomly but avoiding overlap between targets, calibration observations and station keeping.
- Crossover, mutation and replacement GAs are applied as well to this initial set of solutions in order to generate the following generation of solutions.
- For each individual solution, the slew time is taken into account. Thus before each observation, the slew time of the telescope to go from the previous target to the following one is added. This can produce unfeasible observations if, for example, observations and slew times of one target overlaps with other targets or operations.
- A reparation mechanism of the solution is defined in this step. This reparation mechanism removes from the plan the target observation that has a conflicting overlap time slot. Then, it tries to place the removed observation in a valid slot in the plan, and if it cannot be placed without overlapping, the target observation is not planned.
- The objective functions evaluated for each individual solution are based in the planning efficiency and the scientific return. Both the total time devoted to target observations and the total number of completed targets is optimized, thus maximizing the number of surveyed targets and minimizing slew and idle time. Optimized solutions are used to generate subsequent generations of solutions.
- The best solution of the last generation of individual solutions represents the best LTMP at this step.
4.2.5 Re-schedule time of uncompleted targets (Step 4)

The LTMP obtained in the previous step can include targets with a number of re-visits smaller than the requested observations given in the target list. In order to increase the efficiency of the survey, this targets can be removed from the mission plan and the time used for further observations.

Therefore, this phase of the scheduling is devoted to fill the gaps of waiting time that remain between the observations in the LTMP obtained after dropping uncompleted targets. It tries to plan as many new target events as possible distributing them between all the remaining targets in the LTMP. It must be emphasized that if this process is not applied, calibrations and station keeping could be planned in this step to fill these gaps.

After this final step, a final LTMP is suggested. It includes only completed exoplanet targets, and calibrations and station keeping operations without overlapping between them. The survey optimization functions are then recomputed to be used as indicators of the survey efficiency.

4.3 SCHEDULING RESULTS: PLANNING OF THE MISSION REFERENCE TARGETS

For the present exercise, we have obtained the results of the LT-MPT assuming the three different samples in [RD1] (January 2017). First of all, we have studied the total time required to make sure that all the highest priority targets (459 planets) are observed and in order to understand which are the most restrictive planets and how much time is left available to observe other planets. Then, we have included in the list all the planets, and scheduled them according to their priority. For each target we include in the planning the number of required events (either transit or occultation) for each tier, and the LT(MPT) does only schedule the number of observations to complete each tier.

The optimization functions evaluated are the number of completed targets and the telescope working time, but the fraction of working time spent on slewing, and calibrations and station keeping operations is as well indicated in the results. We evaluate the efficiency of the survey for different mission lifetimes, assuming a baseline concept mission of 4 years. In all cases, commissioning time is set to 6 months. During this time no observations are planned, thus, it is not taken into account in the results (leaving 42 months of science operations). All ratios in forthcoming tables are given as a function of the available time for science observations (lifetime − 6 months, unless otherwise indicated). The genetic algorithms used in the LT-MPT obtain an optimized solution starting from possible random solutions. For this reason a total of 25 simulations have been performed and standard deviations are given as uncertainties in tables when significant.

4.3.1 Scheduling high-priority targets and early science results

In this section we have included in the survey only the 459 targets with the highest priority. To complete this subsample, a total of 2207 events lasting about 17000h need to be obtained. Table 2 shows that all priority targets can be observed in 4 years using about 60% of the mission lifetime and observing 2117±18 events. Therefore, 459 planets are observed in the survey mode (Tier 1), from which 207±1 reach Tier 2 (Deep Survey) requirements, and from this 64 targets reach Tier 3 (Benchmark Planets). The most restrictive planetary systems are those with a large number of requested observations, long periods and with limited visibility along a year. In particular, this is the case of a cold-Jupiter for which more events than actually visible are required to reach Tier 3, a warm Jupiter with a long period, and few Tier 2 sub-Neptune like planets for which the criticality is below 0.4 (i.e. more than 60% of observable events need to be scheduled) and hence, they are only completed up to Tier 1.

In any case, assuming a 4 years mission lifetime, there is about 40% of waiting time that can be used to add further observations of lower priority targets.

In this simulation, we have checked as well how much time would be required to complete Benchmark planet targets; high-priority planetary systems for which early science results can be obtained. Tier 3 survey includes 66 planets that need between 1 and 45 observations. For the scheduling purpose this is equivalent to a sample of 66 targets with the number of requested observations equivalent to the addition of Tier 1, Tier 2 and Tier 3, adding up to 730 events (66 to complete Tier 1 survey and 179 to reach Tier 2, and 485 to reach Tier 3 level of SNR) and about 5000 hours of observations.
Our results show that this subsample could be almost completed in 2 years. Actually, more than half of the targets can be observed up to Tier 1 and 2 during the first 6 months of the survey (we remind that observations during the 6 months of commissioning phase are not considered), and most of them (60 planets) are completed during the first 1.5 years, using about 30% of the available time. Only 4 planets demanding more than 45 events and 2 planets with limited visibility require few more observations in subsequent years. This suggests that the mission planning can be optimized to have interesting results available even during the first year of the mission. This minimizes the risks of non-achievement of key science goals.

4.3.2 Scheduling the MRS

Given that high-priority targets does only need about 60% of the mission lifetime, we have added to the LT-MPT all the planets in the Mission Reference Sample with their corresponding priority as a weighing factor to choose some targets among the others. The whole sample comprises 3716 observations for about 1102 targets. Between 1 and 45 observations are required for each target (depending on the planet type and tier). A total of 1352 are needed to achieve Tier 1 requirements for all targets, 1879 observations would be needed to reach Tier 2 for 480 targets, and 485 additional events would be needed to reach Tier 3 for 66 planets. This means a total of about 31250 hours, slightly more than the available time during 4 years (excluding commissioning).

Table 3 shows that, although not all the targets in the sample can be planned in a 4 years mission lifetime, a large fraction of them can be scheduled. About 87% of the systems (953±6 planets) can be surveyed adding up to 2781±22 events observed. From this, 375±4 64 targets are completed up to Tier 2 requirements, and from this 64 reach Tier 3, including the priority targets discussed above. Thus, it would be possible to complete about 80% of Deep survey and Benchmark planets in the MRS to the full goal of resolution. If we look into the evolution of the observations within mission lifetime, about 660 targets are observed in the survey mode (Tier 1) during the first 1.5 years of observations and from this, higher resolution (Tier 2 and Tier 3) is completed for about 200 planets. This proves that there would be a large fraction of planets surveyed during the first years of the mission with low-resolution, for which additional observations can be scheduled if they turn out to be interesting systems.

About 13% of the targets do not get the number of required observations to reach the desired SNR and R for Tier 1 and therefore they are not included (at all) in the schedule. One of these targets require more observations than can be carried out in 4 years due to visibility limitations (being near the ecliptic),
and the others, correspond to Neptune- and Earth-like planets with large periods and long monitoring times. As explained in the former section, this makes these targets particularly difficult to plan avoiding overlaps, but their priority can be increased to make sure they are planned if they are interesting cases.

<table>
<thead>
<tr>
<th>Mission lifetime period (years from launch)</th>
<th>Planned targets</th>
<th>Working time</th>
<th>Waiting time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>On targets</td>
<td>Slewing</td>
</tr>
<tr>
<td>0.5 – 1.0</td>
<td>31.0±0.7%</td>
<td>71.83±0.73%</td>
<td>3.91±0.10%</td>
</tr>
<tr>
<td></td>
<td>(3146±32 h)</td>
<td>(171±4 h)</td>
<td>(235 h)</td>
</tr>
<tr>
<td>0.5 – 2.0</td>
<td>59.8±1.0%</td>
<td>69.62±0.44%</td>
<td>3.83±0.05%</td>
</tr>
<tr>
<td></td>
<td>(9148±58 h)</td>
<td>(503±7 h)</td>
<td>(711 h)</td>
</tr>
<tr>
<td>0.5 – 3.0</td>
<td>75.8±0.6%</td>
<td>67.72±0.37%</td>
<td>3.59±0.03%</td>
</tr>
<tr>
<td></td>
<td>(14830±81 h)</td>
<td>(786±7 h)</td>
<td>(1196 h)</td>
</tr>
<tr>
<td>0.5 – 4.0</td>
<td>86.6±0.6%</td>
<td>64.66±0.45%</td>
<td>3.23±0.04%</td>
</tr>
<tr>
<td></td>
<td>(19825±137 h)</td>
<td>(990±11 h)</td>
<td>(1669 h)</td>
</tr>
</tbody>
</table>

Table 3. Scheduling results for the ARIEL MRS. Ratios given as a function of available time (not including commissioning phase). Uncertainties correspond to the standard deviation of 25 simulations.

In Table 4 the number of planets that are included in the LTMP distributed according to their type and the total number of systems in the sample are shown. Again, as in the former cases, the most difficult targets are warm and cold with long periods or a large number of required observations. However, this does not mean that it is not possible to survey this kind of systems during the mission lifetime, but that their number cannot be large.

<table>
<thead>
<tr>
<th>Planet type</th>
<th>Very Hot</th>
<th>Hot</th>
<th>Warm</th>
<th>Cold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jupiter</td>
<td>170.6±0.4</td>
<td>369.7±2.3</td>
<td>94.3±5.3</td>
<td>6.5±1.6</td>
</tr>
<tr>
<td></td>
<td>171</td>
<td>381</td>
<td>178</td>
<td>22</td>
</tr>
<tr>
<td>Neptune</td>
<td>-</td>
<td>22.2±1.8</td>
<td>8.6±1.4</td>
<td>0.5±0.5</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>24</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>Sub-Neptune</td>
<td>12</td>
<td>145.4±2.5</td>
<td>49.6±3.0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>152</td>
<td>71</td>
<td>-</td>
</tr>
<tr>
<td>Super-Earth</td>
<td>15</td>
<td>49.7±1.2</td>
<td>8.4±1.6</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>52</td>
<td>13</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4. Number of exoplanets included in the LTMP. Planet types correspond to the definition given in [RD1]. The number of exoplanets is the mean value of 25 simulations of the mission plan and their uncertainties are computed as their standard deviations. Figures without uncertainties indicate that all the systems of the corresponding type are always included in the LTMP. Figures in bold indicate the number of planets in the Mission Reference Sample.

Finally, there is about 27% of waiting time between observations even though the larger number of events planned. This fraction of time is mainly due to the difficulty in planning all the events of demanding exoplanet systems without overlapping with other targets. Besides, we remind here that in this exercise we do only plan the observations required for each tier; therefore, any additional observation of completed targets that can be planned without interfering other non-completed targets, are removed from the schedule.
4.3.3 Scheduling the MRS and additional observations

As mentioned above, a fraction of the available time can still be used to monitor planetary events although no more targets could be completed up to Tier 1. Again, we stress that in the former simulations, we have removed from the plan targets for which the required number of observations of a given tier was not completed during the mission lifetime. These intervals of time are then used to complete other targets, but if this is not possible they are set free.

In this section, we analyse how much of these released time can be used for exoplanets by allowing more observations of completed targets in each tier (i.e. we allowed the scheduling of more than 100% of the requested observations). Table 5 shows the results when scheduling the whole sample of exoplanets as in Section 4.3.2 but filling idle periods to plan additional observations. In this case, about 83% of the time would be used for exoplanet science (~74% of time observing transit or occultation events, excluding slewing and calibrations). About 570 additional planetary events can be followed-up, adding more 2800 hours of exposure time. This shows that it would be easy to include more targets requiring only few observations, if a larger sample of planets is available than is assumed from the current conservative analysis, or repeat observations of already completed targets if desirable to increase the SNR achieved above the minimum requirement.

<table>
<thead>
<tr>
<th>Mission lifetime period (years from launch)</th>
<th>Planned targets</th>
<th>Working time</th>
<th>Waiting time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>On targets</td>
<td>Slewing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>73.85±0.21%</td>
<td>3.91±0.04%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(22640±65 h)</td>
<td>(1199±11 h)</td>
</tr>
</tbody>
</table>

Table 5. Scheduling results for the ARIEL MRS allowing more observations than required. Ratios given as a function of available time (not including commissioning phase). Uncertainties correspond to the standard deviation of 25 simulations.

Finally, there is 16.8% of waiting time even though the larger number of events planned, that can be filled with additional observations of exoplanet targets or complementary science, which would increase the fraction of mission lifetime devoted to science to about 91% of the time. We will analyse the possible use of these gaps in the following section.

4.4 IMPACT OF SCHEDULING CONSTRAINTS INTO THE LONG-TERM MISSION PLAN

In the scheduling exercises presented in the previous section we have planned observations of targets, and calibration and house keeping operations. In this section we analyse the planning of downlink operations during target observations, and also the distribution of gaps and the possibility to perform further observations in this gaps. We also analyse the impact of increasing or decreasing the duration of the observation of targets.

4.4.1 Distribution of observations and downlinks

Since downlinks can be done simultaneous to observations, we analyse here what are the typical duration and separation of consecutive observations. Figure 2 shows the distribution of the duration of target observations for the simulation described in section 4.3.2 that only includes the number of observations required to complete each target. The average duration of the observations is 7.1 hours and about 95% of them are longer than 4 hours. Therefore, there are plenty of opportunities to schedule downlink operations during these long observations. Actually, the mean separation between observations longer than 4 hours is about 10 hours, being the maximum distance about 2 days.

Figure 3 show the same results when waiting time in the former simulations is used to schedule further observations of available targets (simulations described in section 4.3.3). As expected, in this case observations have a lightly shorter mean duration of 6.7 hours, but still about 90% of them are longer than 4 hours. The lower average is a consequence of filling the short gaps of waiting time between observations. Nevertheless, there is an observation longer than 4 hours every 10 hours as well.
From this analysis, we conclude that downlink operations could be easily planned during long observations fulfilling the requirement of about 14 hours of downlink periods distributed in a week (excluding weekends).

Just for comparison, we have run the LT-MPT assuming downlink operations cannot be done simultaneously to observations; thus, we have fixed slots of 4 hours duration every 2 days. The result shows that in a 4 years mission lifetime, about 2500 hours would be exclusively devoted to downlinks, loosing about 60 completed targets in the survey.

4.4.2 Distribution of waiting time and additional observations

As the simulations in Section 4.3 indicate, there is still a fraction of time available for other science observations and/or satellite operation tasks. This is because the exoplanet events observed are time constrained and also because, for a significant fraction of targets, we need to obtain several observations, which may overlap with the observation of other targets. Our goal in the subsection is to analyse what are the characteristics of idle periods between observations due to these constraints.
In our first set of simulations (in Section 4.3.2) we have assumed that any target that cannot be completed during the survey is not planned and the time is left free for other available targets or operations. In this case, about 27% of the mission lifetime corresponds to periods of waiting time between observations, but we remind here that in this case we do not schedule more than 100% of the requested observations. Figure 4 shows the normalized and cumulative distributions of available gaps as a function of their duration. Most of the gaps have durations of few hours, 50% of them are shorter than 80 minutes, and they are separated by about 8 hours on average. This indicates the high efficiency of the LT-MPT at including observations whenever an exoplanet transit can be fitted in the schedule, and therefore, most of the time lost is distributed in short periods between transits. Only few gaps longer than 6 hours are available, because targets not completed have been discarded and their time slot is not enough to complete other targets. However, some of these gaps can be used to schedule additional observations of exoplanet transit and occultations or to perform additional calibration observations or other satellite operations.

Actually, the simulations described in Section 4.3.3 prove this point. When the LT-MPT allows including in the mission plan more observations than strictly required for each target, it is possible to reduce the waiting time to 16.8% of the total mission lifetime, using about 3000 hours for additional exoplanet observations. This means that the LT-MPT has some flexibility to re-schedule the mission plan according to previous observations or to increase the SNR of some interesting targets. As Figure 5 shows the waiting time still available is mainly distributed in short period gaps lasting less than 6.5 hours. Actually, 77% of the gaps last less than 2 hours, which is about the duration of the shortest planetary events in the mission reference sample. These short gaps cannot be used to plan additional transits or occultations, but they can be used to extend the monitoring of their adjacent planetary events (giving a more accurate determination of the transit depth and hence increase somewhat the SNR achieved). This would add about 2000 hours to the ARIEL survey, increasing the total time used for exoplanets and reducing the waiting time to about 10%, distributed in gaps between 2 and 6.5 hours.

![Figure 4. Left: normalized distribution of gaps duration in hours for simulations described in Section 4.3.2, where only the exact number of required observations for each target is scheduled. Right: absolute cumulative distribution of gaps duration in hours. Error bars show the maximum and minimum range of the 25 simulations used.](image-url)
4.4.3 Impact of the duration of observations

In this ARIEL mission scheduling exercise, we have assumed that the total time during which a transit or occultation event is observed is given by 2.5 times the transit duration \(2.5 \cdot T_{14}\). However, in order to increase the precision of the transit depth measurements or to better correct stellar variability effects (than the minimum requirement), a longer observation duration may be desirable.

As a first test of the impact of this parameter on scheduling, we have proceeded to run the LT-MPT, assuming 4 years mission lifetime, as in the case described in Section 4.3.3, with different observation durations. In Table 6 we compare the results for different values: 2, 2.5, and 3 times \(T_{14}\). Reducing the event monitoring time increases the number of completed targets, and the number of events observed, but results in longer gaps of waiting time between observations. On the other hand, increasing the observation duration, reduces the number of events surveyed and therefore the number of planned targets by about 8%, and increases the length of gaps between observations. As a conclusion, the choice of 2.5\( \cdot T_{14}\) is the best one leaving less idle time between observations. Nevertheless, if needed, larger monitoring times can be set for some specific targets with little impact on the efficiency of the survey by using the gaps between observations as shown in the previous section. However, all of these analyses assume that the out of transit time is equal before and after the transit event. If some flexibility is assumed (i.e. observation of 0.5\( \cdot T_{14}\) before the event plus observation of 1.5\( \cdot T_{14}\) after, giving a total observation time of 3\( \cdot T_{14}\)) then the optimization will likely become much easier – this will be studied in a future phase of this work.

<table>
<thead>
<tr>
<th>Observation duration</th>
<th>Planned targets</th>
<th>Working time</th>
<th>Waiting time</th>
</tr>
</thead>
<tbody>
<tr>
<td>2( \cdot T_{14})</td>
<td>91.5\pm0.6%</td>
<td>69.06\pm0.20% (21175\pm62 \text{ h})</td>
<td>4.51\pm0.03% (1381\pm10 \text{ h})</td>
</tr>
<tr>
<td>2.5( \cdot T_{14})</td>
<td>86.7\pm0.5%</td>
<td>73.85\pm0.21% (22640\pm65 \text{ h})</td>
<td>3.91\pm0.04% (1199\pm11 \text{ h})</td>
</tr>
<tr>
<td>3( \cdot T_{14})</td>
<td>79.1\pm0.7%</td>
<td>71.91\pm0.2% (22047\pm65 \text{ h})</td>
<td>3.26\pm0.02% (998\pm6 \text{ h})</td>
</tr>
</tbody>
</table>

Table 6. Scheduling results for the ARIEL MRS assuming 4 years mission lifetime and different duration of observations. Ratios given as a function of available time (not including commissioning phase).
5 MISSION PLANNING USING THE CNES METHOD

We have carried out another independent mission planning exercise with the CNES (Centre National d’Études Spatiales, France) in order to confirm that the mission is feasible and the desired observations can be scheduled. Being entirely independent, some of the assumptions are slightly different and the methods and philosophy are different. As we will see later, we reach very similar conclusions. We will refer to the method described above in section 4 as the Artificial intelligence, or AI method.

This method is an adaptation of the ones used previously to prepare the EChO mission and published in Morales et al. (2015). It schedules the observations in a sequential manner based on a system of priorities. Different priority schemes were used to produce the observing planning of the complete mission. Note that the work reported here was “evolutive”, in the sense that different mission plans were produced (1) while the planning tool was being adapted, and (2) gaining experience with the tool. Thus, for instance, the first runs did not include calibration observations, which were added later on, or used a fixed slew time, before implementing one depending on the angular distance. We will concentrate here on the results obtained with the most evolved version of the tool, but some runs performed with simpler versions are used to study specific effects.

One of the critical issues of this exercise is that since the observations have to be carried out at specific times (around the occultations or the transits) and the duration of the observations are fixed by the duration of the event (some factor times that duration, in order to obtain proper data on the target before and after the event), the plan will inevitably result in some periods of “waiting” of variable length between observations. One of the purposes of this study is to characterise these inactivity periods and to fill them in with observations insofar as possible.

The starting point is the ARIEL MRS described in Section 3.2 and [RD1]. An early version of the MRS was used for determining the preferred scheduling options, then this method was used with the final (for new) version. For any given target, there can be both transit and occultation observations requested, though for many there is only one or the other. In addition to building an observation plan and determining the overall efficiency of the mission, we will also use the plan to characterise the fraction of time spent slewing, performing calibration observations, or performing other housekeeping tasks.

5.1 SEQUENCES

From the MRS we produced a (ascii) list of “sequences”, one per target, with the information needed for planning, namely

- a sequence number,
- the target names and coordinates,
- the K-band magnitude,
- the orbital period
- the reference times for the transits and the occultations
- the number of transit and occultation observations required for each of the three Tiers,
- a code to indicate whether a calibration check should be performed before and/or after the target observations,
- a priority (e.g., depending for each Tier).

In the sequence list, the number of Survey, Deep, and Benchmark observations are interpreted to be cumulative, in the sense that the observation(s) indicated for the Survey will also count towards the Deep and the Benchmark if they exist. Take the example of HAT-P-11b for which 1, 3, and 6 transit observations are required for Survey, Deep, and Benchmark, respectively, for a total of 10 observations. That source will contribute to the Survey set once the first observation is done, to the Deep set once the 4th observation is done, and to the Benchmark set once the 10th observation is done.

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6 Morales, J.C., et al., "Scheduling the EChO survey with known exoplanets", Experimental Astronomy 40, 655
Note that while in the previous chapter it was assumed that Survey, Deep, and Benchmark observations were assumed done in low, medium, and high (spectral) resolution mode, respectively, here we assume the observing mode will be determined only by the brightness of the target, so that each target will always be observed at the same resolution, and then the data from the different observations can be combined and binned, if necessary, during the ground processing. The sequence list was then transmitted to the CNES group that proceeded to the scheduling exercise proper.

5.2 CONSTRAINTS

The same constraints were used as in the previous section with some minor differences that we describe here. The spacecraft was assumed to be at the location of the Earth (rather than in orbit around L2), with an allowed wobbling angle of ±25° from the normal to the ecliptic plane. The mission of duration 3.5 years was assumed to start on 01.Jan.2027, slews are assumed done at a rate of 5°/min (rather than 4.5°/min in the previous section) and an extra 5 min of settling time is included (to account for acceleration/deceleration and for thermal stabilisation) each after each slew. Calibration observations were included as in the previous chapter, and also the station keeping periods. (We remark that these are assumed to be very conservative: for instance, for Planck there was one "orbit maintenance" manoeuvre every 70 days, on average, and they typically lasted 1–2 hrs.)

Downlink periods, on the other hand, were not explicitly scheduled, as it was understood that the transmission could take place during data acquisition but not during slews. In practice, it is expected that downlink/uplink would be interrupted during a slew, and restarted once the satellite finished its manoeuvres.

5.3 COMPARING THE RESULTS

Different plans can be produced with different methods; the criteria on which different plans will be judged are:

- **G1.** The planning should maximise the fraction of available time spent on targets, i.e., the observing efficiency.
- **G2.** The Benchmark observations should be considered of the highest priority, and thus they should all be performed.
- **G3.** The Survey observations should be considered as second priority, and at least 500 of them should be performed. Furthermore, they should be observed early in the mission (i.e., the first year or the first 18 months) in order to use the results to select source for the Deep. These "early" results will also be made available to the community in order to get feedback on the target selection.

There is no specific objective set on the Deep observations. In the course of this exercise will also estimate the fraction of time spent slewing and settling, on performing calibration observations, and more.

5.4 VISIBILITY AND PRIORITISING

The first part of the exercise consists in determining when an event (transit or occultation) occurs and is visible, and in prioritising the sources. First, windows of visibility for each target were computed given the location of the spacecraft in its orbit and the position of the target on the sky. An example for the first 20 targets in the sequence list is shown in Figure 6.
Figure 6. Visibility of the first 20 planets computed as a function of the spacecraft orbit.

Given the ARIEL orbit, any given point of the sky is visible for some period of time that depends on its ecliptic latitude during a 6-months period. Hence the 6-month cycle in the visibility, and source no. 12, which is close to one of the poles, is visible all the time.

Next, a “flexibility factor” $F = 1 - (N_{req}/N_{pos})$, where $N_{req}$ is the number of observations requested and $N_{pos}$ is the number possible given the visibility of the target, is assigned to each target. With this definition, a source with high $F$ will be simple to schedule, while those with low $F$ will be difficult, and could be given higher priority. Note that negative $F$’s are possible, namely for targets with long periods (there are some targets with periods of $\sim 70$ d) and needing many observations. Such targets will be discarded.

The Flexibility factor alone turns out to be a weak discriminant: any target is visible during a certain block of time of, typically, a duration of a few months, every six months. Given the short orbital periods of most targets, each block is usually sufficiently long to perform several observations, and thus only targets with long periods and requiring many observations (namely some of the ones in Deep) risk to have a low $F$. Thus this flexibility factor tends to separate the Survey only targets from the Deep and Benchmark ones. Also, nearly all Survey targets have $F$ above 0.95, so that in practice $F$ provides little discrimination. Figure 7 shows the Flexibility factor for all targets, showing that only two are indeed negative.
5.5 SCHEDULING

The scheduling exercise consists of adding sequences to the observing plan based on a set of criteria. When building the observing plan, we schedule all the observations of a sequence for one target in a given Tier. Then move to the next target. We note that an alternative approach (that we did not follow here) could have been to schedule sequentially individual observations, rather than full sequences, according to a set of priorities on the targets themselves and on the slew times. A sequence will be deemed "incomplete" if all the requested observations cannot be scheduled. This becomes more and more of a constraint as more and more sequences are scheduled and the observing plan becomes filled. If it is a multiple Tier sequence, then only the observations of the Tier(s) that can be completed will be added to the schedule. If it is a single Tier sequence, i.e., Survey only, then it will not be scheduled at all.

The scheduling is done in a sequential manner, so that different criteria can be used to determine which target is scheduled next. We tested the following set of criteria in different realization of the scheduling exercise:

- C1. The next target is the one with the lowest Flexibility factor: as described above this will schedule Deep and Bench observations first, and Survey only ones last.
- C2. The next target is the one with the highest Flexibility factor: this will schedule Survey targets first, including those that are part of Deep and Bench sequences, followed by the remainder of the Deep and Bench observations.
- C3. The next target is the visible one closest on the sky to the current one: the goal here is to minimise the slew time over the full mission.
- C4. Schedule first all the Benchmark, then as many as possible Deep, and finally as many as
possible Survey. In each Tier use either increasing or decreasing flexibility, so there are 8 possibilities here of which 6 were analysed.

- C5. As above for Bench and Deep, but for Survey the closest target in the sky is chosen, independent of its flexibility factor (so there are 4 possibilities here).
- C6. Schedule Bench first, then Survey only for the first (or 1.5 or 2) year, and continue with both Tiers 1 and 2 for the rest of the mission

Note that the first two criteria do not take into account the slew time, assuming that it will be a small fraction of the overall time used. These two criteria were used to determine the effect of the Flexibility factor.

The third criterion does attempt to minimise the slew time, but note that this can be done only for the first observation of each sequence, as the subsequent ones are placed into the observing plan where there is a sufficiently large block of time available. Their placement is thus constrained by the previously scheduled observations, and they will constrain the observations scheduled later.

Each criterion will produce an observing plan, and a section of a plan is shown graphically in the top panel of Figure 8 for a period covering about 50 hours of observing. In blue is the on-target time, in red the slews, in green the calibration observations, and in black the waiting times between observations. The target names are shown along the top, and below the names is the observation duration (decimal hours), while the dash vertical lines indicate the beginning and the end of the transit. Just above the green lines is the calibration star number, below that is the observation number, and finally the black lines along the bottom indicated the waiting periods, with their duration just below. These waiting times come as a result of having to perform the observations at specific times, and we will address in Sections 6.8 how to make use of them.

![Figure 8. Section of a plan showing 50 hours of the mission. Top and bottom are before and after assigning the blocks of waiting time to the pre-event observation of the next target; the latter is explained in 5.8.](image)

Each plan can be analysed in terms of the three criteria C1–C6 above. Table 7 summarises the main characteristics of several observing plans obtained with some of the criteria described above, where the
case number is indicated by the digit after the P in the RunID column. In all cases, all the Benchmark sequences are completed. The first three columns give: “N1 surv”, the number of Survey sequences completed during the first year, “N surv”, the total number of Survey sequences completed, and “N deep”, the total number of Deep sequences completed. The last four columns give, as a fraction of the total available time, the on-target observing time (observing efficiency), the time spent slewing, the time spent on calibration observations, and the waiting time.

Case C3 (minimization of slew time) is not shown for the reasons explained above, and the six cases of method C4 area also not listed as they were run in a simplified mode to test only the different prioritizations, but they produce total observing times that range from 69% to 73%, depending on the sense of the flexibility factor used in each Tier. The two worst cases are the ones where Tier 2, which globally requires the largest number of observations, was scheduled by decreasing Flexibility factor, while the other four are all close to 73% total efficiency. This goes in the sense that one would expect, namely that a higher efficiency is obtained by scheduling first the difficult observations (low Flex).

Case C6 is the one that produced the best overall results. While it became clear that the Benchmark sequences, if scheduled first, would always be completed during the first year of the mission, it then became a question of what priorities to give to the Survey and Deep observations in order to have about 500 Survey sequences completed early in the mission (goal G3). This can be done by maintaining the priority of the Survey observations high during the first 18 months.

<table>
<thead>
<tr>
<th>Run ID</th>
<th>N1 surv</th>
<th>N surv</th>
<th>N deep</th>
<th>obs.eff</th>
<th>slew</th>
<th>calib</th>
<th>waiting</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1a (slew 0)</td>
<td>431</td>
<td>438</td>
<td>238</td>
<td>76.4</td>
<td>0.1</td>
<td>4.2</td>
<td>19.3</td>
</tr>
<tr>
<td>P1b (slew 180)</td>
<td>400</td>
<td>407</td>
<td>206</td>
<td>70.6</td>
<td>7.2</td>
<td>4.2</td>
<td>18.0</td>
</tr>
<tr>
<td>P2 (slew real)</td>
<td>270</td>
<td>515</td>
<td>85</td>
<td>67.8</td>
<td>2.6</td>
<td>4.8</td>
<td>24.8</td>
</tr>
<tr>
<td>P5a (12mo)</td>
<td>411</td>
<td>422</td>
<td>218</td>
<td>72.7</td>
<td>4.5</td>
<td>4.0</td>
<td>18.8</td>
</tr>
<tr>
<td>P5b (15mo)</td>
<td>489</td>
<td>490</td>
<td>187</td>
<td>72.6</td>
<td>4.5</td>
<td>4.1</td>
<td>18.8</td>
</tr>
<tr>
<td>P5c (18mo)</td>
<td>544</td>
<td>544</td>
<td>145</td>
<td>72.3</td>
<td>4.5</td>
<td>4.2</td>
<td>19.0</td>
</tr>
<tr>
<td>P6a (12mo)</td>
<td>279</td>
<td>385</td>
<td>218</td>
<td>73.6</td>
<td>4.5</td>
<td>3.8</td>
<td>18.1</td>
</tr>
<tr>
<td>P6b (15mo)</td>
<td>282</td>
<td>471</td>
<td>187</td>
<td>74.4</td>
<td>4.5</td>
<td>3.7</td>
<td>17.4</td>
</tr>
<tr>
<td>P6c (18mo)</td>
<td>282</td>
<td>554</td>
<td>145</td>
<td>74.3</td>
<td>4.5</td>
<td>3.8</td>
<td>17.4</td>
</tr>
</tbody>
</table>

Table 7. Summary of the main characteristics of several observing plans.

Notes to Table 7:

- P1a,b: assume slews of 0° and 180° (these were in order to investigate the effect of the slew time before the physical slewing model was implemented; they can be considered as the best and worst cases).
- P2: implements a slew time proportional to the angular distance and method C3. This plan works well to minimise the slew time, but at the cost of moving to a target whose time of observation is not imminent. Thus the waiting time (waiting) turns out to be significantly larger than the slew time saved.
- P5a,b,c: uses method C5, with the Deep beginning after 1, 1.5, and 2 years after the beginning of the mission.
- P6a,b,c: uses method C6, with the Deep beginning after 1, 1.5, and 2 years after the beginning of the mission.

A full plan for the mission was prepared using C6. In addition to the target observations it includes also calibration observations and Housekeeping activities as defined above. In this last case, target observations occupy 74.4% of the mission time, calibrations occupy 3.7%, slews occupy 4.5%, and the remaining 17.4% is unscheduled at this time, waiting for the next event. We discuss this in more detail in the Section 6.7 below. In the other cases, the slew and calibration fractions are nearly identical, but the total observation time was somewhat lower and the waiting time slightly higher.
5.6 Preliminary Conclusions

The main conclusion at this time is that it is relatively simple to achieve observing efficiencies of 73–75% given the constraints imposed, and that slewing and settling will take ~ 4.5% of the time, while calibration observations will require somewhat less that 4%. This leaves ~17-19% of the time as unscheduled, waiting for the time of the transit or occultation of the next; more on this in the next section. These overall results are very similar to those obtained with the Artificial Intelligence method in the previous chapter.

5.7 The final plan using the updated MRS

The various plans presented in the previous sections were produced with a preliminary version of the MRS that was used to determine the preferred planning method (C6-18 months). Once the final MRS became available, a new plan was produced using that. The final MRS contains considerably more targets. Table 10 gives some properties of the two MRSs (remember that most of the targets are simulated in both cases, the number of real targets is given in parenthesis).

<table>
<thead>
<tr>
<th></th>
<th>Preliminary</th>
<th>Final</th>
</tr>
</thead>
<tbody>
<tr>
<td>Num. targets (real)</td>
<td>713 (164)</td>
<td>1102 (121)</td>
</tr>
<tr>
<td>Num. Deep</td>
<td>304</td>
<td>480</td>
</tr>
<tr>
<td>Num. Benchmark</td>
<td>61</td>
<td>66</td>
</tr>
</tbody>
</table>

Table 8. MRS characteristics.

From the Flex factor analysis, 12 targets (all simulated ones and mostly with periods longer than 100d) turn out to be unfeasible, which leaves 1090 targets to choose from. Of the 12, there is one Benchmark target, one Survey target, and 10 Deep targets.

A total of 2924 observations are scheduled. Of the 65 feasible Benchmark targets, three could not be completed, resulting in 62 targets completed (540 observations). Of the Deep, 379 targets are completed (including the Benchmark ones) using 1537 observations; and of the Survey, 472 targets are completed (including the Deep and the Benchmark) with 481 observations. This leaves 366 observations of Deep targets for which the sequences are incomplete. Also, 395 Survey observations are carried out during the first year, including 42 Benchmark (and thus also Deep) targets.

The overall statistics do not differ significantly from those obtained with the preliminary MRS:

- On-target, observing time: 76.3%,
- Calibration time: 3.4%
- Slew and settling time: 4.1%
- Waiting time: 16.2%

The smaller fraction of calibration time is the result of no longer performing short calibration observations immediately before and after observations of the Gliese and M stars (48 observations for the new MRS), which results in a slight increase in the observing efficiency and possibly a slight decrease in the slew & settling time. The slightly lower waiting time is probably a consequence of the ephemerides of the events to be observed. Note that Fig. 7 above was produced with the preliminary MRS.

5.8 The nature of the waiting time and how best to make use of it

The inaction time occurs because the observations have to be performed at specific times. Increasing the number of possible targets from which the scheduler can select and optimum set will decrease the inaction time, but one quickly runs into diminishing returns, as most targets require several observations.
Furthermore, the blocks of inaction time are mostly short, with 3650 shorter than 3 hr, 656 longer, and only 30 longer than 6 hr, the longest one being 9.1 hr. A histogram of the duration of the inaction time blocks is shown in the top-left panel of Figure 9, while the top-right panel shows the same data in cumulative form. In the lower panels we show the amount of time accumulated instead of the number of cases. Those figures demonstrate that the very numerous waiting periods of 15 min or less actually add up to very little time in total, and that about half of the waiting time is in the ~650 slots longer than ~3 hr.

![Histogram and cumulative histogram of inaction time blocks](image)

Figure 9. Top: Histogram (left) and cumulative histogram (right) of the duration of the inaction time blocks. Bottom: Histogram (left) and cumulative histogram (right) of the amount of total time accumulated in inaction time blocks (in hours).

How could these empty periods be used? Some possibilities are:

**P1.** One simple solution is that the target observations before and after the inaction time are lengthened by half the available time (or unequally, pondering then by the brightness of the target, or privileging the pre-event observations to give extra time for the system to settle). With this solution all of the inaction time becomes time spent on target, thus bringing the fraction of time spent on target to > 90%. This will add redundancy to improve the characterisation of the behaviour of the star (and the instrument).

**P2.** Slots longer than ~3 hr could be used to perform phase curves of a (small) set of selected targets: given an average slew of ~90°, two such slews (plus settling) would require ~ 45 min, leaving more than 2–3 hr for acquisition of one point along the phase curve. The longer ones could even be used to obtain two points on two different targets. One could thus envisage somewhere between 650 and 700 phase curve points in total, or some 30–35 phase points for some 20 targets. We realize, nevertheless, that we will have to check in practise if the required stability is reached by the satellite while flying, and will not incorporate it as a requirement for the mission.

**P3.** If necessary some of these could be used for additional calibration observations. Slots of ~ 2–3 hrs could easily be used for the short calibrations, while the few very long one could be used for the long ones.

By adopting a combination of P1 and P2, we see that most of the inaction time becomes time spent on target, adding redundancy to secure our monitoring of the activity of the star and the instrument, thus
reaching an overall observing efficiency of ~ 90% or higher. As an example, the bottom panel of Figure 8 shows the same section of the mission plan as in the top panel, but with the waiting times, which here are all shorter than 3 hours, used to lengthen the target observations, while the longer ones have been left in to be filled in later with other observations.
6 CONCLUSIONS AND FUTURE WORK

In this technical note we have presented Mission Planning Tools developed by the ICE-CSIC and the CNES for the ARIEL mission, and we have studied the scheduling of the observations defined in the Mission Reference Sample, which comprise a list of ~1100 targets requiring about ~4000 observations of a total of ~31000 hours of observing time. We summarize here our main conclusions given the results of both approaches:

- The results of both LT-MPT show that it is possible to survey more than 500 exoplanets in 4 years using ARIEL, including, ~300, and ~60, Tier 2, and Tier 3 planets, respectively. Although some planets are challenging (e.g. warm Neptunes, hot super-Earths), few of them are automatically included in the mission plan by the ICE-CSIC scheduler without assigning them any particular priority. However, our experience from previous projects (García-Piquer et al. 2015\textsuperscript{7}, 2017\textsuperscript{8}) indicates us that it may be possible to include more of these targets adding priority constraints to the scheduler, minimizing overlapping conflicts with other targets.

The CNES analysis actually shows that it is possible to use different sets of priorities in order to (1) ensure that nearly all Benchmark sources were observed, (2) that at least ~500 Survey targets were observed in the first 1.5 year, and (3) maximise the fraction of on-target time.

- Both approaches include observations of calibration targets, other slots for “Housekeeping” tasks, and time for slews. Overall, pushing the time devoted to exoplanet observations, slewing takes ~4% of the mission time, calibration and other Housekeeping tasks take ~4-5%, on-target is ~74-76%, and ~16% is initially unscheduled. This waiting time available in gaps can be used to extend the observations beyond nominal observation duration to minimise errors from stellar variability and instrumental systematics. It can be as well used for non-time constrained ancillary science, additional calibration observations or monitoring phase curves of few planets.

- The main issue is that since the observations have to be performed at specific times, there will always be a block of “unused” time between two observations. At first, after scheduling observations of duration 2.5 times the event (transit or eclipse) time to give adequate observations before and after the event, these unscheduled blocks comprise ~16% of the mission time. The vast majority of these blocks, however, are very short, and can be used to extend the pre- or post-event observations by minutes or up to about an hour. A few slots are large enough (several hours) to eventually slew to another source and do another observation, or possibly to be used for other technical activities. While an extra observation can easily be introduced for calibration targets, which can be observed at any time and of which there is always one nearby, this becomes more difficult for other exoplanet targets, which have to be observed at fixed times.

Following the ICE-CSIC LT-MPT, the distribution of gaps indicates that a large fraction of them are shorter than 2 hours, summing up ~2000 hours. This is confirmed by the CNES activity that gives broadly similar distribution of the gap lengths. Planning of additional targets is not possible due to the transit duration constraint; but they can be used to enlarge the total on-target time of each source. This would help to the characterization of the variability of the target. Therefore, if all waiting time available is used this way, the total time on targets would increase to about 91%, and ~9% of the time would be used for slewing, calibrations and house keeping operations.

Following the CNES results, if all the unscheduled blocks are used to extend the adjacent observations, the on-target time rises to ~92%, which is well above the requirement and very satisfactory.

\textsuperscript{7} García-Piquer, A. et al. "Artificial intelligence for the EChO mission planning tool", 2015, \textit{Experimental Astronomy} 40, 671

\textsuperscript{8} García-Piquer, A. et al. "Efficient scheduling of astronomical observations: Application to the CARMENES radial velocity survey", \textit{Astronomy & Astrophysics}, submitted
The observation duration of planetary transits or occultations (2, 2.5 or 3 times $T_{14}$) has a significant impact on the fraction of targets that are completed. We have shown here, that following-up planetary events during $2.5 \cdot T_{14}$ optimizes the total mission time spent on exoplanet targets. Future work will consider flexibility in the scheduling of this out-of-transit observation time around the transit, allowing observations not centred on the transit. This may help to optimize the size of gaps of waiting time between observations in order to schedule more events.

Summarising, these results of the scheduler based on Artificial Intelligence and the CNES algorithms are in agreement. They both demonstrate that the baseline mission and payload design satisfy (and even go beyond) the mission science requirements.