Boosting Small Satellite Missions for Earth Observation at Regional Level: Main Drivers and Experiences

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Abstract The Earth Observation (EO) of specific regions requires tools operating on a stable and a repetitive basis. Small satellites (SS) are nowadays a mature technology, allowing continuous and high quality terrain observation. Consequently, space EO is becoming more affordable for new actors. A regional EO mission can become the driver to introduce geoinformation in the management, planning, evaluation, and analysis chains. Therefore, it represents a strategic opportunity to initiate or strengthen the leading on geoinformation activities. In this paper we describe our experience with the preparation and design of the MEDIMAP (MEDIterranean MAPping) projected SS mission for EO of Catalonia (Spain). We present the high-level mission analysis and design, with a set of constraints concerning the technological parameters of the satellite. The goal is to maximize both the final product quality and the benefits to the region. We also perform a specific analysis of the requirements of the payload. The analysis shows that MEDIMAP is an optimal approximation to establish collaborative and excellence generation in knowledge and economical activity in the strategic sector of geoinformation. Furthermore, the experience gained in MEDIMAP can be applied to other missions.

Keywords: Small satellite, regional, Earth Observation, MEDIMAP, multispectral

1. Introduction

The spatial and temporal variability of many regions has exponentially increased, mainly due to the increasing social, economic and environmental intervention of humans. Hence, regions need more effective tools for EO. The information generated can be used in reconnaissance, evaluation, planning and management of the territories. On the other hand, SS represent a mature technology, delivering high quality material (e.g. observational data) on a repetitive basis. The successful incorporation of COTS (common-off the shelf) technologies has opened a new scenario for the feasibility of the access to space. COTS components bring low-power and compact elements together with important decreases in costs. Consequently, previous impossible scenarios have turned into feasible options in just a few years. In this context, the Catalan Programme for Earth Observation (PCOT), acting as the main actor, has coordinated the studies and design of a SS mission named MEDIMAP, currently in phase B0. Its main statement is to catalyse the introduction of satellite geoinformation in Catalonia running an owned platform, while maximizing the return to the local industry and the added value public and private actors.

	696.68 (km) I 98.17º, Cycle 7	623.54 (km) I 97.88º, Cycle 10	687.43 (km), I 98.14º, Cycle 10
Max. coverage gap **(days)**	4.79	4.98	4.79
Min. coverage gap **(days)**	2.275	3.315	3.196
Time average gap **(days)**	3.94	4.94	4.72
Mean response time **(days)**	1.97	2.47	2.36

Table 1. Merit figures for several MEDIMAP orbits studied for the mission

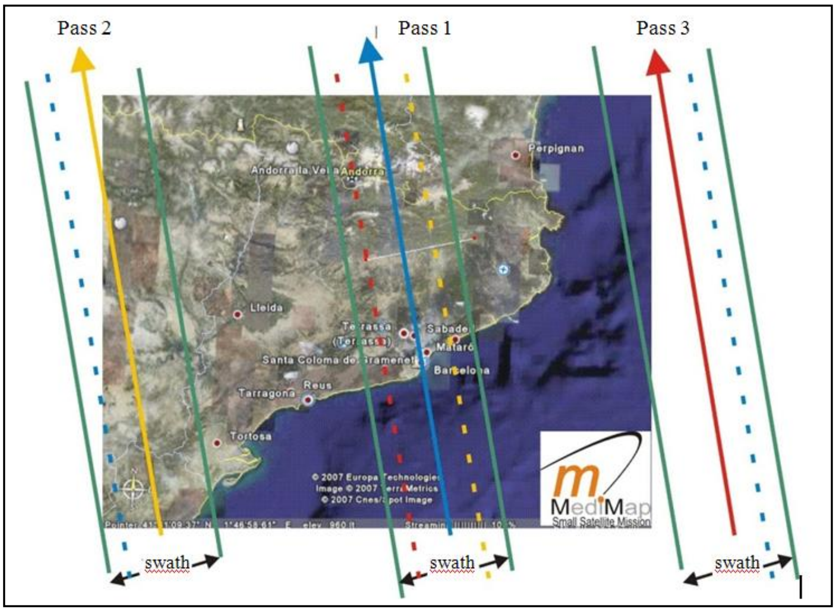

Figure 1: There are three different passes over Catalonia inside a repetition cycle (7 or 10 days). The dotted lines represent the limits of the access over the territory for each colour. Thanks to the off-pointing capability the mean access time is lower than 3 days.

2. Mission Description & Analysis

The main requirements for an EO satellite are related to the solar illumination conditions of the territory, its revisit time, the spectral bands available and the ground sample distance (GSD). These boundaries ultimately impose a certain level in the time response and the data quality. Hence, they affect the quality of the products and services that MEDIMAP offers to the society. Considering all these constraints, we have found that the optimal orbit is a sun-synchronous one – to guarantee a constant illumination – between 550 and 700 km (LEO). Specifically, the ascendant node should be around 10h30. Moreover, the revisit time must allow weekly access planning over the territory. These two values concern the orbit. On the other hand, to have an optimal quality and utility of the data, the GSD must be lower than 10 m. Currently, most of the multispectral missions use only 4 bands. However, a higher number of bands would be welcome.

The orbital analysis performed has allowed us to identify 3 different orbits which comply with the previous requirements. Their revisit, access and response times are shown in Table 1. However, MEDIMAP requires an off-pointing capability of 20º. The angle has been found through the orbital and coverage analysis. The response time of the last row of Table 1 has been evaluated considering this off-pointing. In Fig. 1 the simulated trace and coverage of the different satellite passes over Catalonia are displayed.

The communications requirements, e.g. transmission bands, data rate, contact times, etc., will determine the data volume generated by the satellite. Furthermore, they will also condition the ground segment architecture and the number of ground stations (GS) required. This ultimately defines the kind of data exploitation strategy that can be applied. Consequently, we have designed a model to simulate the capacities, priorities and dimensions of the communications system. In this way, the data exploitation capacities of the ground segment can be evaluated for different scenarios. In the simulation model several parameters have been considered such as the telemetry and scientific data frequency bands, transmission rates, instrumental bands, GSD, storage capacity, latitude location of the *GS* and priorities over different territories (Catalonia, Spain and the rest of the World).

PCOT OPTICAL/MULTISPECTRAL INSTRUMENT

Initial data		
Swath	**70**	km
Pixel	**8**	m
bits/pixel	12	
Security ratio in data transmission	1,1	
Compression ratio	1,4	
MS bands	**6**	
Cycle	10	dies

	Pass 1	Pass 2	Pass 3
Typ. Adq. Length Catalonia (km)	180	170	150
Typ. Adq. Length Spain (km)	800	800	800
Typ. Adq. Length Rest of world (km)	16000	16000	16000

Adquisition Scenario	Adquisition passes	km2/cycle visible	Adquisition Criteria	%	km2/cycle Image
Catalonia	3	35000	Maximum	100	35000
Spain	3	168000	Prioritary	100	168000
Rest of the world	97	108640000	Minimum	1,0000	1086400
Total					142 GBytes/cycle

Station	Barcelona (Latitude 41)			Svalbard		
Number of passes with visibility	19	8	8	55	21	17
Max. Visibility time (min)	8	6	4	8	6	4

Transmission scenario (Mbps)	50	100	200	
Barcelona	87	174	348	GBytes/cycle
Data adquisition ratio	61%	122%	244%	
Barcelona + Polar station	237,75	475,5	951	GBytes/cycle
Data adquisition ratio	167%	334%	668%	

Table 2: Simulation of the ground segment with the data exploitation model. Results obtained with the model depend on the spacecraft bus and communications performance.

Spectral Band	Recommended SNR	Recommended MTF (@ Nyquist freq.)
Blue Band	70	0.25
Green Band	85	0.25
Red Band	85	0.25
Red Edge Band	75	0.20
NIR Band	75	0.20
Extra Bands	>60	> 0.20

Table 3: Summarize of the minimum requirements of radiometric quality for MEDIMAP payload.

Attitude requirements	Recommended value	Units
Pointing knowledge at nadir	20	arcsec
Pointing accuracy	120	arcsec
Pointing stability	2.5	arcsec/sec
Navigation accuracy	<40	meters

Table 4: Summary of the pointing requirements to guarantee the image quality.

In Table 2 we show that with a satellite design of 6 spectral bands and a GSD of 8 m we need to use the two GSs scenario for a 50 Mbps data link. On the contrary, for data links equal or greater than 100 Mbps a GS in Barcelona is enough. Therefore, the exploitation of MEDIMAP with a single GS in Catalonia is feasible but with priority-based information recovery.

A satellite can be ultimately considered as a bus together with different subsystems, e.g. electrical, attitude, etc. The most interesting subsystem from both the scientific and the exploitation point of view is the payload. In order to define an EO payload an analysis of its optical and geometrical characteristics is mandatory. The main objective of the planned mission is to provide quality EO data, products and services, i.e. geoinformation. Thus, we need to analyse and to define the quality requirements of the payload. The radiometric conditions have been defined according to the information gathered from different suppliers of satellite payloads. We have defined a technological feasible scenario and its associated quality. Concerning the SNR and the modulation transfer function (MTF), for each band different levels have been imposed. In Table 3 these levels have been detailed.

A key set of parameters of the spacecraft – for mapping agency as ICC – is the pointing budget. They have also been set from the information disclosed by different suppliers. These values are very important, as they guarantee the image quality and optimise the added value chain. The selected values are shown in Table 4. At this point it is also necessary to consider the off-nadir angle orientation impact on the sensor. This is important because the angle allows maintaining a good access time over the territory. Nevertheless, it also increases the geometric distortion in the image (GSD degradation). We have determined that an angle lower than 20º fulfils both requirements.

Summarizing, our analysis shows that it is feasible to define a series of constraints that match the requirements of the payload subsystem for mission analysis, within the current technological scenario of small satellites. This mission can be thus designed in response of the Catalan EO particular necessities.

3. Ground Segments Analysis

The GS deals with the spacecraft control and mission data reception tasks. Moreover, this segment must also manage the data exploitation and the user service. The starting point for has been the consideration of two different scenarios. The first one is a unique *GS* located in Catalonia. The second scenario is a combination of two different *GS*s, namely, a Catalan station (first scenario) and an additional one in higher latitude.

Considering the economical impact and the costs (both recurring and non-recurring), the GS design has been oriented to size up both the exploitation capabilities and the architecture. The goal was to optimise the performance and the regional industrial return. Therefore, the modelling of these requirements has been done, although constrained by some realistic assumptions [1]:

- The masking for a correct reception/transmission between the ground segment and the spacecraft is 10º.
- The minimum contact time is 2.5 minutes.
- In the passes where the satellite is retrieving EO data it is not allowed to download scientific data with the spacecraft.

Considering these conditions, the visibility time and the number of passes with satellite communication at 41º latitude has been calculated. They are displayed in Table 5. We can see that the total contact time may differ significantly for orbits with a similar height. Hence, it is extremely important to consider this feature. Consequently, both scientific and technical criteria must be considered in the orbit designing phase.

H (km)	***T total (min)***	***Min. T (min)***	***Max. T (min)***	***Number of intervals***
696.68	*180.51*	*2.56*	*9.53*	*25*
623.54	*220.36*	*3.01*	*8.73*	*32*
687.43	*251.49*	*2.55*	*9.44*	*34*

Table 5: Summary of the contact and communication times for different orbit candidates for a ground station located at a 41º of latitude.

4. Feasibility and Utility

The concept and the mission architecture have been defined to provide society with geoinformation. This covers from data and products to related added value services. The basic aim is to offer data with different processing levels: from raw images in different capture or projection modes, to elaborated products and services with a high added value (e.g. change detection and tracking). Thus, the GS analysis must also address the regional necessities in data, products and generation and exploitation services. Bearing this objective in mind, the following considerations have been established:

- The GS responsible of the processing and storage of the satellite data will be based in Catalonia.
- A platform and a control segment will be built paying special attention to the parameters associated with the attitude and orbit control. This is carried out to guarantee the quality of the geoinformation.
- Data, services and product requests will be centralised. Additionally, it would be interesting to centralize the planning of the tasks in order to guarantee the resource optimization and the operational activity of the satellite.

The GS design features two different antennas, one in the S-band – satellite control – and another in the X-band for mission data reception. Although it is technologically possible to group both communications on the same channel, the GS is further optimised with different antennas. However, the front-end may be common.

Measuring the utility of a satellite mission consists on establishing a trade-off between the design, cost, risk and established planning to achieve a certain performance. In other words, we look for the lowest mission requirements that can accomplish the planned objectives. The mission utility is derived from the necessity of coupling the technology and its possibilities together with the knowledge and the necessities of the potential users. This utility includes the generation of data, products and services to answer the Catalan society necessities. All this production will be used to evaluate, manage and create policies that suit better to the territorial changes. Table 7 presents a summary of the potential applications of the mission, considering its current definition.

MEDIMAP will use the VNIR spectra range. Specifically, we have allocated 3 bands in the visible part, and 2 additional ones in the NIR. There is an extensive knowledge on this range, and it perfectly suits the objectives of the mission in EO with the best ratio between performance, risks and costs. Additionally, the heritage of ICC provides tools and techniques to extract the territory information with a high added value. Furthermore, there is a wide range of spatial and temporal series of data, and sensors covering this range of frequencies. This allows a synergy with other sources of information. Finally, it gives continuity to the current segment of knowledge and applications on EO inside the Catalan region. The different bands are to be used for different purposes, such as obtaining bathymetric information of coastal zones (solids in suspension, water eutrophication, cloudiness, etc.) , discrimination between snow and clouds, the type and state of the vegetation (absorption by the vegetal pigments, namely, chlorophylls, carotenes and xanthophylls), ground humidity and evapotranspiration, fire risks and vegetation and desertification indexes, among others.

Parameters	**Value**		
Orbit	Sun-synchronous		
Height (candidates)	623 km, 689 km, 696 km		
Off-pointing range	Across scan orientation between -20º and 20º		
Swath	50 km < swath < 70 km		
GSD	Nominal 7 m. During off-pointing < 10 m		
Response time over the territory	3.5 days (696 km), 2.5 days (623 and 689 km)		
Revisit time	7 days (696 km), 10 days (623 and 689 km)		
Pointing knowledge at nadir	20 arcsec		
Pointing accuracy	120 arcsec		
Pointing stability	2.5 arcsec/sec		
Navigation accuracy	40 m		
Spectral range	Visible (3 bands) and NIR (2 bands)		
Spectral bands	450 nm – 890 nm (VNIR)		
	Range	**SNR**	**MTF**
Band 1	440-510 nm (blue)	70	25
Band 2	520-590 nm (green)	85	25
Band 3	620-680 nm (red)	85	25
Band 4	690-730 nm (IR 1)	75	20
Band 5	850-890 nm (IR 2)	75	20
Additional spectral bands	Possibility of 3 additional bands		
	Range	**Utility**	
	440-460 nm (band 6)	Water quality and solids in suspension	
	760-840 nm (band 7)	IR, vegetation and biomass	
	520-540 nm (band 8)	Xanthophylls, pigmentation and eutrophication	
Ground Segment and exploitation	Different stations:		
	Satellite control in S-band		
	Mission data in X-band (40 – 70 Mbps)		

Table 6: Summary of the features and requirements for a small satellite mission to answer the necessities of the Catalan society.

Emergencies - Risks	Efficiency	Management - Planning	New applications
Risk maps	Agriculture	New infrastructures	Agreement monitoring
Damage evaluation	Forest status	Afectation and monitoring	Tourism
Vulnerability studies	Hydric resources	Changes and cartography	Synergy sensors
Emergency situations management	Land use	Feasibility studies	Projects in the world

Table 7: MEDIMAP will obtain territorial data for a wide segment of applications. They are differentiated between basic and thematic applications.

Concept	Relative Cost (%)	Concept	Rel. Cost (%)
Satellite	48	Launch assurance	9
Payload	17	Spatial infrastructure Total	96
Launch and logistics	21	GS: command and control	2
Orbital-test phase	1	GS: mission data	2
MEDIMAP satellite Total	87	Ground infrastructure Total	4

Table 8: Infrastructure relative cost of the MEDIMAP mission.

5. Economical Analysis

An extensive economical analysis of all the factors involving the mission has been carried out. The first premise is that nowadays the only projects entirely founded by private companies show Internal Rate Returns (IRR) around 25%, for a 5-year mission lifespan [2]. Unfortunately, EO is still far from these parameters. Consequently, it seems reasonable to split the cost of such a mission in two parts (*ppp* model). The private industry could found the GS and the data exploitation side. On the other hand, the public financing will be responsible of the strategic infrastructure and equipment, assuming the higher level of risk. Nonetheless, it is important to be aware of the potential risks of this approach. There is an increase of management and coordination costs, and a *private* GS could imply some lost of control over the mission by the public entities.

Three different approximations have been used for the cost estimation, depending on the type of cost and the sources of information available. Firstly, the *bottom-up* approach has been used to estimate the non-recurrent costs – those linked to the satellite and GS development. Secondly, the *analogy* approach has been used to evaluate the space infrastructure and the recurrent costs, i.e. platform operation and exploitation. Finally, the *parametric* approach has been used to evaluate the operational costs [1]. On the other hand, in parallel to the previous approaches, a request for information (RFI) was launched to have a reference cost for the satellite construction and placing into orbit.

The relative cost of the infrastructure (both space and ground) is detailed in Table 8. Unfortunately, the absolute cost figures can not be unveiled due to the NDA signed with different suppliers, although we can state that a typical SS spacecraft costs less than 5 M$ [3]. The recurrent costs, e.g. staff, HW and SW devoted to management, operation and exploitation, etc., are estimated in the literature [1] to be in a range between 3% and 12% of the non-recurrent costs. According to our study, the calculated value for MEDIMAP is 4.5%. This value agrees with the range found in the bibliography, and translates to roughly 1.30 M€/year. Thanks to the deep knowledge of ICC in EO products and services, we have generated a direct benefits simulator. According to this simulator, the direct benefits would be of 7.1 M€ for a 5-years lifespan mission, and 4.0 M€ in case of an additional 2-year extension. The indirect benefits have been estimated at 21.0 M€ for a 5-year mission and 11.1 M€ for a 2-year extension. This estimation may be biased for several causes. There is a difficulty in the evaluation of the market potential for a SS mission which is not currently available. Furthermore, there is an inherent complexity in the calculation of the indirect benefits and its multiplicative effect. Finally, we must also consider that the availability and costs of the launcher market is subject to high oscillations.

5. Conclusions

The small satellite approach represents the scenario with the highest benefit-cost ratio to provide a region with presence in the space. This approach also grants an infrastructure with suppliers for data, products and services. MEDIMAP offers high social return but low private return. Therefore, the recommended economical scenario is a public model with the participation of the private industry in the mission exploitation – commonly known as ppp model.

The MEDIMAP characteristics (5 to 10 m GSD, 5/6 spectral bands at the VNIR and the 50-70 km swath) suit the main goal of the mission with the best ratio between performance, risks and costs. They place the mission as an essential complement to other EO capacities, thus creating new synergies and territorial knowledge to industrial, academic and public. Besides, it provides continuity to the current segment of knowledge and applications on EO inside the region. Space activities at regional level will play a key role in the future to satisfy the necessities of federate users. MEDIMAP is the Catalan approach to take advantage of this scenario.

References

[1] Wertz, J.R.; Larson, Wiley J.; *Space Mission Analysis and Design*, Series: Space Technology Library, Vol. 8, 3rd Edition, Springer (1999)
[2] Peeters, W. *et al*.; "Classifying and evaluating space projects: a unified method for estimating social and private returns," *Proceedings of Recent Advances in Space Technologies (RASP)*, pp. 834- 839 (2005)
[3] Sandau, R.; "International Study on Cost-Effective Earth Observation Missions," *Proceedings of ISPRS Comission I Symposium* (2006)