Towards the Design of Space Missions with Optimal Accessibility via Relay Satellites

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***Abstract*—Satellites on low-Earth orbit usually have scarce opportunities to contact ground stations. Resulting contact windows define the satellite *access time*, which depends on the satellite's orbit and the ground facilities distribution on Earth's surface. In recent years, the cost of constructing and launching small satellites has decreased dramatically, introducing a new possibility for space agencies: to take into consideration small relay satellites to increase access times. This paper presents Maximum Asset Accessibility Algorithm (M3A), a novel methodology based on simulated annealing parametric search to design satellite missions with maximum access times. Orbit constraints and possible locations for ground facilities are considered on the task of selecting the optimal combination of orbital parameters for the assets of a space mission. Results show that the use of M3A drastically reduces the required design time, while providing parameters of similar quality than those obtained by processor-demanding brute force search.**

I. Introduction

Satellites are typically classified by their orbital parameters. Specifically, the semi-major axis of a satellite orbiting the Earth determines three main groups: ***(i)*** Low-Earth Orbit (LEO) which corresponds to heights between 400 and 1000 Km, ***(ii)*** Medium-Earth Orbit (MEO) for heights around 10000 km, and ***(iii)*** High-Elliptical Orbits (HEO), which fall between LEO and MEO with high eccentricity. A fourth group called High Earth Orbit, is exclusively used for geosynchronous satellites [11]. In all cases, the orbital elements determine the amount of time that a satellite can be accessed from a given ground station location.

For LEO satellites, the proximity to the Earth's surface makes very short and opportunistic contacts with ground stations be the default. To maximize access times, a careful selection of orbital elements and/or ground stations placement is needed. This presents two obstacles: the orbit of the satellite might present hard constraints in terms of parameters (such as the LEOs used for Earth observation) and the cost associated with constructing or hiring ground stations at different locations. Relay networks can provide a solution for both limitations [6], [7], [8], composed of satellites fulfilling the primary mission objectives and supported by *relay satellites* relaying the data to a nearby ground station.

The use of a large number of ground stations or of relay satellites is not new. Leading space agencies such as NASA or ESA have used these strategies and continue to do so, mostly on sensible missions such as the International Space Station [9], [10]. These endeavors are always challenging and require a considerabel financal budget, which is prohibitive for the majority of small agencies or, nowadays, companies. Nevertheless, the advances in technology allows the development of smaller satellites, which combined with reduced launch costs, brings the possibility of satellite missions based on relay nodes in simpler and budget-constrained projects [1].

Simulating access times for a specified mission configuration and duration is a costly process, especially in terms of computing power. In particular, it requires the use of an orbital propagator and knowledge of what assets and constraints have to be taken into account. This information is not always available at early stages of the mission. Furthermore, a significant group of orbital/ground parameters are left open, but need to be explored, especially in relay missions. This drastically increases the degrees of freedom of the analysis. In this context, considering every possibility by brute force will ensure the best option at a great processing cost.

Finding the optimal solution of a given space mission architecture is a fundamental step towards defining and validating high and low-level mission requirements, weather or not based on relay satellites. Heuristics can be leveraged both for finding a quick solution that efficiently meets the mission objective, while being close to the optimal mission parameters [12], [13]. In this paper, we prove that the use of heuristic parametric search algorithms is a valuable tool for mission design and analysis, especially suited for problems where a classical brute force approach is slow or unfeasible. We present Maximum Asset Accessibility Algorithm (M3A), a simulated annealing technique closely tied to state-of-the-art satellite propagators. M3A is validated by designing a realistic relay-based mission. Resulting accessibility metrics are compared with those obtained by brute force, showing that M3A solution is very close to the optimal set, at a fraction of the processing time.

This paper is structured as follows. In Section II, the simulated annealing M3A technique is introduced including a discussion of the parameters considerations for space dynamics. In Section III an appealing and realistic case study is presented and analyzed by M3A as well as compared to determine the value of the algorithm in relay-based mission design. Finally, Section IV concludes and closes the paper.

II. System Model

A. Assets access times

Access time is defined as the period of time where there is a possibility of establishing contact between two assets. We will define two types of contacts between ground stations and satellites: *direct* and *indirect*. Direct contact refers to a direct link between two assets (e.g. an RF link between a ground station and a satellite) while indirect contact refers to any link that uses one or more relays as intermediary, as illustrated in Figure 1.

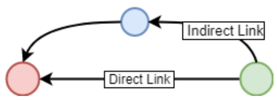

Fig. 1. Direct and Indirect Links.

Given that there is an extensive and reliable communication network on the Earth's surface, it is assumed that ground stations are networked with mission operations via direct link. For contacts between ground facilities and satellites, or between satellites and satellites, we will declare them to be feasible whenever a direct straight line of sight is present between the assets. However, constraints can be applied, such as height above the horizon (a.k.a. elevation).

The input data for obtaining the overall system access time is composed of lists of direct link events between any two assets in the system, for a specified period of analysis time. This list is provided by the orbit propagator and can be seen as a set of time intervals, which represents the initial (ti) and final (tf) times for the access period, for a total of n events between an asset M and an asset N:

$$\begin{Bmatrix} ti_1 & tf_1 \\ ti_2 & tf_2 \\ ... & ... \\ ti_n & tf_n \end{Bmatrix}_{Asset\ M \rightarrow Asset\ N}$$

There are three types of access groups, based on the type of assets that are in contact: ground station (GS), mission satellite (MS) and relay satellites (RELAY). The groups and their interaction intersect as shown in Figure 2.

- GS to RELAY: all intervals where a given ground station has direct link access to given member of the relay network.
- GS to MS: all intervals where a given ground station has direct link access to a given member of the flight segment.
- MS to RELAY: all intervals where a given member of the flight segment has access to a given member of the relay network.

B. Cost function

A cost function can be defined with the objective of optimizing assets access times. Some considerations are presented as follows.

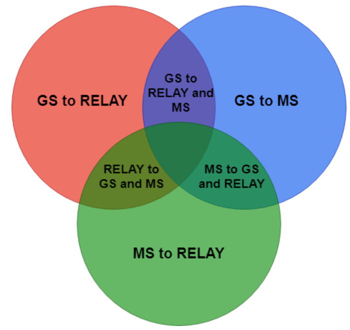

Fig. 2. Types of access groups according to assets.

- *Relay network with Inter-Satellite Link (ISL):* Members of the relay network might have the capability of communicating with each other via ISLs. In this case, when flying in low-Earth orbits, it is possible to choose a topology in which a satellite in a network has continuous direct link access to another. This is the case of an along-track formation where satellites shares the same orbital plane. In any case, by relying on ISLs, mission satellites can indirectly access the ground segment and thus increase the access time. In Figure 2, this is represented by the intersection between GS to RELAY and MS to RELAY (RELAY to GS and MS). If maximizing the real-time access is a requirement for a mission, it can be included in the cost function.
- *Usage of relay networks in delayed time (Store and Forward):* Relay satellites can be used as data collection systems or time-tagged command upload. Any time that the flight segment contacts the relay network, it can not only download data to be transferred later to the ground segment (as a data collection system would do), but also be commanded by previously uploaded time-tagged commands onto the relay satellites. These types of accesses are represented by the MS to RELAY section in Figure 2.
- *Minimizing redundant accesses:* Although the objective is to maximize access times, some redundant contacts have to be especially considered in the cost function, as they might not be desirable. This applies to any redundant contact to the relay network and most importantly, to overlapping contacts with the flight segment, represented in Figure 2 by the intersection between GS to RELAY and GS to MS (GS to RELAY and MS). The fact is that a mission is unlikely to need access to the relay network at the same time that it has access to the flight segment. In some cases, however, such a feature can be leveraged in the cost function to enhance redundancy.

Taking these considerations into account, an example cost function is defined using a) the total access time from ground segment (i stations) to flight segment (k satellites) via indirect real-time link through the the relay network (j satellites), b) the total access time from the the MS to the relay network via direct link, and c) the overlapped times between ground segment to flight segment and ground segment to relay network.

$$Cost = \sum GS_i \rightarrow Relay_j + \sum MS_k \rightarrow Relay_j - \sum \{GS_i \rightarrow Relay_j\} \cap \{GS_i \rightarrow MS_k\} \qquad (1)$$

It is important to note that the sum symbols stands for the total amount of time that there is a contact between one set of assets to the other. This implies that overlapping times are excluded. For example: if the ground segment has access to more than one satellite of the Relay Network at any given time, it is considered a single access. On the other hand, the intersection symbol serves to indicate the overlapping or 'intersecting' times, where redundant access to the flight segment via direct and indirect link from the ground segment is happening.

C. Simulated Annealing

To optimize the cost function, a combinatorial search space needs to be explored. Kirkpatrick, Gelatt and Vecchi developed the simulated annealing technique for solving combinatorial optimization problems back in 1983 [3]. In this article, we leverage this technique.

In local combinatorial optimization, special care needs to be taken as (greedy) search can fall in local optima. Simulated annealing is an approach that attempts to avoid such issue by allowing an occasional downhill move. The method is motivated by a physical analogy on crystal growth processes [4]. The execution is based on a random number generator and a control parameter known as *temperature*. The algorithm, listed in Figure 3 involves a pair of nested loops and two additional parameters: a *cooling ratio* r, $0 < r < 1$, and an integer *temperature length* L. In Step 3 of the algorithm, the term *frozen* refers to a state in which no further improvement in cost (S) seems likely. The core of this procedure is the loop at Step 3.1. Note that $e^{\frac{-A}{T}}$ will be a number in the interval (0, 1) when A and T are positive, which can be interpreted as a probability that depends on A and T. The probability that a downhill move of size A will be accepted diminishes as the temperature declines, and, for a fixed temperature T, small uphill moves have higher probabilities of acceptance than large ones. Furthermore, the concept of *resets* will be used. If the algorithm loops by a given number of iterations without finding a better solution, it will reset to the last best known set of parameters.

1. Get an initial solution S.
2. Get an initial temperature $T > 0$.
3. While not yet *frozen* do the following.
   - 3.1 Perform the following loop L times.
     - 3.1.1 Pick a random neighbor S' of S.
     - 3.1.2 Let $\Delta = cost\ (S') - cost\ (S)$.
     - 3.1.3 If $\Delta > 0$ (uphill move),
       Set $S = S'$.
     - 3.1.4 If $\Delta \leqslant 0$ (downhill move),
       Set $S = S'$ with probability $e^{-\Delta/T}$.
   - 3.2 Set $T = rT$ (reduce temperature).
4. Return S.

Fig. 3. Generic simulated annealing algorithm.

D. Neighbour Search

In the simulated annealing algorithm, moving to a neighbour solution refers to finding a new set of parameters to evaluate the cost function. This can be done in two ways: fully random or with some control over the chosen parameter set. In the first case, the algorithm alters one or more parameters *moving* it within a finite search space based on a uniform random number generator. The second case involves a criterion depending on the current algorithm state, and can also involve a reduction on the search interval. Reducing the search interval produces convergence in late iterations, resulting in the algorithm functioning with a greed or hill climbing behaviour once a certain amount of the search space has been explored.

In the context our application, ground stations are represented in the parameter set by a list of coordinates of possible locations. In the case of satellites, orbital elements have defined limits that need to be considered. These limits can be further constrained taking into account some mission parameters such as launching capabilities or maximum range between satellites. In Table I, we present a list of orbital elements considered and the initial search interval.

TABLE I
SPACE SEGMENT PARAMETER BOUNDS

Orbital Element	Search Limits
Semi-major axis (a)	Admitted launch range
Inclination (i)	0 - 180 (degrees)
Long. of Ascending Node (Ω)	0 - 360 (degrees)
Argument of periapsis (ω)	0 - 360 (degrees)
Eccentricity (e)	0 - 1

It is of interest to further constrain the satellite parameter search space if targetting a desired formation. For example, satellites sharing the same orbit at different values of periapsis (along-track formation), renders a configuration that can be obtained with the same launcher, and can be designed to ensure ISL at constant distance between satellites. For an along-track formation, the limits have to be set according to the satellites height, and the desired margin above the earth for the line of sight between them. According to the Figure 4, for a given satellite formation height (H), the radius of the Earth (Rt) and a margin accounting for the atmosphere (atm) in a circular orbit, the maximum separation is given by:

$$\alpha = 2\cos^{-1}\left(\frac{Rt + atm}{H}\right) \qquad (2)$$

E. Maximum Accessibility Algorithm

The proposed simulated annealing algorithm is coined Maximum Asset Accessibility Algorithm (M3A). M3A can be depicted in eight steps, as illustrated in Figure 5. In S1 the assets initial states and the period and time step of analysis are defined. In S2 and S5 the orbit is propagated using an

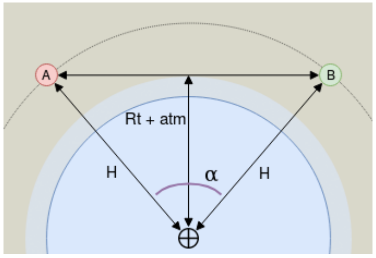

Fig. 4. Satellite formation phase.

orbit propagator, some options are J2, SGP4 or HPOP [5], [14]. As the precision of the propagator increases and the time step of analysis decreases, more computational resources will be required to execute the algorithm. In S3 and S6, the cost function is computed. In S4 the M3A algorithm finds a neighbour solution for the current iteration. In S7, the neighbour solution can be accepted either because the cost function has increased its value, or because the probabilistic criteria described in the annealing process is met. Lastly, in S8, the M3A algorithm checks if the stop criteria is fulfilled: either the temperature has decreased enough, or certain number of iterations have been successfully executed.

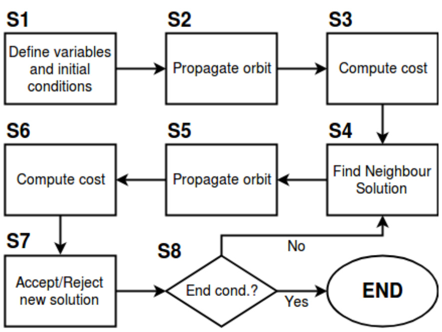

Fig. 5. M3A Algorithm flow

III. Case Study

To illustrate the M3A performance, the following case study is proposed. An hypothetical mission needs to put a satellite in a Low Earth Orbit with strong constraints. Said mission accounts for two ground stations, and budget to put three relay Cubesats flying in formation at a given height in a circular orbit, with continuous contact (ISL) between consecutive members of the formation. The goal is to optimize the inclination (i), Right Ascension of the Ascending Node (Ω) and Argument of Perigee (ω) of the relay network. Given that the Cubesats are flying in formation, the only parameter that will differ between them is the argument of perigee. Taking this into consideration, the parameter selected to be optimized will be the angle separation between them or *phase shift*, which will be considered equal among all relay satellites[1].

[1]A first guess on the optimal formation might be based on the maximum separation of relays as per Figure 4, however, this will also depend on the mission satellite orbit and the ground station location

TABLE II
Ground and Space Segment Parameters

Ground Station	Latitude	Longitude
CETT (ET 1)	-31.5253	-64.4628
Tolhuin (ET 2)	-54.5065	-67.0699

Satellite	Parameter	Value
MS	Semi-major axis (a)	6993 Km
MS	Eccentricity	0
MS	Inclination (i)	97.16 degrees
MS	Ω	211.41 degrees
MS	ω	79.57 degrees
Relay (All)	a	7371 Km
Relay (All)	Eccentricity	0
Relay (All)	inclination (i)	TBDA
Relay (All)	Ω	TBDA
Relay 1	ω	TBDA
Relay 2	ω	TBDA
Relay 3	ω	TBDA

This data is summarized in Table II, where TBDA stands for *to be determined by the algorithm*. The mission's satellite orbital elements stands for a realistic LEO Earth observation mission satellite which will be referred to as MS. The relay satellites will be named as Relay N where N = 1, 2 or 3. The analysis time is a 6-day period from July 1^{st}, 2019 to July 7^{th}, 2019.

Regarding the M3A, equation (1) will be used as the cost function. The minimum phase shift for the relay satellites is set to 5 degrees, and the maximum is given by the equation (2). The cost function will be visualized as percentage of the analysis period covered, meaning that 100% equals continuous access between the ground segment and the Relay Network and continuous access between the flight segment and the Relay Network. The free version of the System Tool Kit$^{\text{TM}}$(STK) will be used to propagate the orbits and obtain the access times.

1) Brute Force Analysis: To establish a baseline for comparison, a brute force analysis is performed with 10 degrees steps for inclination in a range from 0 to 180, 10 degrees step for the longitude of the ascending node in a range from -90 to 270, and 5 degrees step in a range from 5 to 53.85. This last figure is obtained from applying the equation (2). This analysis required 4536 iterations, the cost function values through iterations can be observed in Figure 6. The maximum value obtained for the cost function is 53.56%. Results for the optimization parameters using the brute force are showed in Table III. It is evident that the best phase shift value obtained is the maximum allowed by the algorithm. If this parameter is frozen, it is possible to plot the cost function against Ω and inclination, where multiple local maximums are evidenced, as shown in Figure 7. This type of behaviour makes heuristics capable of backing out from unattractive local optima especially useful, as previously discussed in Section II.

2) M3A Algorithm: Optimization using M3A algorithm is performed with the following parameters:

- Starting temperature: $Ti = 67.221$
- Final temperature: $Tf = 1$

- Temperature reduction factor: $r = 0.9832$

By running M3A for 250 iterations, the maximum value for the cost function obtained is 53.792%. The cost function values through iterations can be observed in Figure 8, while variation of parameters across iterations are showed in Figure 9. Final results for the optimization parameters are showed in Table IV.

A. *Results analysis and comparison*

The best value obtained by the cost function only varies by 0.43% between brute force and M3A methods. The M3A approach obtained the best value due to the unrestricted step in the parameters, unlike the brute force method where this constraint was applied to avoid excessive process time. Moreover, the optimization method was approximately 23 times faster than brute force. Simulating by brute force at smaller steps in a closer interval around the best value obtained earlier and considering the maximum phase shift, is possible to obtain a better optimal value. Running 400 iterations closer to the optimal point, provides a final cost of 54.063%. Resulting values can be observed in Figure 10. The resulting parameters are summarized in Table V and illustrated in Figures 11 and 12.

Results show that, for the proposed scenario, relying only on

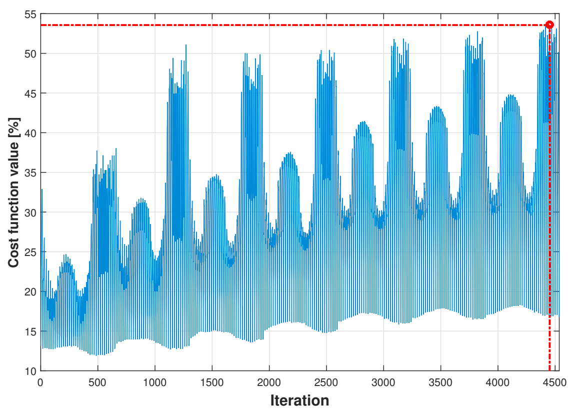

Fig. 6. Cost function values through iterations in brute force approach

TABLE III
PARAMETERS OBTAINED BY BRUTE FORCE

Satellite	Parameter	Value [degrees]
Relay (All)	inclination (i)	60
Relay (All)	Ω	220
Relay 1	ω	53.85
Relay 2	ω	107.72
Relay 3	ω	161.57

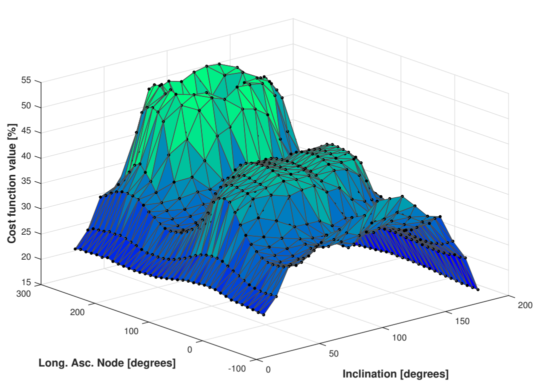

Fig. 7. Cost function against Ω and inclination in brute force approach

TABLE IV
PARAMETERS OBTAINED BY M3A

Satellite	Parameter	Value [degrees]
Relay (All)	inclination (i)	58.57
Relay (All)	Ω	202.15
Relay 1	ω	52.391
Relay 2	ω	104.78
Relay 3	ω	157.17

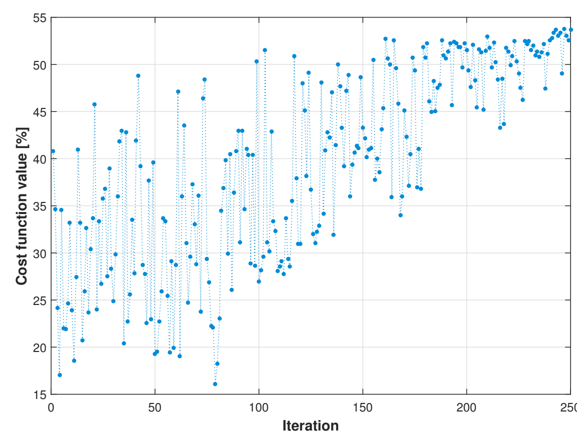

Fig. 8. Cost function values through iterations in M3A approach

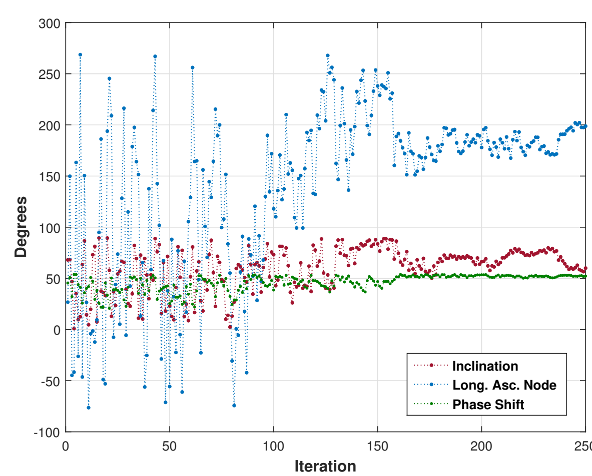

Fig. 9. Parameters variation through iterations in M3A approach

ground stations provides approximately 636 minutes of total real time access for the analysis period (8640 minutes). Then, the use of the relay network adds an additional 1527 minutes of real time access, for a total of 2163 minutes. The relay network can access the MS for 6685 minutes while the ground segment can access the relay network for 2769 minutes.

TABLE V
PARAMETERS OBTAINED BY BRUTE FORCE + 400 ITERATIONS

Satellite	Parameter	Value [degrees]
Relay (All)	inclination (i)	58
Relay (All)	Ω	205
Relay 1	ω	53.858
Relay 2	ω	107.72
Relay 3	ω	161.57

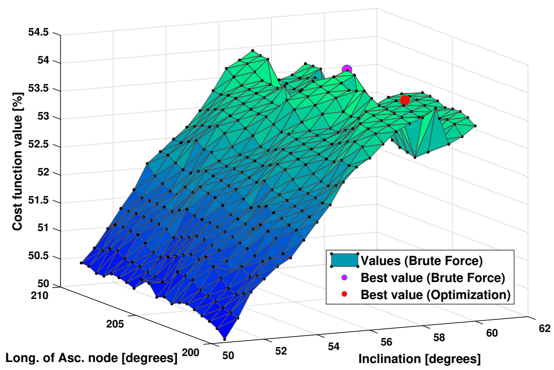

Fig. 10. Cost function against Ω and inclination at small steps

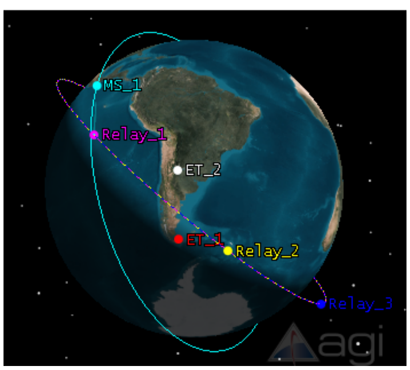

Fig. 11. Orbits overview in 3D

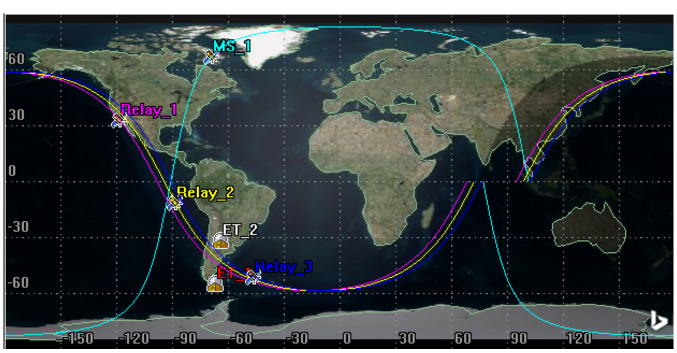

Fig. 12. Orbits ground tracks

IV. CONCLUSION

Obtaining access times for a given set of assets in a space mission requires a considerable amount of computational resources, especially if relay satellites are part of the flight segment. Although brute force may be used to obtain the best possible combination of values when some parameters are set fixed, different approaches are needed. In this context, we introduced M3A based on simulated annealing, which yields valuable results in reduced time. In a realistic case study, M3A provided a cost value of 53.79% when the optimal is 54%, however, exploiting a total of 250 iterations against more than 4500 in a brute force search approach. M3A is thus a valuable tool to explore the wide spectrum of possibilities that future satellite constellations can offer in the near future.

ACKNOWLEDGEMENT

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