Mission Planning Approach for an Exoplanet Characterization Satellite

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ABSTRACT

As space observation techniques evolve, more and more astronomical objects and events are discovered. This large number of observable objects need to be precisely characterized by observation satellites; therefore a good planning of the observations is required. In addition, observation satellites are orbiting a planet, typically the Earth. Consequently, the target visibility will be affected by several constraints which will produce interruptions in the observation because of either the occultation of the targets or the possibility of damage in the sensor. In this work, we will optimize the observations of an exoplanet characterization satellite, considering key parameters. To proceed with the optimization, we first have to calculate the visibility of the targets by determining its constraints, such as the occultation produced when the Earth is between the satellite and the target. This work shows that the major driver of the visibility problem is the Sun's exclusion angle constraint, which allows to reduce the spectrum of solutions of the optimization problem. The optimization is performed maximizing the effective visibility time and the number of observations with Local Search and Monte Carlo methods.

KEYWORDS: *targets visibility, exoplanet characterization satellite, observations planning, observations optimization, visibility and optimization constraints.*

NOMENCLATURE

Latin
C_{p_i} - Coefficient of priorities
E - Earth
$Eocc$ - Occultation by the Earth
$\vec{EC}$ - Vector Earth's center to p, s intersection
$\vec{ET}$ - Vector Earth's center Earth's tangent
f - Cost function
M - Moon
$Mocc$ - Occultation by the Moon
P_t - Period of exoplanet-host star revolution
$\vec{r}$ - Position vector
S - Sun
t - General instant of time
T - Orbital period
t_c - Time instant when a transit occurs
$t_{c_{i/0}}$ - Time instant for first transit of target i
$t_{c_{i/n_p}}$ - Time instant centred on the transit
T_{div} - Time interval division in during one orbit
t_0 - Reference time
t_f - End of the mission instant of time
w - Visibility logical matrix
w_b - Beginning of the nominal time interval
w_f - End of the nominal time interval
w_s - Selected nominal interval
X/Y - X relative to Y

Greek
α_t - Angle determined by the position of the satellite relative to the terminator line
γ - Required half cone angle
θ - Actual half cone angle
θ_t - Parameter of the terminator circle
τ_d - Transit duration
τ_{eff} - Effective time interval duration
τ_n - Nominal duration of the observations

Subscripts
i - Subscript for the target considered
k - Instant of time considered
s - Visibility intervals for the Sun's constraint
sat - Satellite
str - Stray Light
$term$ – Terminator

1 INTRODUCTION

Currently, we have the possibility to observe the universe not only from Earth, but also from space. Observation satellites, such as space telescopes, allow us to reach much more precision in the observations because they are free from the Earth's atmosphere, which distorts and blocks light from the cosmos [1].
An observation satellite requires a precise and detailed mission planning because we have to consider the recurring lack of visibility produced by eclipses, and the damage that can be caused to the sensor by radiation, amongst others.
An exoplanet is a planet that orbits a star other than the Sun [2]. Exoplanets are an important field of study because, although we already know about the existence of many exoplanets, we are still not able to determine accurately their structure and establish a precise classification of all their properties [3].
Planetary transit surveys are one way to detect exoplanets that consists of the record of the stars that are partially hidden during a certain amount of time due to the movement of an exoplanet around them. The observation of exoplanets transiting bright stars (Visual Magnitude less than 12) will allow to get more information about their key parameters, such as mass and radius, in order to make a good characterization [3]. The large number of transit surveys that take place from both ground and space, makes necessary to classify exoplanets and highlight those more relevant for research [3].
After the success of the Kepler satellite observing transits pointing to faint stars in only one fixed large area of the sky, next missions from ESA and NASA are going to focus on Earth-like exoplanets transiting bright stars. This work focused on the CHEOPS satellite, which will be able to point to anywhere in the sky and accurately characterise exoplanets transiting bright stars. The number of relevant target transits and the precision required for CHEOPS science mission makes necessary a very precise observation planning [3].
In this work, we will explain the procedures to reach two main goals:

- First, we will calculate the visibility windows for the CHEOPS satellite. In order to do this, we will develop a computational program to identify CHEOPS' orbit and to combine it with the most important visibility constraints.
- Then, we will define the mission planning, optimizing some parameters, such as the effective time, by means of cost functions and artificial intelligence algorithms.

2 VISIBILITY COMPUTATION

We will divide the visibility problem considering each constraint independently. This division of the problem is useful for two main reasons. First, it allows us to simplify the problem and to avoid concatenated errors. Second, it let us identify which constraint is causing visibility problems, which means a time calculation improvement. Calculation time is a very important parameter for this work because of the numerous targets and constraints, and the reduced time intervals.
In order to calculate the targets visibility, we will use two methods. First, we will calculate and represent the effect of the exclusion region generated by the constraint in the spacecraft centred celestial sphere. Then, we will calculate and compare the actual and the required visibility half cone angle to determine the visible periods for each target and instant of time considered, which defines the visibility windows.

2.1 Targets and orbit definition

The targets of the CHEOPS mission consist of 201 stars which are likely to host planets, because it is known that they have a transit with a determined period at a certain epoch. As the precision requirement is very high, we will model the pointing to the target as a vector directed straight to the star. The error is on the side of safety, because we are assuming that the aperture of the sensor is the minimum possible.
By requirement, CHEOPS' orbit must be Sun-synchronous with a preferable local time of ascending node of 6:00 AM, which is a particular LEO altitude and inclination, so that the satellite passes over the equator ridding the terminator line.

2.2 Targets transit visibility

The transits of the targets happen only at a specified interval of time. CHEOPS will have to observe each target amongst certain time intervals in order to not miss any transit, considering useless any observation produced when the transits are not happening. Therefore, we will calculate the time interval required to perform the observations.

The transits are defined by three parameters: the instant of time when the transit was first detected (t_c) - we will assume that the detections were made centred on the transit; the period of the exoplanet revolution around the host star (P_t); and the transit duration (τ_d), which will be neglected because the duration of the observations will be provided by the nominal time intervals duration (τ_n).

As the mission will start after the transit was discovered, we need to add $n_p P_t$ periods to the detection first time (t_0) to obtain the time instants centred on the transit during all the mission $(t_{c_{i,n_p}})$, for each target i and each revolution of the planet around the host star n_p.

The nominal intervals of observation establish the margins of time when the targets should be observed, and they are defined as a continuous period of time of either 12 or 48 hours, which depends and is centred on the target [3]. We will define the beginning and end of the nominal intervals of observation by $t_{i,n_p-1} = t_{c_{i,n_p}} - \frac{\tau_{n_i}}{2}$ and $t_{i,n_p+1} = t_{c_{i,n_p}} + \frac{\tau_{n_i}}{2}$, respectively, see Fig. 1.

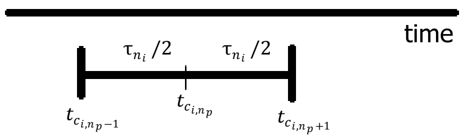

Figure 1: Observation interval definition

Also, we have to consider that the observations are not necessarily continuous during the nominal time interval, because of the constraints that will interfere with the targets visibility. With this, we define the effective time interval (τ_{eff}) as the amount of time that the stars will be visible during the nominal time. Ideally, we would like to have $\tau_{eff} = \tau_n$.

2.3 Occultation by the Earth constraint

As the satellite is orbiting the Earth, there are some intervals of time when the Earth is between the satellite and the target. This occults the target from the satellite sensor making it not visible. To model this constraint, we start to calculate the Earth's eclipse half cone angle (γ_{Eocc}) and the position vector of the Earth in the satellite centred ECI reference frame $(\vec{r}_{E/sat})$, which defines the occultation by the Earth region (see Fig. 2 left). We will represent the occultation by the Earth region in the spacecraft centred celestial sphere considering not visible the targets inside the region (see Fig. 2 right).

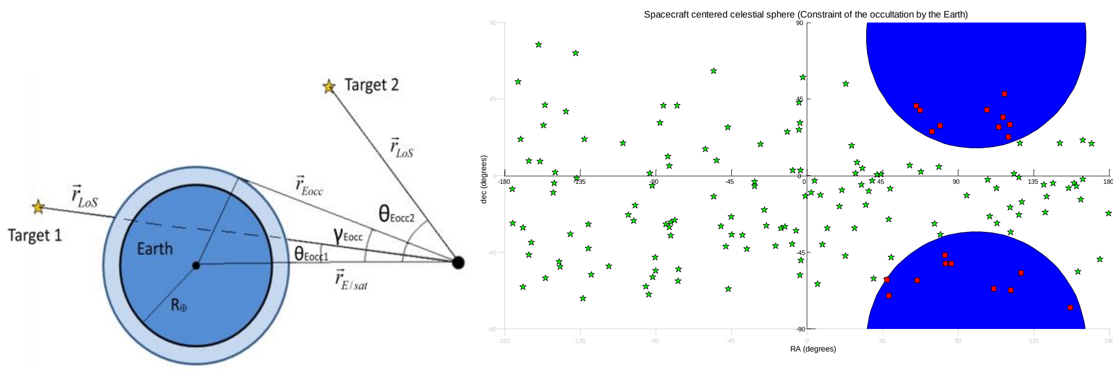

Figure 2: Comparison between the visibility cases θ_{Eocc} and γ_{Eocc} (θ_{Eocc1} target not visible, θ_{Eocc2} target visible), not to scale (left). Spacecraft centred celestial sphere considering the constraint of the occultation by the Earth (right)

The representation of the exclusion region provides a better understanding and visualization of the constraint, letting us observe the sky from the satellite point of view. However, this method is computationally slow. So, we will develop a more efficient model in terms of calculation time, which consists in the calculation and comparison of the visibility half cone angle (θ_{Eocc}) and the Earth's eclipse half cone angle (γ_{Eocc}), stating the next visibility criterion (see Fig. 2 left):

- If $\theta_{Eocc} > \gamma_{Eocc}$ the target is visible in the time instant considered.
- If $\theta_{Eocc} < \gamma_{Eocc}$ the target is occulted by the Earth in the time instant considered.

Finally, we combine the visible and hidden intervals with the nominal intervals to obtain the visibility window (see Fig. 3). The red bars represent the time intervals occulted by the Earth and the green bars represent the effective time intervals, i.e. the observable time intervals during the nominal time intervals.

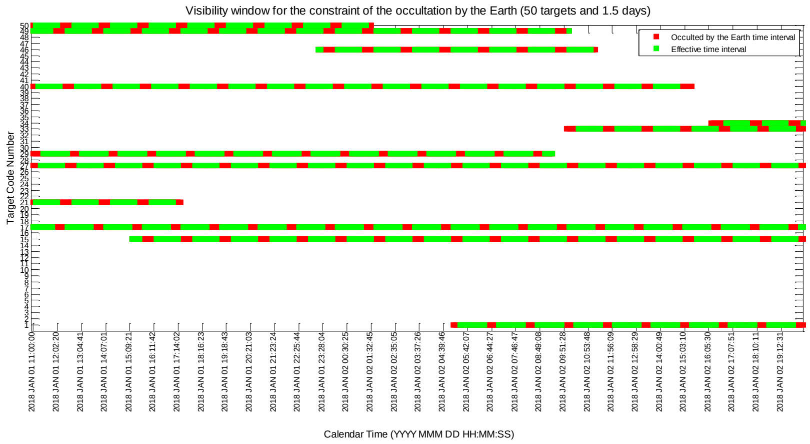

Figure 3: Visibility window for the constraint of the occultation by the Earth for 50 targets and 1.5 days

2.4 Moon's exclusion angle constraint

The Moon is moving with respect to the satellite centred ECI reference frame, so it could hide the target stars from the line of sight (LoS) of the satellite. In addition, the Sun's light is reflected on the Moon's surface, which can produce damage in the sensor. The procedures to model this constraint are similar to the ones explained in the previous subsection. To calculate the position of the Moon in the satellite centred reference frame and to define the exclusion region, we need the Moon's ephemeris, which can be obtained using the SPICE software [4].

2.5 Sun's exclusion angle constraint

The Sun's radiation can blind the satellite sensor making it unable to observe the targets. This constraint will be the driver for the visibility calculation, because of the large exclusion angle of 120º which is defined to avoid the Sun's radiation. Also, it is important to highlight that the Sun's exclusion angle must not interfere with the field of view of the satellite during all the mission, which means that none observations shall be interrupted by the Sun's constraint.

To calculate the Sun’s exclusion region, we will compute the anti-Sun vector ($\vec{r}_{aS/sat}$), and the angle of 60º where the satellite can observe the target γ_{aS}. The exclusion region is the area outside this visibility cone. The targets inside the exclusion will be not visible (see Fig. 4).

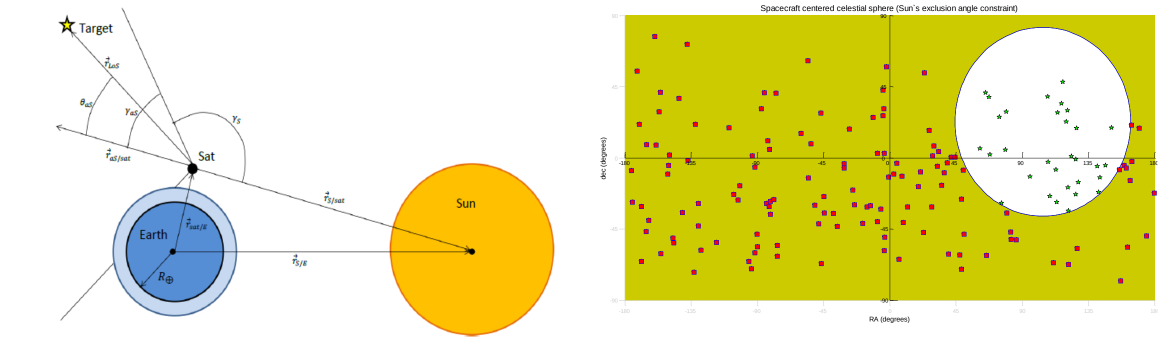

Figure 4: Comparison between θ_{aS} and γ_{aS}, not to scale (left). Spacecraft centred celestial sphere considering the Sun's exclusion angle constraint (right)

Using the method of Aristarchus [5], we can compare the angle of incidence of the sunlight from the centre of the Sun and from the farthest points of the Sun's surface to the satellite. From this comparison, we obtain a maximum error deviation of less than 0.3 degrees. This error will be in the side of safety if we increase 0.3 degrees the exclusion region.
As the observations must never be interrupted by the exclusion region, the nominal intervals cannot be split due to the Sun's constraint. Therefore, we define an algorithm to compute each full visible nominal time interval, discarding any split nominal interval.
Finally, we will determine the exclusion region and the visibility window, considering the following visibility criterion:

- If $\theta_{aS} < \gamma_{aS}$ the target is visible in the time instant considered.
- If $\theta_{aS} > \gamma_{aS}$ the target is in the Sun's exclusion region.

2.6 Earth's stray light constraint

This constraint is based on the radiation reflected on the Earth's surface. The Earth's stray light should be avoided because it decreases the quality of CHEOPS' observations [6].
To determine the Earth's stray light constraint, we locate the visibility cone defined by γ_{str} and $\vec{r}_{LoS}$. The angle γ_{str} belongs to the plane which contains $\vec{r}_{LoS}$ and $\vec{r}_{E/sat}$. This plane (π) provides a section of the Earth, and the visibility cone in the right triangle (Fig. 5).

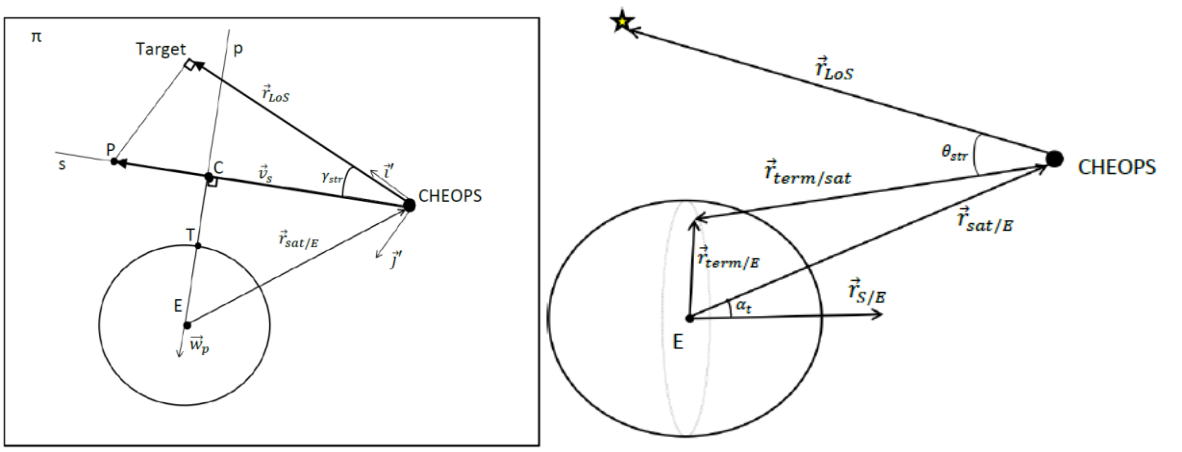

Figure 5: Upper view of plane π, definition of the tangent points T and C, not to scale (left). Descriptive diagram of θ_{str}, angle formed by $\vec{r}_{LoS}$ and $\vec{r}_{term/sat}$, not to scale (right)

The tangent to the Earth's surface is related to the visibility cone by the distance $\overrightarrow{EC}$ on the line p, which is perpendicular to s, which defines the visibility cone surface. The distance $\overrightarrow{ET}$ is calculated as the distance from the centre to the surface of the Earth plus 100 km due to the atmospheric glow. When $\overrightarrow{EC}$ is equal to $\overrightarrow{ET}$ we can assure that the visibility cone is perpendicular to the Earth's surface. We are in conditions to define the visibility criteria comparing $\overrightarrow{EC}$ and $\overrightarrow{ET}$ (see Fig. 5):

- If $|\overrightarrow{EC}| > |\overrightarrow{ET}|$ we can assure that the tangent point is outside the Earth. Therefore, the visibility cone does not intersect the Earth and the target is visible for the instant of time considered.
- If $|\overrightarrow{EC}| \leq |\overrightarrow{ET}|$ the visibility cone is tangent or intersects the Earth. In both cases we have to study the position of the satellite relative to the Earth's surface and the Sun's orientation $\vec{r}_{S/E}$, in order to know if the visibility cone intersects the dark or the illuminated side of the Earth. Therefore, we compute the satellite position with respect to the terminator and the target, considering three possible cases (see Fig. 5 right):
  - If $\alpha_t \leq \frac{\pi}{2}$, the satellite is above the illuminated part of the Earth and the visibility cone intersects the Earth, so the target is not visible.
  - If $\alpha_t > \frac{\pi}{2}$, and $\min(\theta_{str}) \leq \gamma_{str}$, the satellite is above the dark part of the Earth but the visibility cone intersects the terminator, hence the target is not visible.
  - If $\alpha_t > \frac{\pi}{2}$, and $\min(\theta_{str}) > \gamma_{str}$, the satellite is above the dark part of the Earth and the visibility cone does not intersect the terminator, hence the target is visible.

2.7 South Atlantic Anomaly constraint

CHEOPS' sensor must be switched off when it passes through the SAA region because the high radiation from the inner Van Allen belt can damage the satellite subsystems. Therefore, CHEOPS cannot observe any target inside the SAA region, reducing the sky visibility to 0 %.
We will define the position of the SAA region in the Geographic reference frame, and then we will calculate its rotation respect to the ECI reference frame. The difference between the Geographical and ECI reference frames is determined by the GST (Greenwich Sidereal Time) angle, which is the angle between the first point of Aries and the Greenwich meridian, for a defined instant of time [7].

2.8 Combination of orbit, constraints and targets to compute visibility windows

In this subsection we merge all the constraints calculated previously with the nominal time intervals in order to obtain the visibility window and the effective time intervals, which is the input for the optimization problem.
In Fig. 6 we represent the celestial sphere and the visible targets seen from CHEOPS for two different instants of time: the satellite is not over the SAA region (left) and the satellite is passing over the SAA region (right). The yellow area is the Sun's exclusion region, and the blue and grey areas represent the regions of occultation by the Earth and the Moon, respectively. We represent the SAA constraint as a black area covering all the sky. The visible targets are characterised by green stars and the not visible targets by red squares. It is important to notice that we are representing only the target stars during nominal intervals of observation.

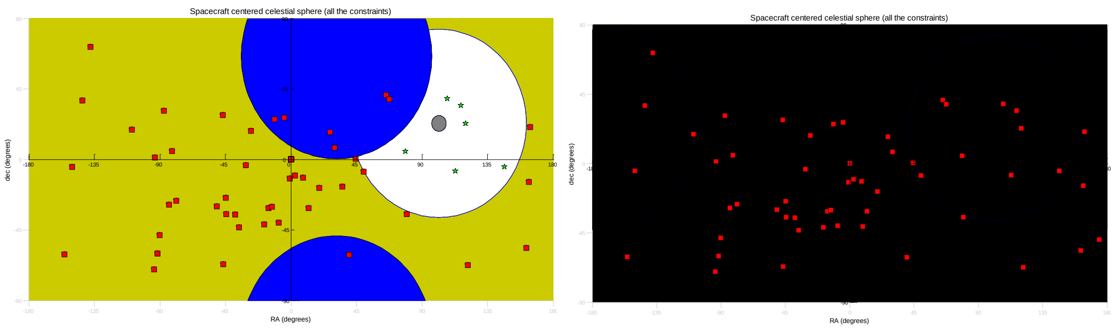

Figure 6: Spacecraft centred celestial sphere with all the constraints. Satellite outside the SAA region (left). Satellite inside the SAA region (right)

Next, we compare the sky visibility for each constraint (see Table 1) and calculate the effect of each constraint on the number of visible targets (Fig. 7 left). Finally, we calculate the visibility window for all the constraints during a certain time (Fig. 7 right).

Table 1: Sky visibility for each constraint for a general instant of time

Constraint	Occult. by the Earth	Moon's excl.	Sun's excl.	Stray Light (Min)	Stray light (Max)	SAA (Min)	SAA (Max)
Sky visibility (%)	79.2	99.9	17.3	52	100	0	100

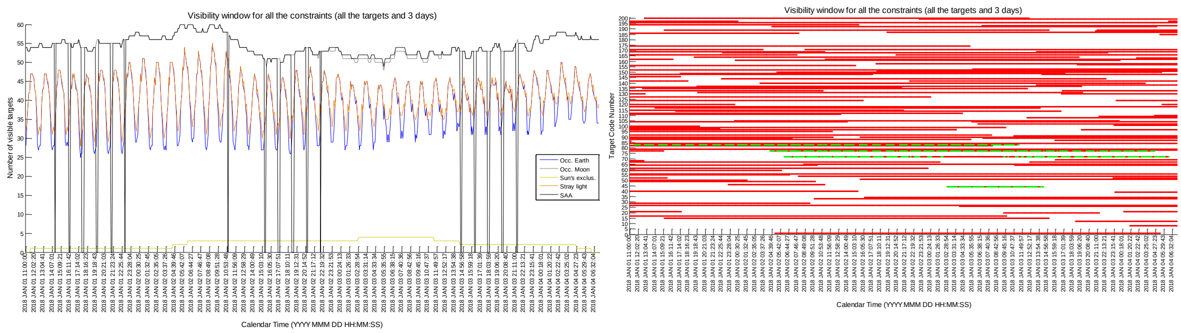

Figure 7: Effect of each constraint on the number of visible targets (left). Visibility window considering all the constraints and targets for 3 days (right)

3 MISSION PLANNING

3.1 Concept of planning and scheduling

Planning consists of devising and maintaining a workable scheme to accomplish the business need that the project was undertaken to address [8]. In the CHEOPS' mission the needs are the observations of the targets and the resource is the mission time. Therefore, we can define a cost function which optimizes the quality of the observations regarding the mission time. We can analyse the quality of the observations depending on the following key parameters:

1) Maximum effective time, the most important parameter because it determines the maximum time of target observation.
2) Maximum number of targets observed, also important, although it can involve a reduction of the observing time.
3) Observation priority of the target, whether for scientific reasons or because of its transit visibility during the year.
4) Minimum sensor adjustment time among observations; if two consecutive targets are separated by a large (angular) distance, the sensor adjustment time will be larger. As the Sun's exclusion angle constraint allows the visibility only of a small portion of the sky, this parameter will not be as important as the previous ones.

3.2 Optimization of the observations

The visibility logical matrices represent the effective time by zeros and ones organized in rows and columns, for each target and time instant respectively, providing information if the target is visible (*one*) or not visible (*zero*). We can add coefficients to the visibility logical matrices in order to consider the remaining optimization parameters. For example, as each target has a different scientific priority, we can multiply each target by a coefficient to consider its priority. Also, we can subtract a quantity from each element in the visibility logical matrix to take into account the sensor adjustment time. Therefore, we will define the cost function as

$$f = \sum_{1 \le i \le n} C_{p_i} \sum_{1 \le k \le m} \left(w_{i,k} - d_{i,k} \right), \qquad 1.$$

where C_{p_i} is the coefficient of priorities, $w_{i,k}$ is the visibility logical matrix, $d_{i,k}$ the sensor adjustment time, and the subscripts i and k are each target and instant of time. As we can observe, the cost function is linear, being C_{p_i} and $d_{i,k}$ constants provided previously.

The optimization process consists in the maximization of f considering the optimization constraints defined by CHEOPS' mission requirements.

1) The first constraint we will consider is that CHEOPS can only observe one star at a time. This constraint can be modelled as

$$\sum_{1 \le i \le n} (w_{i,k}) x_{i,k} \le 1, \qquad 2.$$

which means that during an instant of time we can only observe either one or zero targets.

2) Next, we have to consider the observations duration, whose maximum is determined by the nominal intervals duration T_n; observing a target for more time will produce useless solutions. This constraint is expressed as

$$\sum_{1 \le k \le m} \left(w_{i,k} - d_{i,k}\right) x_{i,k} \le T_n. \qquad 3.$$

3) Finally, we also have to consider that the nominal time intervals are continuous, meaning that CHEOPS cannot observe the next target until it finishes the nominal observation time for the current target. This constraint is a more restrictive variation of the eq. (3.3) because it implies that the sum of effective time only during one nominal interval per target.

The third constraint requires a redefinition of the visibility window so that it only shows one random nominal interval per target. To solve this problem we will use Local Search [9] and Monte Carlo [10] methods. We define the neighbourhood relation of the local solutions by the optimization constraints fulfilled by the nominal intervals of the visibility window. Then, we generate random solutions with the Monte Carlo method and select the solution that maximizes or minimizes the optimization parameter considered. The main algorithm steps to consider constraint 3) are:

1. Import the data of the nominal time intervals combined with the exclusion by the Sun time intervals $(s_{i,k})$.
2. Locate the positions of change from 0 to 1 (w_b) and from 1 to 0 (w_f) in the nominal time intervals logical matrix.
   I. Calculate the difference for every two consecutive elements of each row i, $w_{i,k+1} - w_{i,k-1}$.
   II. Find the number of changes $w_{i,k+1} - w_{i,k-1} = 1$ and $w_{i,k+1} - w_{i,k-1} = -1$
3. Using the Monte Carlo method, generate a random number to select one of the nominal time intervals.
   I. The random numbers generated must be between 0 and maximum number of $\mathrm{w_b}$ and $\mathrm{w_f}$ per row.
   II. The random number generated will determine the selected nominal interval.
   III. We will denote the selected nominal interval as $\mathrm{w_s}$.
4. Assign the value of zero to all the row except for the selected nominal interval.
5. Repeat n times.

As now we have only one nominal interval per target, the constraint 2) is automatically fulfilled. Finally, we define the algorithm to take constrain number 1) into account:

1. For each instant of time k, sum the rows of $\mathrm{w_s}$: $\sum_{\mathrm{i=1}}^{\mathrm{i=n}} \mathrm{w_{s_{i,k}}}$.
2. If $\sum_{\mathrm{i=1}}^{\mathrm{i=m}} \mathrm{w_{s_{i,k}}} \ge 2$, it is possible to observe more than one target for the instant considered. In this case,
3. Use the Monte Carlo method to generate a random number to select a nominal interval for each instant of time k.
   I. The random numbers generated must be between 0 and $\max\left(\sum_{\mathrm{i=1}}^{\mathrm{i=n}} \mathrm{w_{s_{i,k}}}\right)$.
   II. The random number generated will determine the nominal interval selected for each instant of time k, as the satellite can one observe one target at a time.
4. Assign the value of 0 to every target other than the selected for each instant of time k.
5. Repeat $\mathrm{n_2}$ times.
6. Repeat n times for each $\mathrm{w_s}$.

We then combine the visibility window considering all the constraints with the selected nominal intervals in order to obtain the effective observation time solution (Fig. 8 left). Finally, we calculate the optimal from the n times n_2 solutions generated which depend on the two main optimization parameters: the maximum effective time, and the maximum number of targets observed. To calculate the maximum total effective time, we sum all the effective time intervals for each solution, and calculate the maximum number of targets observed by summing the number of observed nominal time intervals. In Fig. 8 right, the effective time and number of targets per solution are represented.

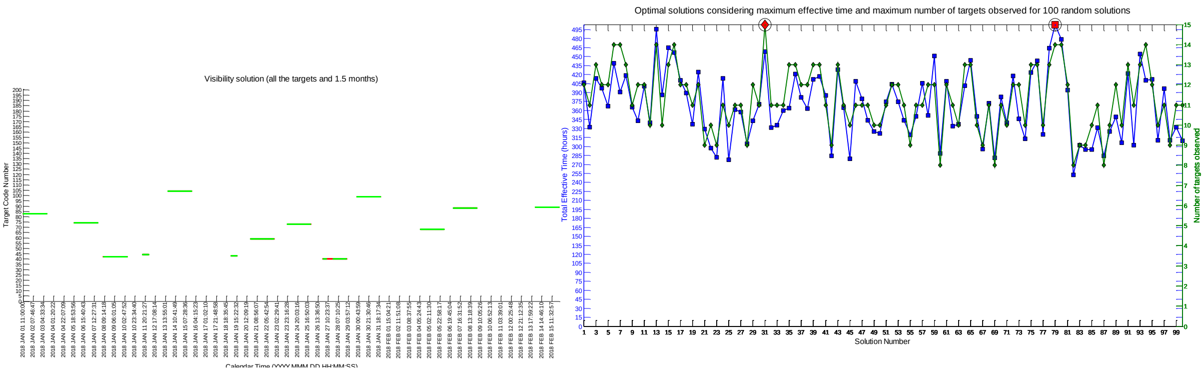

Figure 8: Visibility random solution (all targets, 1.5 months), left. Solutions graph, right

4 CONCLUSIONS

In this work we have solved the problem of the transit observation scheduling taking several optimization and visibility constraints into account by its division in two main parts: the visibility calculation and the optimization of the observations.
We determined that the constraints can be divided in two groups depending on its frequency:

- Short period constraints: the occultation by the Earth, the Earth's stray light and the SAA constraint. These constraints reduce the visibility during short and frequent periods of time, diminishing the effective time.
- Long period constraints: the Sun and the Moon's exclusion angle, which hide the targets for most or all the nominal time, making us to discard directly the observation of the targets affected by them.

The Sun's exclusion angle constraint is the major driver of the visibility problem, which reduces the sky visibility to 17.3% at each instant of time. The second driver is the SAA constraint, which is present in all the 48-hour duration nominal intervals, decreasing the effective time.
The visibility windows and the logical matrices calculated provide important information about the nominal and effective time, which will define the cost functions for the optimization.
Most targets are only visible during a specific time of the year because of the Sun's constraint. So, a precise optimization is required to fulfil the observation requirements of the mission.
The observations optimization of CHEOPS mission is an NP-hard problem that can be reduced to a P problem.
There are several optimization parameters that we can consider, being the effective time the most important to fulfil the observation requirements. There are three optimization constraints that we have to consider in order to maximize the cost function, because they affect the number of possible solutions for the optimization. We selected the Sun's exclusion angle constraint to discard most of the useless nominal intervals and improve the computation time.

5 FUTURE WORK

We used the Local Search method because it proves to be enough to solve the optimization problem. However, there are also other optimization methods that can be used to solve this problem, such as Genetic Algorithms.
We must highlight that the goal of this work is not the particular application to the CHEOPS satellite, but the application to any other observation satellite. For example, space telescopes or other exoplanets observation satellites. The main calculations, algorithms and methods developed in this work will be useful for related missions in the future by changing the inputs properly.

Having the above in mind, we intend in the future to improve the scripts and algorithms towards a highly efficient target observation planning software. For example, by comparing the Local Search method with other optimization methods such as Genetic Algorithms. Also, the consecutive and cumulative sky visibility can be calculated to check if the requirements of the mission are fulfilled.

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