Dedicated Ground Segment Design for Small Satellites

Stefan Vlad Tudor[a*], Giovanni Zanotti[a]

[a] *Leaf Space S.p.A., via Cavour 2, Lomazzo, Como, 22074, Italy*
** Corresponding Author*

Abstract

The growing number of CubeSat and small platform being launched provides a large quantity of opportunities for various kinds of missions, from Earth observation, telecommunications, service delivery, and to scientific research. The possibilities are even wider considering formation flying or even constellation of small satellites. However, the deployment and operation of these platforms require extensive effort in defining concepts of operations and consequently the design of the dedicated ground segment. This paper examines the critical factors influencing ground segment design and satellite operations, considering the problem of selecting ground station locations to comply with the mission requirements.

The analysis addresses diverse mission requirements across various kinds of mission objectives, including Earth Observation (EO): High-resolution imaging and environmental monitoring, Telecommunications: Broadband and IoT connectivity, Scientific missions: precise positioning or pointing for payload acquisition.
Each mission type imposes unique demands on the ground segment infrastructure, such as latency requirements, data throughput, and ground station geographical distribution, based also on the orbital scenario it is posed into. We can categorise the missions also based on their orbits within the LEO orbital regime (equatorial, mid-inclination and Sun Synchronous Orbits) and the number of platforms involved which drives largely the concept of operations and the ground segment design. We can consider indeed three categories: Single Satellite missions, which involve straightforward contact allocation but may have more complex requirements; Formation Flying missions, which being orbitally clustered, pose more challenging contact allocation; Constellations, which present complex interdependencies between the satellites, also in this case requiring more complex ground contact management, such as automatically capacity allocation.

Contact management emerges thus as a fundamental component for managing increasingly complex satellite constellations. The paper discusses modelling approaches that generalise scheduling across diverse mission types, taking into account the satellite visibility and access windows, data throughput requirements, prioritisation and conflict resolution within multi-satellite systems.

Different cost functions are developed then to align with mission-specific constraints, balancing also infrastructure costs.

To define the potential ground station sites, different concerns are needed, emphasising peculiar infrastructure, regulatory, but also geopolitical limitations. Basic infrastructures needed for the ground station functioning, such as electricity, high-speed internet connectivity and security. Furthermore, the complexity to obtain authorisations for telecommunication by the national entities and the related costs is considered. Moreover, a lower risk of ground station operation associated with the political stability of the country is desired.

In order to provide a boundary to the problem, mimicking a resource-constraint scenario, cost caps for both CAPEX and OPEX are considered, ensuring financially sustainable ground segment development. Thus, the total infrastructure's cost of ground segment is one of the selection criteria for the optimal solution.

To illustrate the practical applications of the proposed framework, 3 case studies are detailed in the paper: Single Satellite SAR Mission: Operating at a low duty cycle; Scientific Formation Flight: Addressing operational constraints in no-transmission areas for a formation of two satellites; and Walker Constellation: Highlighting scheduling intricacies for a densely packed orbital configuration. These case studies underscore the adaptability of our models across mission types and operational scenarios.

This paper provides a comprehensive approach to addressing the challenges of CubeSat mission design, from ground station selection to advanced scheduling optimisation. By integrating mission requirements fulfilment, infrastructural, and economic considerations, we aim to deliver useful insights for efficient and optimal ground segment and operations design.

Keywords: *Ground Segment, ground station network selection, GSaaS, automatic scheduling*

Acronyms/Abbreviations

AOI	Area of Interest
ConOps	Concept of Operations
GS	Ground Segment
GSaaS	Ground Segment as a Service
LEO	Low Earth Orbit
MIO	Medium Inclination Orbit
PPD	Pass(es) Per Day
RF	Radio Frequency
SS	Space Segment
SSO	Sun Synchronous Orbit
POI	Point of Interest

1. Introduction

Ground segment design and selection is something that is often given less importance in the mission analysis and design process, especially in the CubeSat market, either for a reduced experience in the team or for time limitations. This could be really detrimental for many missions, in particular if the concepts of operations (ConOps) of the satellites are peculiar or demand specific complex requirements.

The design of the ground segment passes through many steps, one of which is defining the ground station network. This, practically speaking, means also defining the exact antennas to use based on their location and the expected performance for a mission.

To approach this task, it is fundamental to start from a set of possible antennas location, given that they are provided by a commercial network of stations or by institutional entities. Then, the orbital framework of the mission is necessary to analyse deeply the expected operativity and the main mission requirements in order to derive the dedicated ground station network requirements, such as minimum daily contact time or latency among others.

The communication scheduling strategy then comes in play, since it is the one in charge of defining which passes among the available communication contacts are to be selected. It could be either an automated algorithm or a manual selection procedure, with the second one practically applicable only in some reduced scenarios.

Once everything is in play, the actual selection of the sites can be performed by simulating and analysing the scenarios, always giving priority to the mission constraints and the associated design drivers.

The goal of this paper is then to present a set of analyses identifying three different categories of missions, from single satellite to a constellation, in order to show challenging scenarios for a ground station network selection.

After this introduction, Section 2 will go through the problem boundaries, identifying the list of considered ground stations for the analysis. Section 3 will present, in three separate subsections, three different case studies, starting from mission setup, passing through requirements and design, arriving to results analysis. Finally, Section 4 will recap the results and drive conclusions.

2. Problem boundaries: the pool of ground stations

As anticipated in the introduction, different aspects need to be accounted for when studying how to select the optimal ground station network, which is defined by two main variables:

- Number of antennas to include
- Location of the sites

The total number of antennas is obviously impacting, since the larger it is, the higher the performance that users of the network can achieve in terms of overall visibility time will be. There's an obvious counteracting factor which is the cost of its installation and utilisation. As a consequence, there is a clear trade-off between these two factors.

In addition to that, the location of the antennas is very important as well for two aspects. Its absolute location first is fundamental to determine the amount of contact opportunities that a given user will experience. This depends strongly on the orbital parameters and with these, quantities such as the number of passes per day, the duration or the latency between successive contacts are largely varying with the site coordinates. For example, in the LEO market, which is composed mainly by SSO satellites, high-latitude stations guarantee a higher performance. The absolute location is of paramount importance also in situations where a certain data latency after exiting a specific area of interest is required. In these scenarios, having antennas placed nearby the area of interest reduces drastically the latency of the acquired data.

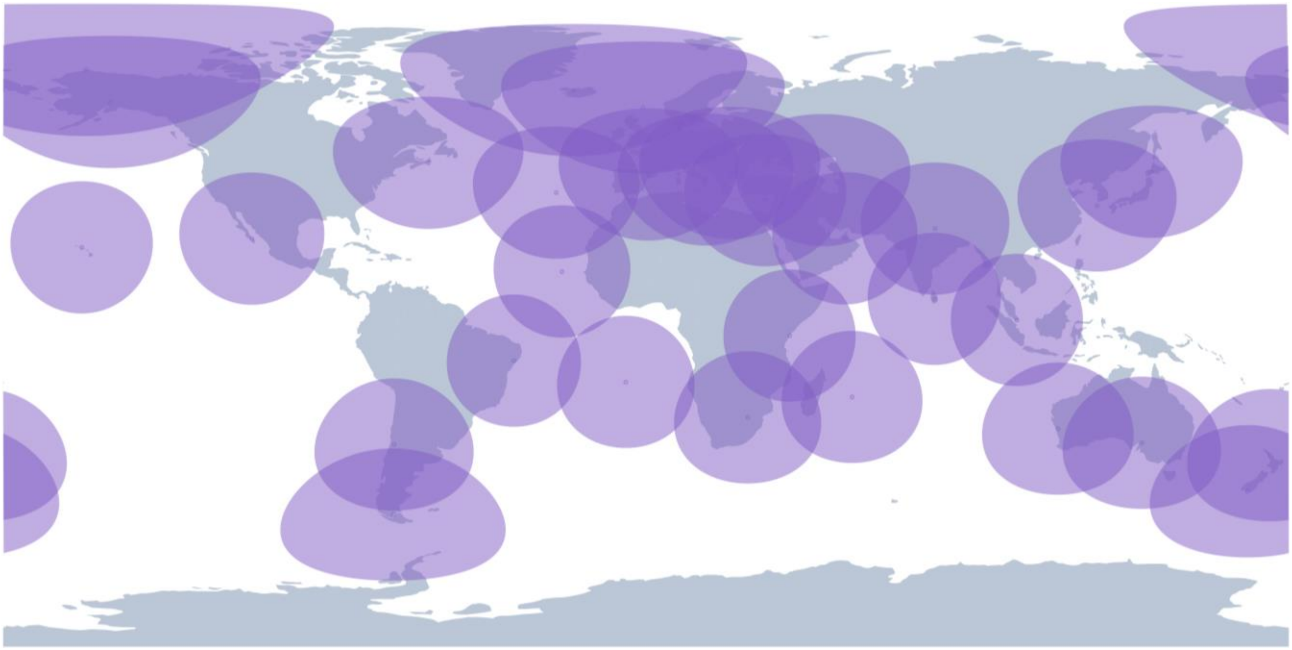

Figure 1: coverage map of the different sites.

Secondly also the sparsity of sites around the globe is fundamental, hence the location of a single site with respect to the others within the network, especially for indicators as latency and possibility to handle conflicting visibility windows. If on one side it is interesting to have antennas all in different locations to facilitate equally distribute opportunities, having multiple antennas on the same site helps in solving conflicts between different users. Such behaviour can be particularly relevant for constellations or formation-flying missions whose platforms can all be served together with separate antennas working simultaneously from the same, or from overlapping, sites.

For the current work, the pool of ground stations that are taken as a reference are composed by two subsets. The first one is represented by the list of ground stations available in the Leaf Line network, which is Leaf Space's proprietary network of antennas, including both already active terminals and those of future activation.

The list of Leaf Line sites is given in Table 1, where the final column indicates the number of antennas active on the site.

Table 1: list of Leaf Line sites (active or pending).

CODE	LOCATION	LATITUDE	LONGITUDE	#
AE02	UAE	24.2	55.7	2
AU01	Australia	-33	138.8	1
AU02	West Australia	-29	115.3	2
AZ01	Azerbaijan	40.5	49.5	2
BG02	Bulgaria	42.5	23.4	1
CA01	Canada	45.3	-61	1
CL01	South Chile	-53	-70.9	4
CL02	Central Chile	-33.5	-70.6	3
ES02	Spain	42.1	0.7	1
IS01	Iceland	65.6	-20.2	5
KR01	South Korea	33.4	126.3	1
LK01	Sri Lanka	7.3	80.7	1
MU01	Mauritius	-20.1	57.7	1
MX01	Mexico	24.1	-110.4	2
NZ01	New Zealand	-46.5	168.4	3
PT01	Azores, Portugal	37	-25.1	2
SH01	Saint Helena	-15.9	-5.7	1
UK01	Shetland, UK	60.7	-0.9	1
US02	Alaska, USA	62.3	-150	1
US03	Hawaii, USA	21.7	-158	1
US04	North Alaska, USA	71.3	-156.8	1
ZA01	South Africa	-25.9	28.5	2

The second subset of sites is provided by a list of potential additional locations that might be increase even more the global coverage of the whole network.

Table 2: list of potential additional sites.

CODE	LOCATION	LATITUDE	LONGITUDE
CV01	Cape Verde	14.9	-23.5
BR01	Brazil	-10	-37
CY01	Cyprus	34.9	33.4
IN01	India	26.9	81
JP01	Japan	42.8	141.6
KE01	Kenia	-3	40.2
IT03	Italy	40.6	16.7
NZ02	North New Zealand	-36.4	174.7
SP01	Singapore	1.4	103.8

All the considered sites are then represented in **Error! Reference source not found.**, where the coverage areas for a generic LEO satellite from each location are presented.

3. Analyses of different case studies

In this section the three different case studies are presented, starting each case with an introduction of the mission, defining main objectives and space segment setup, then deriving the driving requirements for the ground segment and finally performing the design. This will be done by selecting the appropriate sites among the presented ones, providing adequate analyses to support the decision and presenting the final results.

<u>**Case 1 – Single satellite SAR mission**</u>

The first scenario to be analysed is provided by a mission involving a single satellite equipped with a synthetic aperture radar (SAR) payload with the goal of acquiring data of Europe mainland.

The satellite is posed in a circular Sun synchronous orbit (SSO) at a 550 km altitude, thus with an inclination of ~97 degrees. Being Europe mainland the target of the SAR acquisition, a driver is to avoid having communication during the periods in which the satellites flies above the target area of interest (AOI). Given the large amount of data supposedly collected, the total capacity requirement is to have at least one pass per each orbit, hence, around 15 passes per day. It is important to remind that the AOI being quite limited in longitude extension, is visited only during 4 to 5 orbits per day, hence there are 10 to 11 orbits per day in which no acquisition is obtained.

Additionally, a driver in the ground station network selection is to minimise the latency after exiting the AOI. In order to pursue this driver, trying still to minimise the number of ground antennas to be selected, 4 sites are taken into account for this mission, namely IS01, US04, PT01 and SH01. These have been selected since they are near the exit from the AOI for both ascending (IS01, US04) and descending (PT01, SH01) legs. Even though two sites have partial overlap with the AOI, these have still been selected as the best options, since an additional strategy is used to ensure avoiding communication within the target area. This is achieved by trimming the passes above IS01 and PT01 in order to remove that portions of the pass that are within the AOI with an additional 30 seconds of margin to account for slewing manoeuvres. After trimming the passes shorter than 3 minutes of duration are discarded. A graphical representation of the coverage areas and the overlaps is presented in Figure 2, with the AOI in red.

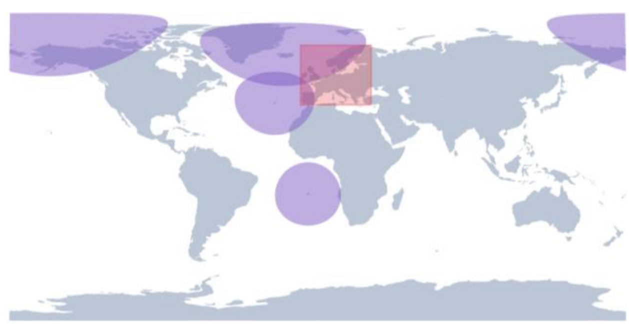

Figure 2: coverage map for the selected stations and the defined area of interest in red.

The passes allocation is then performed in the following way, keeping into account the minimisation of latency and ensuring at least 15 passes per day.
First, the latency minimisation is enforced. This is done by selecting the most suitable pass after each AOI acquisition window. To do this, the decision logics looks for the available passes within 10 minutes of latency. If there are passes, the longest one is selected and added to the schedule. If instead there are no passes within 10 minutes, the first available pass is selected. The strategy of keeping the

best pass among those within 10 minutes, regardless penalising slightly the latency, is used to favour longer passes, hence penalising those that were trimmed due to the overlap with the AOI.
After this procedure, the current schedule is based on a set of 4-5 passes per day, so still missing few to reach the minimum of 15 required. The filling is done by invoking Leaf Space proprietary scheduling algorithm, i.e. an optimisation algorithm to maximise the total duration of the assigned passes handling conflicts management and minimum daily contacts fulfilment (more details of this can be found in [1] and [2]).

The simulation is run for 10 consecutive days and the results are the following. Out of a total of 259 passes per 10 days, the schedule provided 151 passes, hence an average of 15.1 passes per day, amounting to 124 minutes of contact each day. The average latency after AOI experienced in the 10 days is 6.8 minutes, with a maximum value of 11.6 and a minimum of 0.5 minutes. This last minimum value occurs when a trimmed pass is selected, which occurs once per day for only 3 out of 10 days.
The experienced latency among consecutive passes is on average 87 minutes, with a maximum of 121 and a minimum of 65 minutes.

Case 2 – EO satellites

The second scenario focuses on the ground segment design for an SSO at 550km altitude, scientific mission, composed of two satellites flying in a chaser-target formation with an in-track separations of approximately 100km. The mission simulated is of an EO stereoscopic imaging with the mission objection to monitor 10 different points of interest (POI), randomly selected and defined in Table 3, below.

Table 3 Points of interest

POI	LATITUDE	LONGITUDE
Hawaii	21.31	-157.86
Mexico City	19.41	-99.14
Central Chile	-43.46	-72.81
Grindavik	63.84	-22.44
San Juan	18.4	-66.06
Napoli	40.85	14.26
Tenerife	28.29	-16.58
Cape Agulhas	-34.83	20.0
Tokyo	35.71	139.8
Central Australia	-23.71	134.05

It is assumed that observations can be made with an off-nadir angle up to 30degrees, between the zenith and instrument angle. From the geometrical point of view, this requirement can be translated into an Area of Interest (AOI) defined as 30deg around the POI from the ground perspective. The AOI is shown in red in Figure **3**.

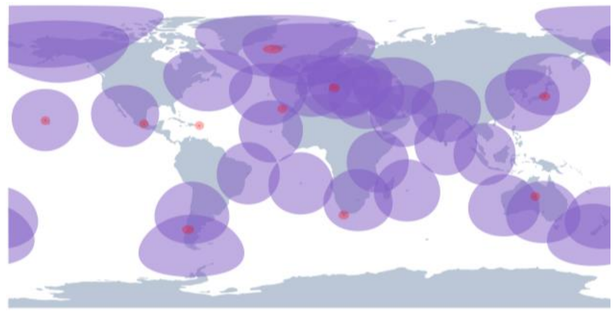

Figure 3 AOI projected on the coverage map with all the potential sites

During the observations, it is assumed that the platforms cannot communicate with the ground, thus all the potential ground contacts overlapping with the AOI shall be discarded. However, this does not mean a potential ground station location shall be excluded from the pool if it overlaps with an AOI, since there might be contacts which are not affected by the observations. Furthermore, pass trimming is not considered an option for this scenario.

The total capacity assumed per S/C is considered at 15passes per day per satellite, with no data latency need.

Table 4 Sites passes performances

CODE	LOCATION	PPD	PPD NON-TX
AE02	UAE	3.22	3.22
AU01	Australia	3.63	3.15
AU02	West Australia	3.5	3.17
AZ01	Azerbaijan	4.07	4.07
BG02	Bulgaria	3.77	3.33
BR01	Brazil	2.73	2.73
CA01	Canada	4.18	4.18
CL01	South Chile	5.22	4.5
CL02	Central Chile	3.53	2.82
CV01	Cape Verde	3.13	2.7
CY01	Cyprus	3.7	3.32
ES02	Spain	4.22	3.48

IN01	India	3.32	3.32
IS01	Iceland	9.97	9.08
IT03	Italy	3.95	3.52
JP01	Japan	4.1	3.5
KE01	Kenya	2.95	2.95
KR01	South Korea	2.27	1.97
LK01	Sri Lanka	2.78	2.78
MU01	Mauritius	3.15	3.15
MX01	Mexico	3.13	2.82
NZ01	New Zealand	4.73	4.73
NZ02	North New Zealand	3.77	3.77
PT01	Azores	3.8	3.37
SH01	Saint Helena	3.18	3.18
SP01	Singapore	2.67	2.67
UK01	Shetland, UK	7.33	6.45
US02	Alaska, USA	7.83	7.83
US03	Hawaii, USA	3.05	2.55
US04	North Alaska	10.7	10.7
ZA01	South Africa	3.2	2.72

Considering the locations pool presented in Table 1 and Table 2 a satellite-ground analysis is made to evaluate the communication opportunities and the impact of AOI. In Table 4 are presented the average number of passes each location provide by excluding the AOI (PPD column) and considering the AOI (PPD NON-TX column), averaged over 30days. In the period there stated there are 318 observation opportunities. The performances provided are per satellite and do not consider the overlaps between satellites or ground stations (overlapping visibility).

Analysing the individual sites performances, a few conclusions can be drawn. Firstly, the number of potential contacts discarded is less than 1 per day per satellite and it is increasing with the site latitude (e.g. the higher the latitude, the higher the reduction). Secondly, there are location that do not have degradations since there is no AOI inside the coverage (e.g. Alaska, Saint Helena, New Zealand ...). Third, the number of contacts is driven by the latitude. As expected, for an SSO orbit, the higher the latitude, the better are the performances of the location. Thus, a location such as IS01 will have better performance than a lower latitude location (such as SH01 or SP01), even though it suffers performances degradations due to satellite operations.

Considering the mission requirements, the above logic and the locations performances, the following network is selected as baseline: 2 antennas in US04 and 2 antennas in IS01. With this ground station network, the EO mission will receive between 36 to 42 passes, which translate between 305-350minutes per day for both satellites. The maximum latency between the consecutive passages is below 196minutes, due to contacts discarded for observations.

Case 3 – Walker constellation

The last case study takes in consideration a generic Walker constellation. The mission objectives in this case is not particularly interesting, since the goal is to define a challenging scenario due to the large number of conflicting satellites. Indeed, the considered space segment is made of a 56°: 24/3/1 Walker constellation, which translates into having 24 satellites on 3 different planes with a 56° inclination.

The requirement in this case is to provide a minimum of 100 minutes of contact per satellite, which can be converted to a minimum of 13 passes per day (considering an average pass duration of 8 minutes).

In this case the full potential of Leaf Space scheduler is exploited to generate an optimal schedule for the satellites, solving conflicts of overlapping passes and ensuring the minimum pass requirement.

The first analysis performed for the ground network selection is to look at the performance obtained assigning the whole network. It is here relevant to highlight how adjacent satellites can experience up to almost 200 conflicts per day in this situation.

Without putting a maximum number of daily passes, the total number of scheduled passes varies from 52 to 60. If using all the ground stations was not a real problem, it would be easy to put a maximum value of e.g. 15 passes per day and just stick to this value. If however, the goal is also to minimise the number of stations used to reduce either CAPEX or OPEX costs, additional work is needed.

In this case, being the satellites at mid inclination, the stations providing the highest performance are those at medium latitude, hence it is advisable to select a basic amount of these stations.

Based on expected performance of the sites for mid inclination satellites, the number of 5 antennas from

5 sites are selected, representing only those with latitude between 30 and 40 degrees in both hemispheres.

The list of stations in this case is the following:
AU01, CL02, PT01, NZ02, CY01. Both CL02 and PT01 have multiple antennas on the site, but for the simulation only a single one has been used.

The results for this optimised case present that all the satellites are able to receive the minimum of 13 passes per day, with peaks of 15 and an average value of 14.4, resulting into an average total contact time of 154.5 minutes per satellite. The average latency between passes experienced by the satellites is instead 86.7 minutes.

4. Discussion and future works

In the previous sections we described and detailed the complexities of designing ground station networks to fit diverse and challenging mission scenarios.

First the problem has been presented from a general perspective, detailing which are the boundaries of the problem and identifying the list of available sites for the selectin of the ground segment for. For the sake of this article, Leaf Space proprietary antennas have been considered, with the addition of a few potentially interesting sites.

Then each one of the three case studies has been detailed, starting with the scenario setup description, the collection of the requirements and then the design and results presentation.

The first case study proposed a SAR mission with a single satellite, whose challenge was to minimize the latency of the contacts after exiting a specific Area of Interest, still maintaining at least one contact per each orbit. The second case study consisted of a formation of two satellites acquiring stereoscopic images on a list of targets around the globe. The goal in this case was to maximize the total contact time avoiding communication within the observation windows. The last case instead considered a Walker constellation of 24 satellites on 3 separate planes, with specific requirements in terms of daily capacity, where the goal was to minimize the total amount of stations used, in order to reduce the operational costs to the minimum.

The solutions provided were not considering specific ground segment operational constraints or requirements, such as total cost and operational of the network, outages due to maintenance, 3rd party outages (i.e. internet, electricity…) or reliability. This types of limitations shall be considered when designing a dedicated ground segment, to ensure the level of service.

The paper overall presented three challenging scenarios in which the ground segment selection is not always straightforward and for which also dedicated concepts of operation are necessary for both identifying and then selecting the passes for a successful communication schedule.

References

[1] Zucchelli, E., Battista, R. D., Pandolfi Bortoletto, G., & Rebellato, L. (2018). Automatic Scheduling for a Ground Segment as a Service Platform Dedicated to Small Satellites.

[2] Pandolfi Bortoletto, G., Stigliano, F., Melli, D., Martin, D., & Gardosi, F. (2021). Maximize contact availability of smallsat clusters through MSPA technique on GSaaS.