

ORB GEO - An Orbit Selection Tool for Satellite Constellations Using the Multiobjective Generalized Extremal Optimization (MGEO) Algorithm

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INTRODUCTION

This paper describes a tool, OrbGEO, to be used in a concurrent integrated environment for space mission design and analysis, currently under development at the Space Systems Division of the Brazilian National Institute for Space Research (INPE). This environment, developed under the project PJESOPRoM (which, in Portuguese, stands for Project for Simultaneous Engineering and Multidisciplinary Design Optimization), is intended to integrate design tools using simultaneous engineering and optimal design methodologies to assist a multidisciplinary team to design and analyze, in a fast and efficient manner, different candidate solutions for a space mission.

OrbGEO will be used to rapidly design satellite constellations to meet the systems requirements, such as, regions of interest for coverage, maximum revisit time, and allowed altitude range. The tool in turn uses a multiobjective version of the Generalized Extremal Optimization algorithm (GEO) [1, 2] to search for a satellite constellation that minimizes the number of spacecraft and the mean orbital altitude, which will reduce the payload complexity, and maximizes the coverage of the regions of interest.

This new tool uses a simple orbit propagation algorithm to decrease the computational burden. Furthermore, the regions of interest are selected as latitude and longitude ranges and are discretized into simplified, uniform grids for coverage analysis. These design constraints are proposed to reduce the computational burden even if the accuracy of the solution is degraded. However it will be capable to quickly provide constellation proposals to meet the mission requirements such that the multidisciplinary team will be able to analyze trade-offs associated to the constellation selection during a design section.

NOTATION AND ABBREVIATIONS

CBERS		China-Brazil Earth Resources Satellite	
FOV		Field of view]
GSD		Ground sampling distance	

RAAN	Right Ascension of the Ascending Node
a	Semi-major axis
e	Eccentricity
i	Inclination
h	Satellite altitude
n	Satellite angular velocity
t_0	Initial simulation time
R_0	Mean Earth radius ($\approx 6371\text{km}$)
Ω	RAAN
ω	Argument of Perigee
α	Half-angle of the payload field of view

PROBLEM DEFINITION

It is proposed to develop a tool for conceptual design of orbits to be used in concurrent integrated environment for space mission analysis. This tool must be able to solve the following multiobjective problem:

- Given an Earth observation device, an analysis interval, and a region of interest, search the satellite constellations that **minimizes** the number of spacecraft and the mean orbital altitude and **maximizes** the accessible area (or **minimizes** the not accessible area).

It can be seen that these optimization objectives are conflicting, since a smaller number of satellites at lower altitudes clearly decreases the accessible area. Thus, it is expected that the Pareto frontier will not collapse into a single point. Instead, it will be a set of points in which the designer should choose the optimal solution for each problem. The OrbGEO is the tool responsible to solve this problem using the Multi-Objective Generalized Extremal Optimization Algorithm (M-GEO) and plot the Pareto frontier. The algorithm used in OrbGEO is described next.

M-GEO ALGORITHM

GEO is an evolutionary algorithm developed at INPE [1] that, along with its multiobjective version (M-GEO), have already been successfully applied to a myriad of optimization engineering problems, e.g., thermal design [3], structural optimization [4], satellite layout design [5], and spacecraft attitude controller for a rigid-flexible satellite [6]. Additionally, M-GEO has already been used for design satellite constellations that minimize the average and the maximum revisit time over a region of interest [2]. Thus, the selection of M-GEO algorithm was based on the heritage available at INPE, which greatly simplified the coding process of OrbGEO.

The flowchart of M-GEO can be seen in Fig. 1. Notice that M-GEO, unlike other Evolutionary Algorithms, has only one free parameter to adjust (τ). This parameter set the determinism degree related to the choice of a new generation. If $\tau \rightarrow \infty$, then the bit which yields the best gain in the selected function will always be selected to create the new generation, otherwise if $\tau = 0$, all the bits will have the same probability to be chosen [2].

MGEOpp

The M-GEO algorithm has been encapsulated into a CPP library called MGEOpp, built at INPE. This library is distributed under BSD license and available for download at <http://www.inpe.br/ete/dse/ronan>. It also supports parallel computing using OpenMP technology, such that the objective function evaluations at each generation (green rectangle at Fig. 1) can be divided into threads to decrease the execution time. This library was used to code OrbGEO.

ORB GEO DESIGN

OrbGEO must be capable to simulate a satellite orbit and to analyze the area on Earth accessible by the payload. Thus, using the M-GEO algorithm, it searches for solutions and compares them to plot the Pareto frontier. Details about the implementation of OrbGEO can be seen below.

Design Variables

The design variables are the six orbital parameters for each satellite in the constellation.

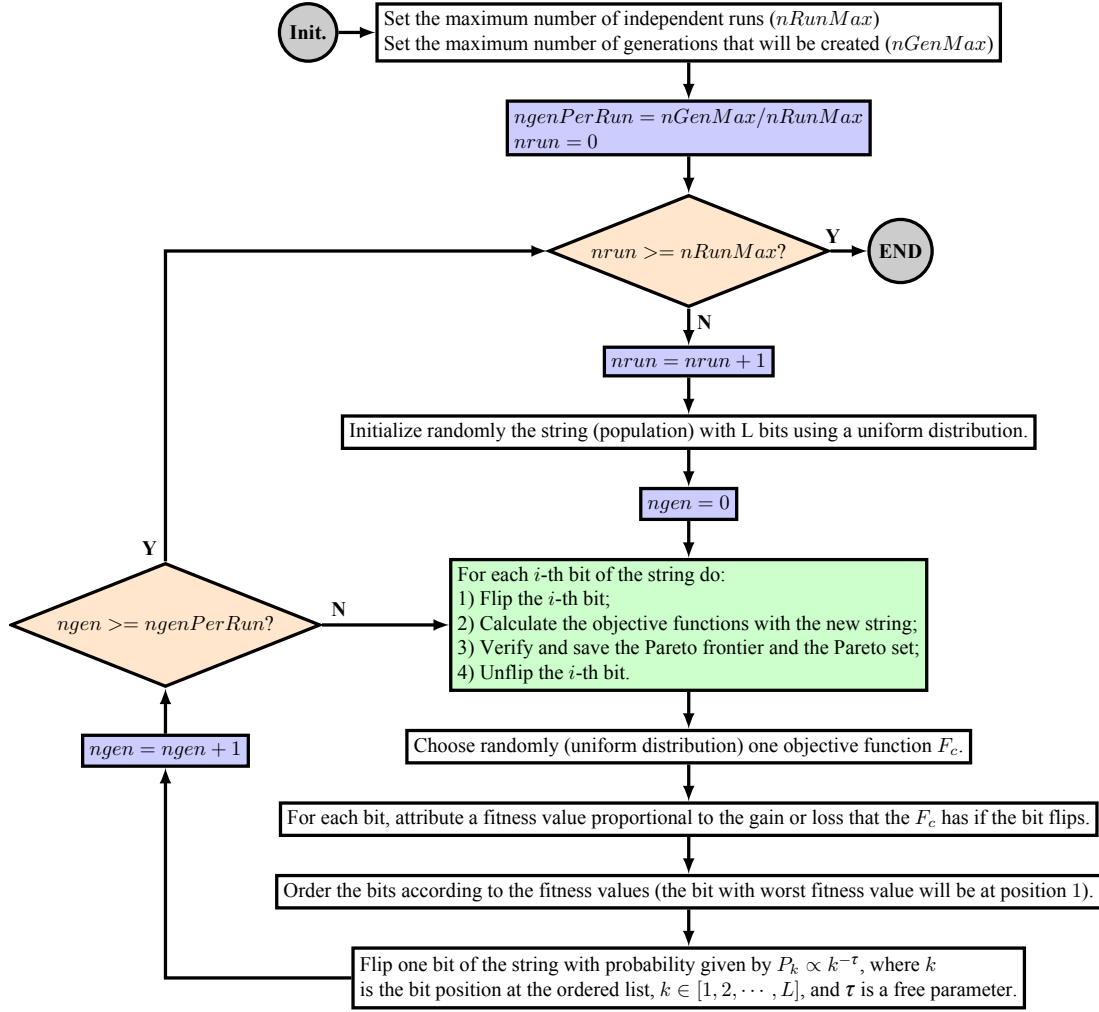


Figure 1: M-GEO flowchart (adapted from [2]).

Orbit Propagation

It is necessary to propagate the orbit within the analysis interval for each satellite. To decrease the computational burden, a simple algorithm was used as described next:

- For each sampling step, propagate the satellite position considering a Keplerian orbit [7, p. 45];
- At the end of each day, compute the new RAAN and the argument of perigee based on the perturbation theory as [7]:

$$\begin{aligned}
 \Omega &= \Omega_0 - \frac{3}{2} \cdot J_2 \cdot n \cdot \left(\frac{R_0}{a}\right)^2 \cdot (1 - e^2)^{-2} \cdot \cos(i) \cdot (t - t_0), \\
 \omega &= \omega_0 + \frac{3}{2} \cdot J_2 \cdot n \cdot \left(\frac{R_0}{a}\right)^2 \cdot (1 - e^2)^{-2} \cdot \left(2 - \frac{5}{2} \sin^2(i)\right) \cdot (t - t_0).
 \end{aligned} \tag{1}$$

Notice that this algorithm gives a very good approximation since the analysis interval is expected to be small.

Coverage Analysis

The coverage analysis was performed by uniformly discretizing the Earth surface in a $N \times M$ latitude-longitude grid, as shown in Fig. 2a. The discretization step in the grid is δ_j rad. Thus, for each sampling step of the orbit propagation

algorithm, the projection of the payload FOV on the Earth surface is computed and the squares that intercept this projection are marked as covered. One example can be seen in Fig. 2b.

Such algorithm is very fast but can lead to misleading results regarding the percentage of the area covered if the discretization step is too high. However, OrbGEO is created to be a fast tool for the first exploration of the possible orbits to accomplish a mission. The selected orbits will be further analyzed and tuned using more accurate techniques, which are not suitable to be used with optimization algorithms that require a high number of objective function calls due to the computational burden and the available hardware.

Notice, however, that this proposed algorithm can indeed be used to verify what areas can be accessed within the analysis interval. It can be proven that, for sufficiently small δ_g , if the satellite is capable to perform a roll maneuver of at least

$$\theta = \tan^{-1} \left(\frac{\sqrt{2} \cdot R_0 \cdot \tan(\delta_g) + h \cdot \tan(\alpha)}{h} \right) - \alpha, \quad (2)$$

then the satellite will be capable to observe any point inside the squares marked by the analysis. Thus, the marked area computed by this algorithm will be called **accessible area** instead of covered area to avoid misconceptions.

Finally, to compute the percentage of the area of interest that is accessible, it is necessary to sum the areas of all marked squares. Notice that the square area must be converted to the equivalent area on the Earth surface. This can be easily done noticing that, if the discretization angle is sufficiently small, then

$$A_{Earth}(i) \propto A_{square}(i) \cdot \sin(90^\circ - \lambda_i), \quad (3)$$

where $A_{Earth}(i)$ is the area on the Earth surface equivalent to the i -th square, which in turn has an area of $A_{square}(i)$ on the grid, and λ_i is the latitude of this square.

An example of result obtained from OrbGEO can be seen in Fig. 3. It was computed during 2 days the accessible areas of a satellite with a camera in which the FOV is $\pm 20^\circ$. The chosen orbital parameters were: semi-major axis of 7000km, eccentricity of 0.05, inclination of 63° , and argument of perigee of 0° . The color map in Fig. 3 indicates the minimum altitude in which a point on Earth can be observed. The algorithm computed that 57.1% of the Earth surface can be accessed by this satellite within 2 days.

Algorithm

OrbGEO algorithm is described next.

- Set the input parameters (see Table 1).
- Code any restriction in the orbit selection, for example, to search for only sun synchronous orbits.
- Execute the M-GEO according to the flowchart in fig. 1 in which the objective functions are computed as follows:
 - FOR each day DO:
 - * FOR each sampling step DO:

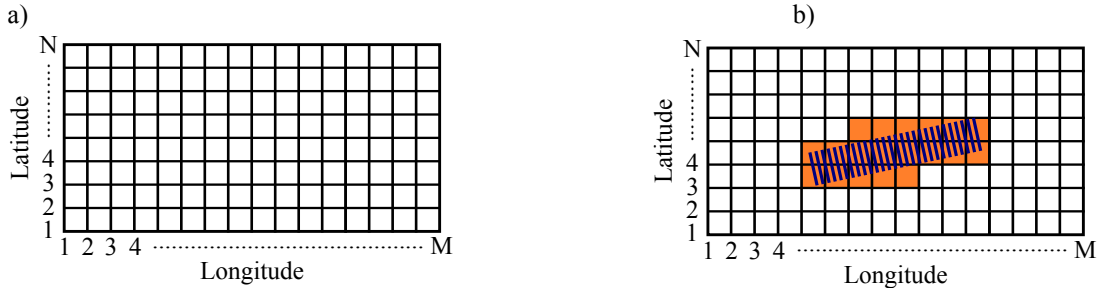


Figure 2: a) Latitude-Longitude grid. b) Example of a coverage analysis.

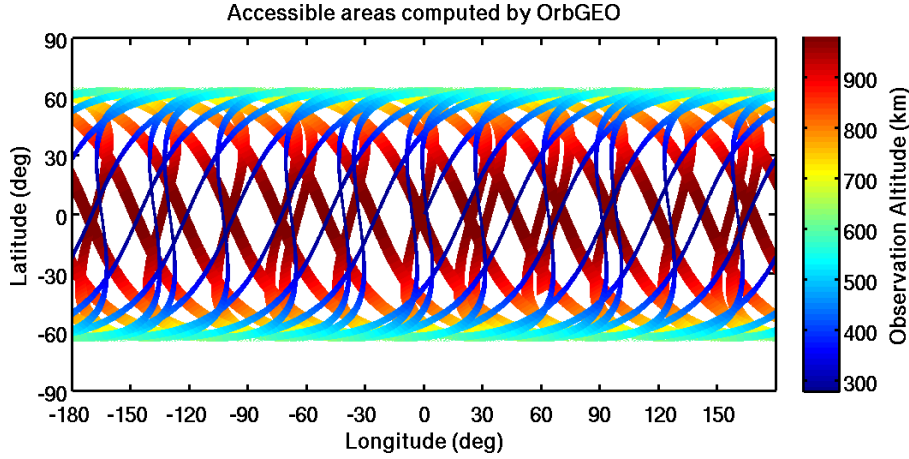


Figure 3: Example of the accessible areas computed by OrbGEO.

Table 1: Input parameters of OrbGEO.

Parameter	Description
<i>initialDay, initialHour</i>	The initial day and hour of the analysis.
<i>latMin, latMax</i>	The minimum and maximum latitude of the area of interest.
<i>lonMin, lonMax</i>	The minimum and maximum longitude of the area of interest.
<i>gridStep</i>	The discretization step of the latitude-longitude grid.
<i>step</i>	Orbit propagation step.
<i>FOV</i>	The payload field of view.
<i>checkLighting</i>	Inform if the payload can only make observations in sunlit areas.
<i>numSats</i>	The number of satellites in the constellation.

- Propagate the orbit using the Keplerian model;
- Compute the payload projection on Earth;
- Fill the latitude-longitude grid.
- * END DO
- * Update the RAAN and the argument of perigee using the perturbation theory.
- END DO
- Compute the percentage of area that is not accessible within the analysis interval and the mean orbital altitude, which are the objective functions.
- Store the Pareto set and plot the Pareto frontier.

This process must be run for $num.Sats \in [1, 2, \dots, S]$ to obtain the solution for satellite constellations with different spacecraft numbers.

EXAMPLE OF ANALYSES POSSIBLE WITH ORBGEO

In order to show the type of results OrbGEO can provide, two hypothetical scenarios were proposed here. The first one studies the accessible area of the entire Brazil territory whereas the second analyzes only the Amazônia rain forest region. Both scenarios consider an analysis interval of three days. For each scenario, two different cameras were tested. The camera 01 is a hypothetical medium resolution camera, with a FOV of $\pm 1.26^\circ$ and GSD of $\approx 5m @ 700 km$. The camera 02 is the WFI (wide-field imaging) camera that is used on CBERS missions, which has FOV of $\pm 28.65^\circ$ and GSD of $\approx 64m @ 700 km$. As stated earlier, this analysis assumes that the spacecraft are capable to perform a roll maneuver of at least 22° when the camera 01 is used and 15° when the camera 02 is used. Thereupon the results presented here are related to the areas that the payloads can access within the analysis interval.

Table 2: Input parameters for each simulated scenario.

Parameter	Scenario 1	Scenario 2
<i>initialDay, initialHour</i>	01-Dec-2014, 12:00 PM (UTC)	01-Dec-2014, 12:00 PM (UTC)
<i>latMin, latMax</i>	-34°, 6°	-14°, +8°
<i>lonMin, lonMax</i>	-74°, -33°	-80°, -45°
<i>gridStep</i>	0.5°	0.5°
<i>step</i>	5s	5s
<i>checkLighting</i>	True	True
<i>numSats</i>	[1,2,3]*	[1,2,3]*

*: For the camera 02, the case with 3 satellites was not simulated.

In these two scenarios, only circular orbits were searched. Additionally, it was considered that all satellites in the constellation have the same altitude. Thus, the design variables are:

- **Semi-major axis:** 6600km to 7500km (7 bits);
- **Inclination (for each satellite):** 0 to 180° (6 bits);
- **RAAN (for each satellite):** 0 to 360° (6 bits).

In previous tests for those scenarios, it was verified that if the initial true anomalies for each satellite are considered as design variables, then the Pareto frontier obtained is similar to that when the true anomalies are initially set to 0°. Thus, these variables were removed from the design space to reduce the execution time. For all simulations, $\tau = 3$ and the other input parameters for each scenario can be seen in Table 2.

The Pareto frontiers obtained by OrbGEO can be seen in Figs. 4 and 5 for the scenarios 01 and 02 respectively. The X axis is the percentage of the area of interest that is not accessible, the Y axis on the left is the altitude of the constellation, and the Y axis on the right is the GSD at Nadir. Additionally, the design variables of the selected points can be seen in Table 3 and 4 for scenarios 01 and 02 respectively. These two analyses were executed in a computer with an Intel® Core i7-7440 (@ 3.40 GHz) processor in openSUSE 13.1 Linux using 6 threads to compute the objective functions. The total number of generations was set to 30,000 and the number of independent runs was set to 50. The execution time was approximately **50 min** per satellite with camera 01 and **120 min** per satellite with camera 02.

A full analysis of the results for those hypothetical scenarios is not pursued here. However it is interesting to note that these curves provide to the orbit designer some constellation options that can be used to fulfill eventual mission requirements. These figures show the trade-off between the number of satellites, the ground sampling distance (or altitude), and the accessible area.

All the analyses presented here, which yielded more than 17,460,000 objective function evaluations (orbit propagation

Table 3: Design variables of the selected points for scenario 01.

Selected Point:	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Altitude (km)	1001	541	229	1122	619	243	782	307	562	364	229	824	534	229
Sat. 1 i (°)	157	174	34	146	149	157	146	149	103	146	140	103	94	100
Sat. 1 Ω (°)	166	17	280	189	137	143	131	143	343	149	165	200	149	194
Sat. 2 i (°)	171	157	6	151	154	149	-	-	77	160	151	-	-	-
Sat. 2 Ω (°)	97	108	303	189	137	177	-	-	154	131	234	-	-	-
Sat. 3 i (°)	149	34	154	-	-	-	-	-	-	-	-	-	-	-
Sat. 3 Ω (°)	137	349	171	-	-	-	-	-	-	-	-	-	-	-
Resolution (m)	7.22	3.90	1.65	8.09	4.46	1.75	5.64	2.21	52.2	33.1	21.0	75.1	48.6	20.9
Area Accessible	62%	56%	49%	53%	44%	39%	30%	24%	100%	98%	88.7%	100%	97%	68%

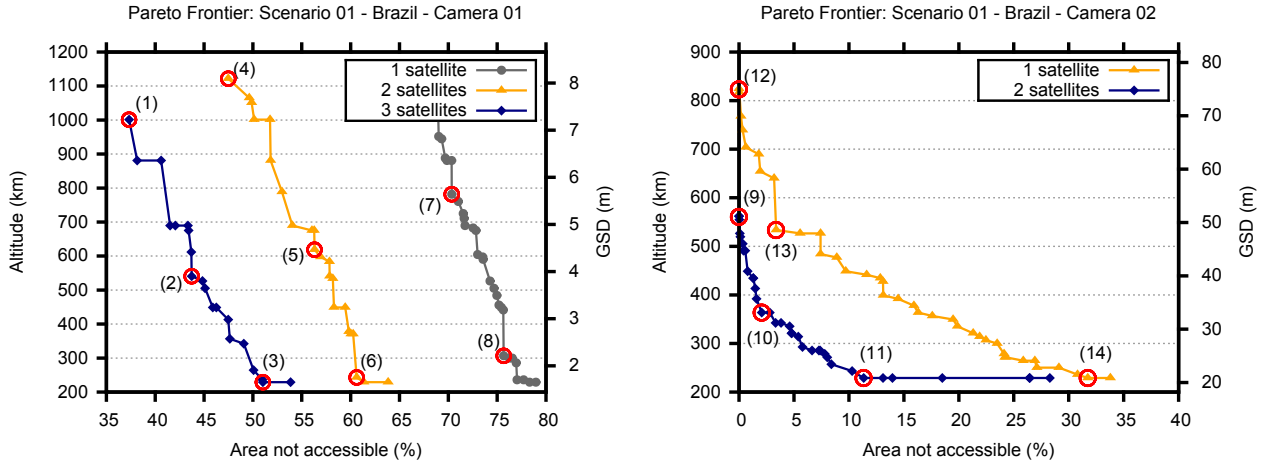


Figure 4: Pareto frontier computed by OrgGEO for the first scenario.

and accessible area analysis), were completed in less than **11 hours**. This result shows how OrbGEO can be used in a fast, efficient manner for the first exploratory search of constellations to meet the mission requirements.

CONCLUSIONS

A tool to be used in a concurrent integrated environment for space mission design and analysis, called OrbGEO, was presented in this paper. It uses the multiobjective version of the Generalized Extremal Optimization algorithm (M-GEO) to search for satellite constellations that, within a defined time interval, minimize the satellite numbers and the mean orbital altitude and maximize the accessible area of a region of interest.

The new tool uses a very simple orbit propagation and coverage analysis algorithm to decrease the computational burden. Thus, OrbGEO can be used in a fast, efficient manner to perform a preliminary broad search for constellations to meet the mission requirements. Thereon the designer can choose acceptable solutions that will be further analyzed and tuned using more accurate algorithms.

Two hypothetical scenarios were analyzed in this paper using OrbGEO. The first one aimed to study the accessible area of the entire Brazil territory whereas the other aimed to analyze only the Amazônia rain forest region. For both missions, it was considered one hypothetical medium resolution camera and the WFI camera that is used on CBERS missions. It was verified that OrbGEO is capable to compute the Pareto frontier very quickly, since all the simulations, which encompass more than 17,460,000 objective function evaluations, were completed in less than 11 hours.

Further improvements to OrbGEO include: 1) add an adaptive orbit propagation algorithm to decrease the computational burden; 2) improve the coverage analysis algorithm; and 3) add the number of spacecraft to the design variables.

Table 4: Design variables of the selected points for scenario 02.

Selected Point:	1	2	3	4	5	6	7	8	9
Altitude (km)	1093	272	1058	243	1065	229	257	456	250
Sat. 1 i ($^{\circ}$)	166	11	171	166	171	11	165	166	165
Sat. 1 Ω ($^{\circ}$)	91	302	0	143	211	286	126	97	63
Sat. 2 i ($^{\circ}$)	174	166	165	171	-	-	171	-	-
Sat. 2 Ω ($^{\circ}$)	97	160	137	217	-	-	257	-	-
Sat. 3 i ($^{\circ}$)	165	171	-	-	-	-	-	-	-
Sat. 3 Ω ($^{\circ}$)	126	251	-	-	-	-	-	-	-
Resolution (m)	7.89	1.96	7.63	1.75	7.69	1.65	23.4	41.5	22.8
Area Accessible	83%	75%	74%	61%	50%	36%	100%	100%	95%

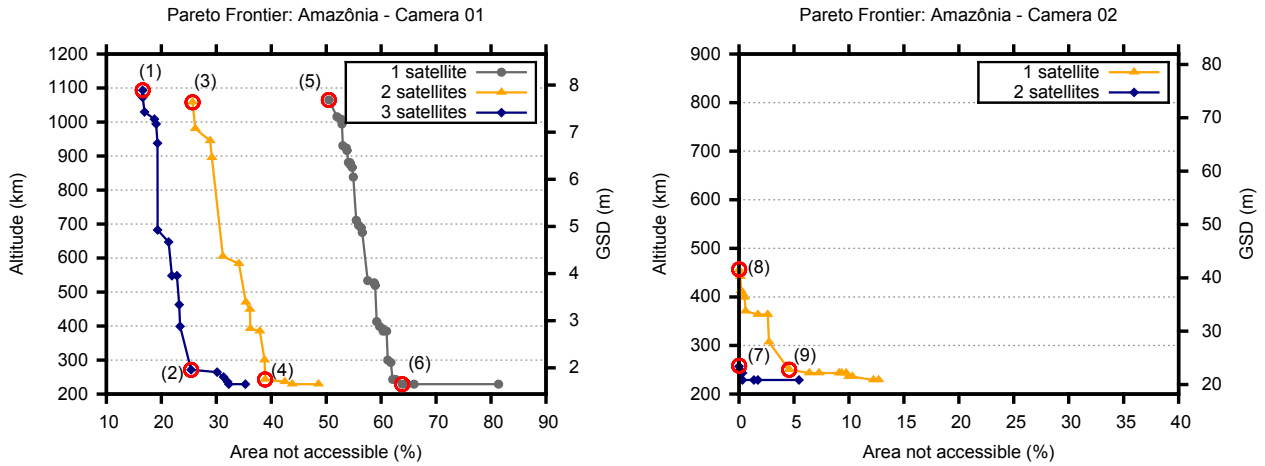


Figure 5: Pareto frontier computed by OrgGEO for the second scenario.

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REFERENCES

- [1] F. L. de Sousa, F. M. Ramos, P. Paglione, and R. M. Girardi, “New stochastic algorithm for design optimization,” *AIAA Journal*, vol. 41, no. 9, pp. 1808–1818, 2003.
- [2] R. L. Galski, F. L. de Sousa, and F. M. Ramos, “Application of a new multiobjective evolutionary algorithm to the optimum design of a remote sensing satellite constellation,” in *5th International Conference of Inverse Problems in Engineering: Theory and Practice*, Cambridge, UK, 2005.
- [3] A. P. C. Cuco, F. L. de Sousa, V. V. Vlassov, and A. J. da Silva Neto, “Multi-objective design optimization of a new space radiator,” *Optimization and Engineering*, vol. 12, no. 3, pp. 393–406, 2011.
- [4] F. L. de Sousa and W. K. Takahashi, “Generalized extremal optimization applied to three-dimensional truss design,” in *18th International Congress of Mechanical Engineering*. Ouro Preto, MG, Brazil: Associação Brasileira de Engenharia e Ciências Mecânicas, 2005.
- [5] A. P. C. Cuco, F. L. de Sousa, and A. J. S. Neto, “A multi-objective methodology for spacecraft equipment layouts,” *Optimization and Engineering (Online)*, 2014.
- [6] I. Mainenti-Lopes, L. C. G. Souza, and F. L. de Sousa, “Design of a nonlinear controller for a rigid-flexible satellite using multi-objective generalized extremal optimization with real codification,” *Shock and Vibration*, vol. 19, pp. 947–956, 2012.
- [7] J. R. Wertz, *Spacecraft Attitude Determination and Control*. Boston, United States of America: D. Reidel Publishing Company, 1978.