Exoplanet Characterisation Observatory (EChO)

Assessment Phase Payload Study

Additional Experiments of the EChO Long Term Mission Planning Tool

ECHO-TN-0002-ICE

Issue 01

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Date: 03/10/2013

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Date:

TABLE OF CONTENTS

Table of Contents iii
List of Figures iv
List of Tables v
1 Preamble vi
1.1 Scope vi
1.2 Purpose vi
1.3 Intellectual Property Rights vi
1.4 Acronyms and Definitions vi
1.5 Applicable Documents vi
1.6 Reference Documents vi
2 Experimental methodology 1
2.1 Algorithm Configuration 1
2.2 Comparison Metrics 1
3 Real Scenario Results 2
3.1 Test Bench Configuration 2
3.2 Analysis of the Experimentation Results 2
3.2.1 Observation of the Orbital Phase Curves of the Rosetta Stones 3
3.2.2 Working Time 3
3.2.3 Gap Analysis 3
3.2.4 Downlinks as Gap Fillers 5
3.2.5 Targets Completed 5
3.2.6 Computational Cost 6
4 Artificial Scenario Results 7
4.1 Test Bench Configuration 7
4.2 Analysis of the Experimentation Results 7
4.2.1 Observation of the Orbital Phase Curves of the Rosetta Stones 8
4.2.2 Working Time 8
4.2.3 Gap Analysis 8
4.2.4 Downlinks as Gap Fillers 10
4.2.5 Targets Completed 10
4.2.6 Computational Cost 12

LIST OF FIGURES

Figure 3.1 Number of gaps for each gap slot. 4

Figure 3.2. Overall duration in hours of the gaps of each gap slot. 4

Figure 3.3. Accumulated number of gaps for each gap slot. 4

Figure 3.4. Accumulated overall duration in hours of the gaps of each gap slot. 4

Figure 3.5. Targets completed by the LT-MPT at the end of each year according to their type (Chemical Census, Origins and Rosetta Stones) in one trial of the real scenario. 5

Figure 3.6. Complete and incomplete targets obtained by the LT-MPT at the end of the mission according to their type (Chemical Census, Origins and Rosetta Stones) in one trial of the real scenario. Each type is represented by a different symbol and green colour indicates a complete target and red colour and incomplete one. Targets are plotted according to their right ascension and declination. 6

Figure 4.1 Number of gaps for each gap slot. 9

Figure 4.2. Overall duration in hours of the gaps of each gap slot. 9

Figure 4.3. Accumulated number of gaps for each gap slot. 9

Figure 4.4. Accumulated overall duration in hours of the gaps of each gap slot. 9

Figure 4.5. Average of targets completed by the LT-MPT at the end of each year according to their type (Chemical Census, Origins and Rosetta Stones) in one trial of the 10 artificial scenarios. 10

Figure 4.6. Complete and incomplete targets obtained by the LT-MPT at the end of the mission according to their type (Chemical Census, Origins and Rosetta Stones) in one trial of the first four artificial scenarios. Each type is represented by a different symbol and green colour indicates a complete target and red colour and incomplete one. Targets are plotted according to their right ascension and declination. 11

LIST OF TABLES

Table 2.1. Parameter configuration of the LT-MPT. 1
Table 3.1. Results obtained in the real scenario (mean and deviation) with the LT-MPT after 25 trials. The deviation is expressed in the same units than the mean. 2
Table 3.2. Average time used, in the 25 trials of the real scenario, for observing orbital phase curves. 3
Table 3.3. Mission duration and working time of EChO in the real scenario. Each time is expressed in hours. 3
Table 3.4. Percentage of downlinks placed in the LTMP gaps with respect to the total downlinks. Each column shows a different flexibility in the downlink position. 5
Table 4.1. Results obtained in the artificial scenarios (mean and deviation) with the LT-MPT after 25 trials. The deviation is expressed in the same units than the mean. 8
Table 4.2. Average time used, in the 25 trials of the artificial scenarios, for observing orbital phase curves. 8
Table 4.3. Mission duration and average working time of EChO in the artificial scenario. Each time is expressed in hours. 8
Table 4.4. Percentage of downlinks placed in the LTMP gaps with respect to the total downlinks. Each column shows a different flexibility in the downlink position. 10

PREAMBLE

1.1 SCOPE

This document presents additional experiments done with the Long Term Mission Planning Tool (LT-MPT) for EChO based on Artificial Intelligence in the form of Genetic Algorithms.

1.2 PURPOSE

The purpose of this document is to prove the suitability of the proposed LT-MPT based on Genetic Algorithms and to demonstrate the feasibility of the EChO mission. Specifically, this document analyses the long term mission plans obtained with the real list of current exoplanets and with several artificial samples of hypothetical exoplanets discovered in 2022. The experimentation takes into account a nominal duration of the mission of 4 years with the real scenario and an extended duration of 6 years with the artificial scenarios.

1.3 INTELLECTUAL PROPERTY RIGHTS

1.4 ACRONYMS AND DEFINITIONS

AI	Artificial Intelligence
EChO	Exoplanet Characterisation Observatory
GA	Genetic Algorithm
ICE	Institut de Ciències de l'Espai (CSIC-IEEC)
LT-MPT	Long Term Mission Planning Tool
LTMP	Long Term Mission Plan
MRS	Mission Reference Sample
T14	Duration of the event of an exoplanet

1.5 APPLICABLE DOCUMENTS

AD #	APPLICABLE DOCUMENT TITLE	DOCUMENT ID	ISSUE / DATE
1			
2			
3			

1.6 REFERENCE DOCUMENTS

RD #	REFERENCE DOCUMENT TITLE	DOCUMENT ID	ISSUE / DATE
1	EChO Long Term Mission Planning Tool	ECHO-TN-0001-ICE	3 (13/09/13)
2			
3			

2 EXPERIMENTAL METHODOLOGY

This section presents the algorithm configuration and the metrics used for analysing the results obtained by the LT-MPT in each scenario. The reader is referred to [Section 4 of RD1] for more details about the LT-MPT and the constraints considered.

2.1 ALGORITHM CONFIGURATION

The LT-MPT configuration consists of planning the observations without considering downlinks, station keepings and calibrations, which will be placed in the gaps between observations.

In terms of parameterization, the LT-MPT is configured as Table 2.1 shows. For notation details see [Section 6 of RD1].

Parameter	Value
Generations	10000
N_I	250
N_P	1500
S	$0.4\cdot\overline{\overline{P}}$
p_c	0.9
p_μ	0.005
m	80
M	100

Table 2.1. Parameter configuration of the LT-MPT.

2.2 COMPARISON METRICS

Four metrics have been defined in order to evaluate and compare the performance of the obtained LTMPs in the aforementioned experiments. The first two metrics are related to time optimization:

- **Occultation and Transit Observation Time:** It is computed as the number of hours that EChO is doing scientific observations (i.e., observing targets). Slewing is not computed in this measure.
- **Slew Time:** It is calculated as the number of hours that EChO is doing slewing.

The other two metrics are related to the scientific return:

- **Events Planned:** It is the number of events observed by EChO.
- **Targets Completed:** It is calculated as the number of complete targets observed by EChO. Note that a complete target is a target observed at least 80% of its required number of events.

Each measure is presented with a mean and deviation because the LT-MPT is executed several times in order to guarantee that it is statistically robust. However, it must be emphasized that in a real situation it is only necessary to run it once for obtaining a LTMP.

3 REAL SCENARIO RESULTS

This section analyses the results obtained in the real scenario, which contains the current list of exoplanets that can be observed by EChO.

3.1 TEST BENCH CONFIGURATION

Some global assumptions for the problem constraints have to be specified when defining the test bench configuration:

- Tests will cover the nominal mission lifetime, which is 4 years. From these 4 years, the first 6 months are for commissioning, so the LT-MPT plans the observations in the remaining 3.5 years.
- In the 3.5 years, 24633 hours are available to be used for scientific observations.
- 192 targets to be observed and 4065 events. The distribution of the targets between Chemical Census, Origins and Rosetta Stones is detailed as follows:
    - 121 Chemical Census exoplanets (52 observed on transit and 69 observed on occultation) that result on 121 targets.
    - 26 Origin exoplanets (each one observed on transit and occultation) that result on 52 targets.
    - 11 Rosetta Stone exoplanets (8 observed on transit and occultation, 2 observed on transit and 1 on occultation) that result on 19 targets.
- 365 downlinks with a duration of 2 hours and a periodicity of 3.5 days are considered.
- 46 station keepings with a duration of 8 hours and a periodicity of 28 days are assumed.
- Two types of calibrations:
    - The first one with a duration of 1 hour each day.
    - The other one with a duration of 1 hour each 36 hours and 10 hours each 10 days.
- Slew time between observations of different targets was taken into account using a slew speed of 45 degrees per 10 minutes plus a flat 5-minute overhead.

3.2 ANALYSIS OF THE EXPERIMENTATION RESULTS

The results obtained in the real scenario are described in terms of the four defined metrics (observation time, slew time, events planned and targets completed). The mean and deviation values of each metric for the 25 trials are given. Note that the deviation is expressed in the same units than the mean. The Total Input Time is expressed in hours and it is referred to the total observation time that the scenario requires to be fully completed.

Table 3.1 shows that the LT-MPT is able to complete the observation, in 3.5 years, of around 190 targets from the 192 required and to observe almost all the events.

Scenario	Total Input Time	Events Required	Occultation and Transit Observation Time		Slew Time		Events Planned		Targets Completed	
Real_sample	22241.60	4065	19730.77	±101.93	1492.99	±11.85	3770.00	±18.07	190.40	±0.52

Table 3.1. Results obtained in the real scenario (mean and deviation) with the LT-MPT after 25 trials. The deviation is expressed in the same units than the mean.

3.2.1 Observation of the Orbital Phase Curves of the Rosetta Stones

EChO has to be able to put the orbital phase curves of the rosetta stones by filling the gaps with them. Due to the fact that it is difficult to find gaps with the size of the full curves, they are divided into smaller parts and each of those parts is placed within a gap (for more details see [Section 7 of RD1]). Table 3.2 shows the number of hours (an average value for the 25 trials) related to orbital phase curve observations that can be filled in the gaps between observations.

Scenario	Orbital Phase Curve Observation Time
Real_sample	797.45

Table 3.2. Average time used, in the 25 trials of the real scenario, for observing orbital phase curves.

3.2.2 Working Time

The duration of the 3.5 years of the mission is 30660 hours and the overall time that EChO will be working (observations, slews, downlinks, station keepings and calibrations) is detailed in Table 3.3, and it is around 25000 hours. Thus, near 6000 hours will be free in the mission for doing other tasks.

Scenario	Mission Duration	Occultation and Transit Observation Time	Orbital Phase Curve Observation Time	Slew Time	Downlink and Station Keeping Time	Calibration Time 1	Calibration Time 2	Working Time with Calibration 1	Working Time with Calibration 2
Real_sample	30660	19730.77	797.45	1492.99	1095	1278	2129	**24394.21**	**25245.21**

Table 3.3. Mission duration and working time of EChO in the real scenario. Each time is expressed in hours.

3.2.3 Gap Analysis

The addition of the Occultation and Transit Observation Time and the Slew Time is smaller than the mission duration, so several gaps between observations can be found along the mission, and they can be used for placing the observations of orbital phase curves, downlinks, station keepings and calibrations. Thus, an interesting aspect to analyse is the number of gaps between observations and their duration. Figure 3.1 shows the number of gaps for several gap slots sizes in minutes for the 3.5 years of the mission. It can be observed that there are a small number of gaps shorter than 10 minutes and longer than 300 minutes (5 hours). Figure 3.2 shows the overall duration of the gaps of each gap slot size for the 3.5 years of the mission. In the accumulated gap distribution shown in Figure 3.3 and Figure 3.4, it can be observed that there are around 3500 gaps longer than 10 minutes, and consequently there are around 9000 hours of gaps with considerable size. Therefore, it can be concluded that the gaps can be filled with the operation tasks.

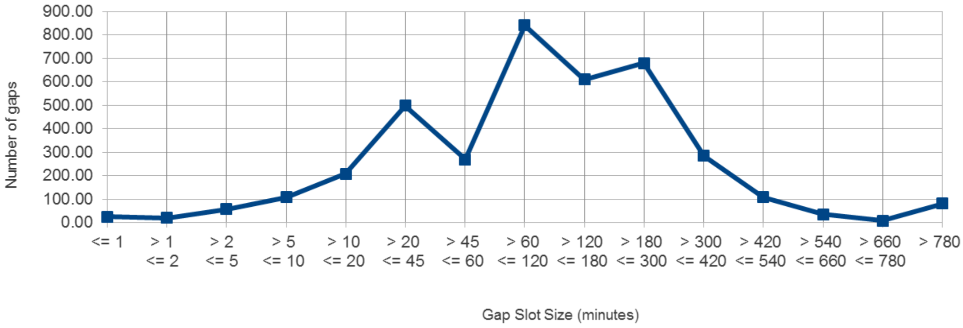

Figure 3.1 Number of gaps for each gap slot.

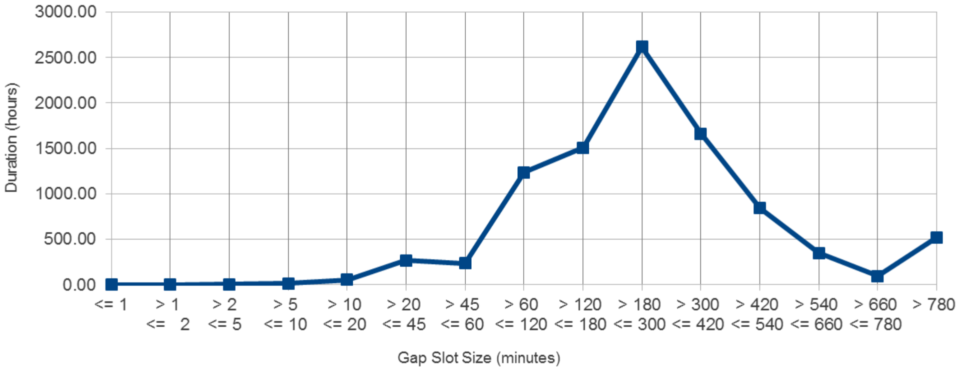

Figure 3.2. Overall duration in hours of the gaps of each gap slot.

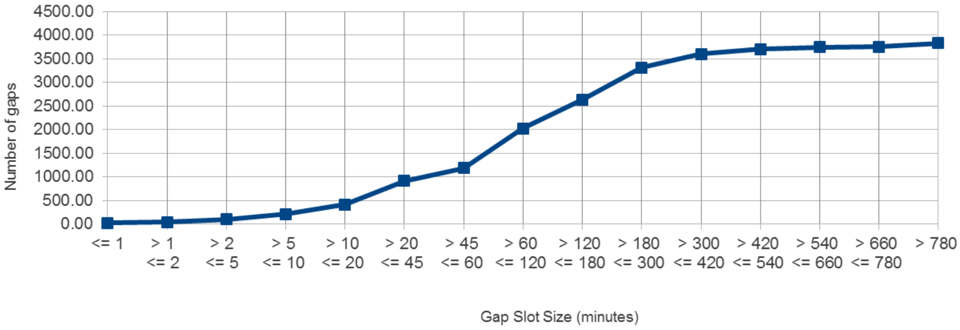

Figure 3.3. Accumulated number of gaps for each gap slot.

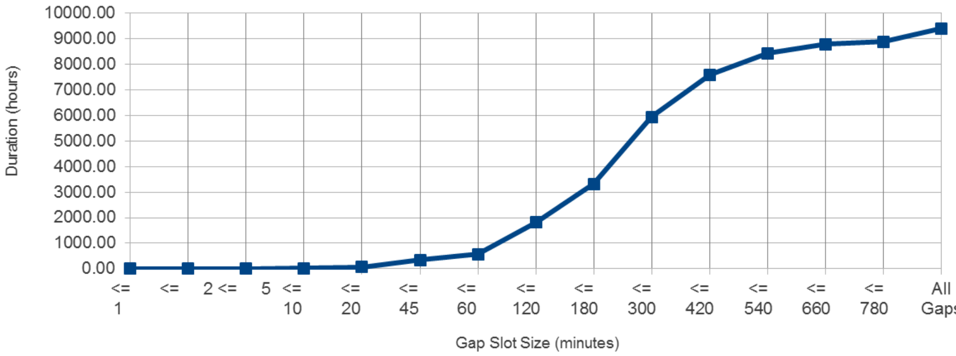

Figure 3.4. Accumulated overall duration in hours of the gaps of each gap slot.

3.2.4 Downlinks as Gap Fillers

One exercise for complementing the previous analysis is to test the feasibility of placing downlinks in the gaps between observations. In this experiment we want to test the feasibility of placing these operations with this strategy. For brevity, the experiment only considers the placement of downlinks, but the process is the same when station keepings and calibrations are considered. For details about this process see [Section 6 of RD1]

Table 3.4 summarizes the downlinks rate that can be placed according to several flexibilities (from 0% to 40%). It can be observed that more than 85% of the overall downlinks can be placed with 10% of flexibility (8 hours from the fixed time of each 3.5 days). Moreover, the number of downlinks allocated raises when the flexibility increases, being able to place almost all downlinks with a flexibility of 20%. The downlinks not allocated in this procedure will be inserted by replacing the observations in the same time interval.

Scenario	3.5days +/- 10%	3.5days +/- 20%	3.5days +/- 30%	3.5days +/- 40%
Real_sample	85.82	96.87	99.44	99.82

Table 3.4. Percentage of downlinks placed in the LTMP gaps with respect to the total downlinks. Each column shows a different flexibility in the downlink position.

3.2.5 Targets Completed

At the end of the mission almost all the targets have been completed (see Table 3.1), but an interesting analysis from a scientific point of view is to test how many targets are completed at the end of each one of the four years of the mission (considering that the first year has only available 6 months) according to the type of targets (Chemical Census, Origins and Rosetta Stones). Figure 3.5 shows the number of targets completed at the end of each year according to each target type. It can be observed that in the last year of the mission, a high number of targets are completed. Moreover, we can see that the distribution of the target type in each year is similar.

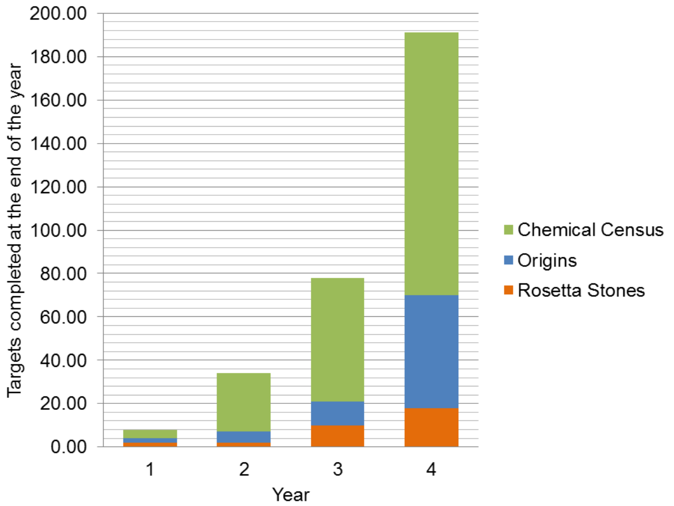

Figure 3.5. Targets completed by the LT-MPT at the end of each year according to their type (Chemical Census, Origins and Rosetta Stones) in one trial of the real scenario.

Figure 3.6 depicts the targets of one trial of the real scenario according to their right ascension and declination. Moreover, it shows the type of target and if its observation is completed at the end of the mission. Note that the incomplete target is referred to exoplanet Gliese 436b, it is a rosetta stone and requires the observation of 306 occultations. It is impossible to complete this target because in 3.5 years only 204 occultations are visible for EChO.

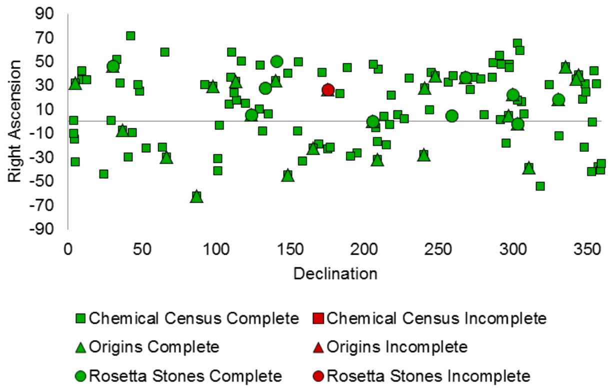

Figure 3.6. Complete and incomplete targets obtained by the LT-MPT at the end of the mission according to their type (Chemical Census, Origins and Rosetta Stones) in one trial of the real scenario. Each type is represented by a different symbol and green colour indicates a complete target and red colour and incomplete one. Targets are plotted according to their right ascension and declination.

3.2.6 Computational Cost

The algorithm has been executed in a CPU Intel® Core™2 Duo Processor E6600 2.40 GHz with 6GB of RAM, and the planning results of one trial are obtained in approximately 15 minutes.

4 ARTIFICIAL SCENARIO RESULTS

This section analyses the results obtained in the artificial scenarios, where each scenario contains a different sample realization based on the Mission Reference Sample. See [Section 6 RD1] for more details about how the artificial scenarios are built.

4.1 TEST BENCH CONFIGURATION

Some global assumptions for the problem constraints have to be specified when defining the test bench configuration:

- Tests will cover the extended mission lifetime, which is 6 years. From these six years, the first 6 months are for commissioning, so the LT-MPT plans the observations in the remaining 5.5 years.
- In the 5.5 years, 48180 hours are available to be used for scientific observations.
- 285 targets to be observed and around 8500 events. The distribution of the targets between Chemical Census, Origins and Rosetta Stones is detailed as follows:
    - 205 Chemical Census exoplanets (94 observed on transit and 111 observed on occultation) that result on 205 targets.
    - 33 Origin exoplanets (each one observed on transit and occultation) that result on 66 targets.
    - 10 Rosetta Stone exoplanets (4 observed on transit and occultation, 2 observed on transit and 4 on occultation) that result on 14 targets.
- 574 downlinks with a duration of 2 hours and a periodicity of 3.5 days are considered.
- 72 station keepings with a duration of 8 hours and a periodicity of 28 days are assumed.
- Two types of calibrations:
    - The first one with a duration of 1 hour each day.
    - The other one with a duration of 1 hour each 36 hours and 10 hours each 10 days.
- Slew time between observations of different targets was taken into account using a slew speed of 45 degrees per 10 minutes plus a flat 5-minute overhead.

4.2 ANALYSIS OF THE EXPERIMENTATION RESULTS

The results obtained in the artificial scenarios are described in terms of the four defined metrics (observation time, slew time, events planned and targets completed). The mean and deviation values of each metric for the 25 trials are given. Note that the deviation is expressed in the same units than the mean. The Total Input Time is expressed in hours and it is referred to the total observation time that the scenario requires to be fully completed.

Table 4.1 shows that, in 5.5 years, the LT-MPT is able to complete the observation of around 273 targets from the 285 required and to observe a high number of events.

Scenario	Total Input Time	Events Required	Occultation and Transit Observation Time		Slew Time		Events Planned		Targets Completed	
MRS_rand_0	37379.37	8407	31347.96	±230.00	2996.06	±16.54	7501.00	±16.82	273.40	±1.67
MRS_rand_1	37972.49	8408	31760.24	±136.62	3058.14	±16.20	7466.20	±13.74	273.40	±1.52
MRS_rand_2	37273.15	8463	31229.95	±96.73	2951.65	±17.31	7474.20	±39.67	271.60	±0.89
MRS_rand_3	38918.26	8918	31306.30	±102.65	3056.16	±15.10	7672.80	±14.86	268.60	±0.89
MRS_rand_4	37159.94	8331	30838.18	±199.22	2948.08	±14.54	7352.00	±40.56	273.20	±0.84
MRS_rand_5	35096.48	8382	31570.89	±87.23	3144.31	±19.13	7835.80	±25.77	278.00	±0.00
MRS_rand_6	35692.47	8198	30650.53	±134.90	3036.88	±16.77	7440.00	±11.07	275.60	±1.14
MRS_rand_7	36659.25	8114	31454.03	±115.93	2851.45	±11.45	7354.60	±13.22	276.20	±0.84
MRS_rand_8	37074.06	8463	31094.10	±127.91	2997.08	±21.49	7464.00	±38.15	276.20	±1.10
MRS_rand_9	37674.82	8479	29899.01	±158.19	2943.10	±27.22	7234.20	±16.62	268.40	±1.52
MRS_rand Average	37090.03	8416	31115.12	±138.94	2998.29	±17.58	7479.48	±23.05	273.46	±1.04

Table 4.1. Results obtained in the artificial scenarios (mean and deviation) with the LT-MPT after 25 trials. The deviation is expressed in the same units than the mean.

4.2.1 Observation of the Orbital Phase Curves of the Rosetta Stones

Table 4.2 shows the number of hours (an average value for the 25 trials) related to orbital phase curve observations that can be filled in the gaps between observations.

Name	Orbital Phase Curve Observation Time
MRS_rand_0	862.90
MRS_rand_1	855.84
MRS_rand_2	884.92
MRS_rand_3	934.24
MRS_rand_4	897.58
MRS_rand_5	887.34
MRS_rand_6	914.67
MRS_rand_7	866.88
MRS_rand_8	889.27
MRS_rand_9	916.54
MRS_rand Average	891.02

Table 4.2. Average time used, in the 25 trials of the artificial scenarios, for observing orbital phase curves.

4.2.2 Working Time

The duration of the 3.5 years of the mission is 48180 hours and the overall time that EChO will be working (observations, slews, downlinks, station keepings and calibrations) is detailed in Table 4.3, and it is around 39000 hours. Thus, near 9000 hours will be free in the mission for doing other tasks.

Name	Mission Duration	Occultation and Transit Observation Time	Orbital Phase Curve Observation Time	Slew Time	Downlink and Station Keeping Time	Calibration Time 1	Calibration Time 2	Working Time with Calibration 1	Working Time with Calibration 2
MRS_rand Average	48180	31115.12	891.02	2998.29	1721	2008	3346	**38733.43**	**40071.43**

Table 4.3. Mission duration and average working time of EChO in the artificial scenario. Each time is expressed in hours.

4.2.3 Gap Analysis

Figure 4.1 shows the number of gaps for several gap slots sizes in minutes for the 5.5 years of the mission. There are a small number of gaps shorter than 10 minutes and longer than 300 minutes (5 hours). Figure 4.2 shows the overall duration of the gaps of each gap slot size for the 5.5 years of the mission. In the accumulated gap distribution shown in Figure 4.3Figure 3.3 and Figure 4.4Figure 3.4, there are around 8000 gaps longer than 10 minutes, and consequently there are around 15000 hours of gaps with considerable size. Therefore, it can be concluded that the gaps can be filled with the operation tasks.

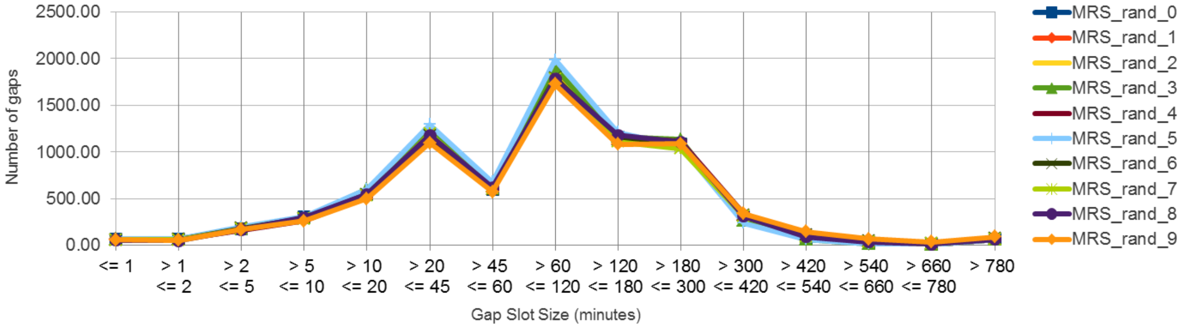

Figure 4.1 Number of gaps for each gap slot.

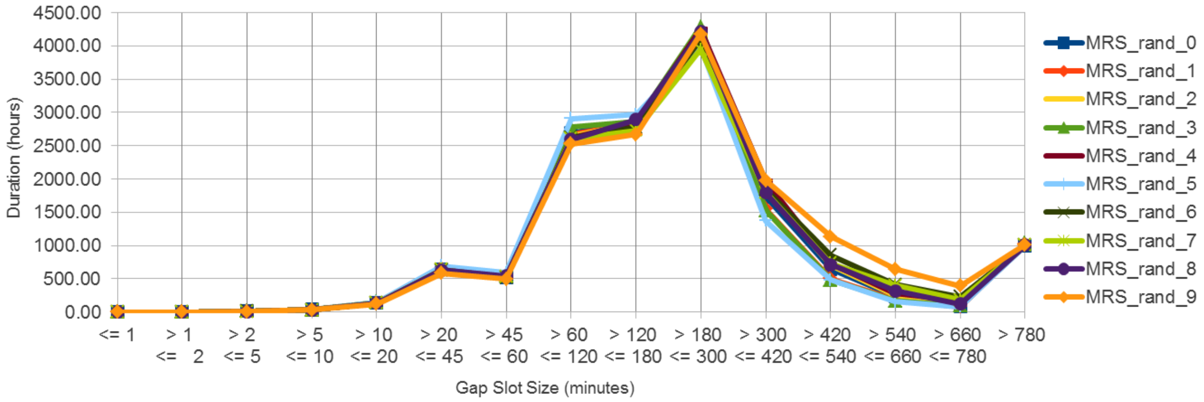

Figure 4.2. Overall duration in hours of the gaps of each gap slot.

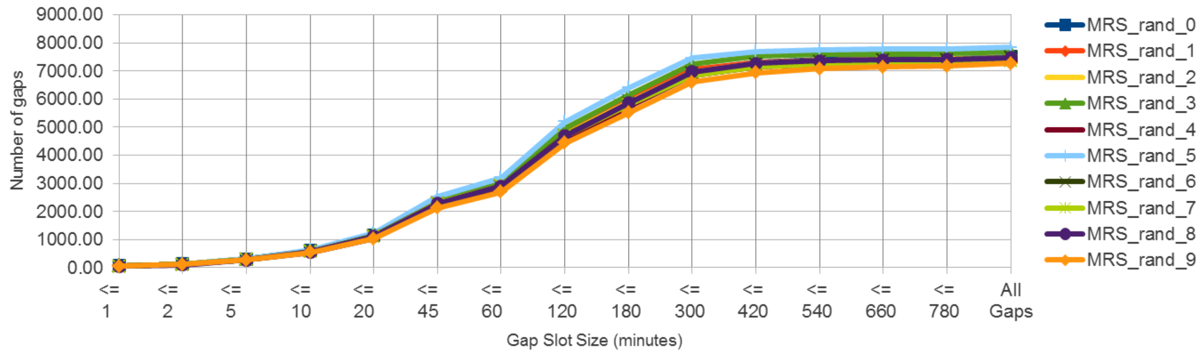

Figure 4.3. Accumulated number of gaps for each gap slot.

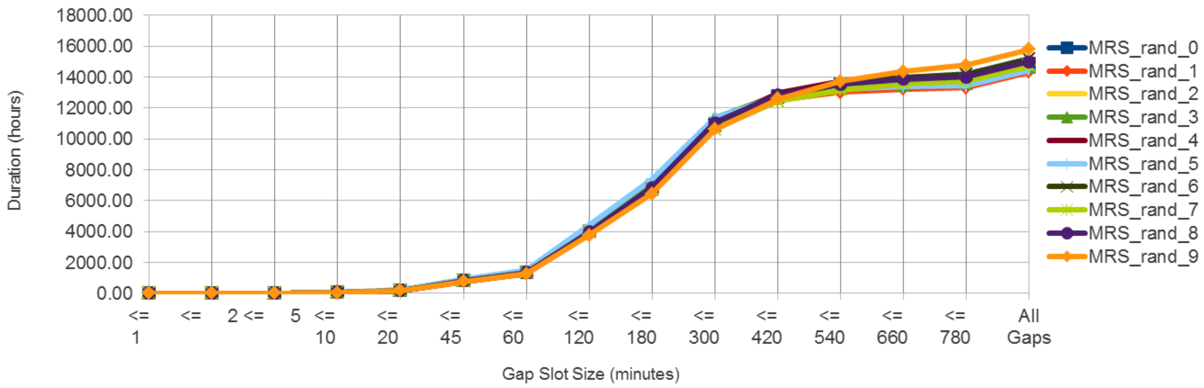

Figure 4.4. Accumulated overall duration in hours of the gaps of each gap slot.

4.2.4 Downlinks as Gap Fillers

Table 4.4 summarizes the downlinks rate that can be placed according to several flexibilities (from 0% to 40%). It can be observed that around 80% of the overall downlinks can be placed with 10% of flexibility (8 hours from the fixed time of each 3.5 days). Moreover, the number of downlinks allocated raises when the flexibility increases, being able to place almost all downlinks with a flexibility of 20%. The downlinks not allocated in this procedure will be inserted by replacing the observations in the same time interval.

Name	3.5days +/- 10%	3.5days +/- 20%	3.5days +/- 30%	3.5days +/- 40%
MRS_rand_0	79.97	94.13	98.54	99.34
MRS_rand_1	77.89	94.00	98.16	99.05
MRS_rand_2	78.41	94.32	98.16	99.34
MRS_rand_3	77.61	93.46	97.90	99.21
MRS_rand_4	79.72	94.96	98.74	99.53
MRS_rand_5	77.54	92.79	97.46	99.12
MRS_rand_6	80.20	94.68	97.97	99.37
MRS_rand_7	78.82	93.33	97.78	99.18
MRS_rand_8	80.42	94.87	98.54	99.37
MRS_rand_9	82.69	95.03	98.61	99.47
MRS_rand Average	**79.33**	**94.16**	**98.19**	**99.30**

Table 4.4. Percentage of downlinks placed in the LTMP gaps with respect to the total downlinks. Each column shows a different flexibility in the downlink position.

4.2.5 Targets Completed

Figure 4.5 shows the number of targets completed at the end of each year according to each target type (Chemical Census, Origins and Rosetta Stones). Note that the first year has only available 6 months. It can be observed that in the last year of the mission, a high number of targets are completed. Moreover, we can see that the distribution of the target type in each year is similar.

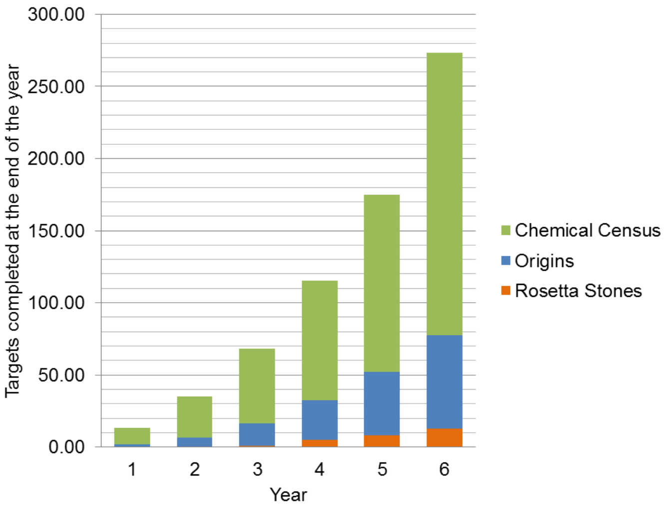

Figure 4.5. Average of targets completed by the LT-MPT at the end of each year according to their type (Chemical Census, Origins and Rosetta Stones) in one trial of the 10 artificial scenarios.

Figure 3.6. Complete and incomplete targets obtained by the LT-MPT at the end of the mission according to their type (Chemical Census, Origins and Rosetta Stones) in one trial of the real scenario. Each type is represented by a different symbol and green colour indicates a complete target and red colour and incomplete one. Targets are plotted according to their Figure 4.6 depicts the targets of one trial of the first four artificial scenarios according to their right ascension and declination. Moreover, it shows the type of target and if its observation is completed at the end of the mission. It can be observed that the incomplete targets are scattered around the sky and that the Rosetta Stones are always completed. Also, we can see that the distribution of the exoplanets is more spread in the sky with the artificial scenarios than with the real scenario, so artificial scenarios can be considered a more complete exoplanet list.

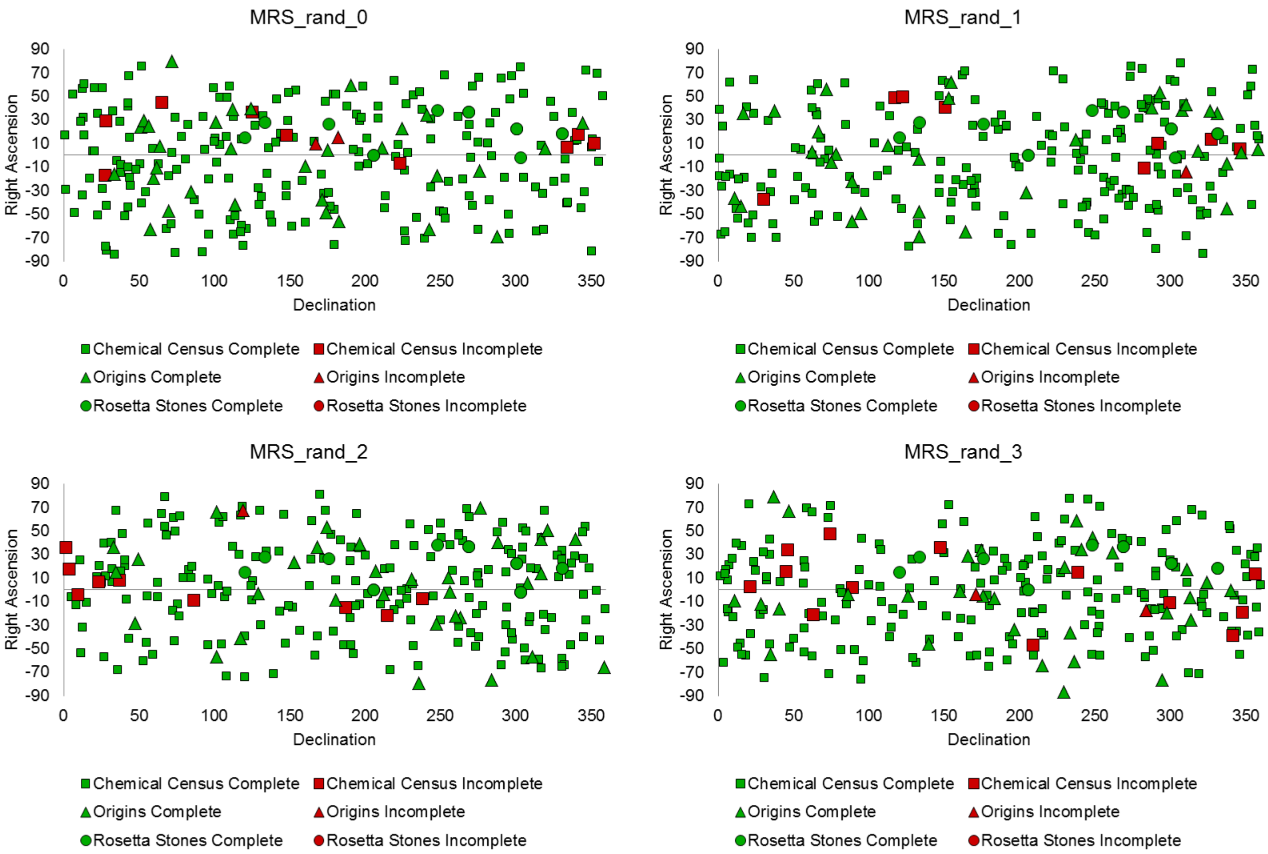

Figure 4.6. Complete and incomplete targets obtained by the LT-MPT at the end of the mission according to their type (Chemical Census, Origins and Rosetta Stones) in one trial of the first four artificial scenarios. Each type is represented by a different symbol and green colour indicates a complete target and red colour and incomplete one. Targets are plotted according to their right ascension and declination.

4.2.6 Maximization of the Target Completeness at the End of Each Year

As Figure 4.5 shows, the number of objects that are completed each year is not linear. This is because the optimization of the LTMP is done according to maximize the occultation and transit observation time and to have a high number of complete targets at the end of the mission (see [Section 5 of RD1]). However, the LT-MPT is able to increase the number of complete targets at the end of each year by changing the optimization objectives. We have defined a new objective F_Y (see Equation 4.1), based on maximizing the average number of complete targets at the end of each year. In the equation, O_I contains all the target observations planned by individual I, where $PriorityLevel_t$ indicates the priority level of target t (as it is defined in [Section 4.2.2.1 of RD1]), $\overline{\overline{T}}$ is the cardinality of the set of existing targets T, and $\overline{\overline{Y}}$ is the cardinality of the set of years of the mission Y.

$$F_Y(I) = 1 - \frac{\sum_{y \in Y} \frac{\sum_{t \in T} \; if\ t\ is\ incomplete\ in\ O_{Iy},\ then\ \bar{\bar{T}} - PriorityLevel_t}{\sum_{t \in T} PriorityLevel_t}}{\bar{\bar{Y}}}$$

Equation 4.1

Three combinations of objectives have been analysed in the LT-MPT:

- LT-MPT_{GT} optimizes the LTMP according to the combination of two objectives: (1) the occultation and transit observation time at the end of the mission and (2) the number of complete targets at the end of the mission. The objectives (F_G and F_T) are defined in [Section 5 of RD1]. This is the approach used in the previous results of this document.
- LT-MPT_{GY} optimizes the LTMP according to the combination of two objectives: (1) the occultation and transit observation time at the end of the mission and (2) the average number of complete targets at the end of each year. The first objective (F_G) is defined in [Section 5 of RD1], and the second one is F_Y.
- LT-MPT_{Y} optimizes the LTMP according to one objective: the average number of complete targets at the end of each year (F_Y).

Table 4.5 shows the number of targets completed at the end of each year by each combination of objectives in the LT-MPT. It can be observed that LT-MPT_{GY} and LT-MPT_{Y} can complete a high number of targets each year, but at the end of the mission they observe fewer targets than LT-MPT_{GT}. According to the transit and occultation observation time (Table 4.6), LT-MPT_{GT} also observes more hours than the other approaches. For this reason, due to the fact that we want to obtain the highest scientific return at the end of the mission, we consider that LT-MPT_{GT} is the best approach because it looks for a LTMP that highly optimizes, at the end of the mission, the transit and occultation observation time and the number of complete targets.

Year	LT-MPT_{GT}	LT-MPT_{GY}	LT-MPT_{Y}
1	13.4	22.6	27.8
2	35.0	60.4	69.1
3	68.1	102.7	111.3
4	115.5	150.2	160.6
5	174.9	201.2	208.1
6	273.4	271.5	267.5

Table 4.5. Number of targets completed at the end of each year for each combination of objectives in the LT-MPT. The results are the average value obtained for all the artificial scenarios with one trial.

Year	LT-MPT_{GT}	LT-MPT_{GY}	LT-MPT_{Y}
6	31105.28	30755.59	30194.44

Table 4.6. Transit and occultation observation time at the end of the mission for each combination of objectives in the LT-MPT. The results are the average value obtained for all the artificial scenarios with one trial and they are expressed in hours.

4.2.7 Computational Cost

The algorithm has been executed in a CPU Intel® Core™2 Duo Processor E6600 2.40 GHz with 6GB of RAM, and the planning results of one trial are obtained in approximately 45 minutes.