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Design of a satellite-based solution to the wildfires problem in the Mediterranean region

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Al mezzogiorno d'Italia,

e alle comunità afflitte dagli incendi.

Abstract

This thesis is an early phase design of a space mission in which the goal is to develop a service that, based on small satellites, is able to address the wildfire problem in the Mediterranean area with reliable fire forecasting and active monitoring.

Wildfires are becoming a serious issue in the Mediterranean area, as in 2022 more than 2700 fire events caused an area loss of more than 800 000 hectares, with a trend that is rapidly worsening. Major initiatives to tackle this phenomenon are taken by the Copernicus programme of the European JRC, in which is developed the idea of using remote sensing as a tool for rapid mapping to support rescue teams in case of natural disasters as wildfires, but there is still some gap in the current operational approach. Namely, this mission aims to satisfy two primary needs: improving fire-forecasting accuracy and providing near real time fire monitoring and high-resolution mapping.

To date, fire forecasting is based on Fire Weather index (FWI), an index based on weather data that does not use any info about vegetation conditions. In this thesis it is therefore proposed to enrich FWI with Fuel Moisture Content (FMC), a visible and SWIR band-based index estimating water content in vegetation which has been shown would improve fire-forecasting accuracy. Here it comes one of the primary activities the constellation should perform: collecting visible and SWIR imagery over the whole area of interest once every 10 days.

As far as active monitoring is concerned, this is currently carried out by the fire fighters who physically perform on-site inspections, so it can take several hours to begin the first rescue operations after a fire has started. In this thesis, a satellite constellation with near real-time fire monitoring and high-resolution mapping capability is presented. Here it comes another one of the primary functions the constellations should perform: scanning the Mediterranean area with a temporal resolution less than 1 hour, identifying fire spots and mapping them with a Ground Sample Distance (GSD) of less than 10 m, and sending mapping product directly to fire fighters close to the affected location.

Once these science goals are established, several mission concepts and architectures have been evaluated using STK simulation tools as the main tool to identify the optimal mission configuration.

In this context, several technological and design challenges are underlined and tackled, such as the necessary numerosity of the needed constellation and the advanced technological solutions the mission must adopt to ensure necessary performances, for example about the propulsion system and in particular the payload system, where it is unavoidable to design one of the instruments from scratch since none of off-the-shelf alternatives meets all the identified measurement requirements.

Once the technical study over the mission is done, the thesis is concluded with considerations about cost and value of the services offered by the mission and about the technological achievements that, in future years, could noticeably improve performances or reduce cost and complexity of the mission realisation.

Sommario

Questa tesi consiste nel progetto preliminare di una missione spaziale in cui lo scopo è sviluppare un servizio che, adoperando satelliti di piccola dimensione, sia in grado di fronteggiare il problema degli incendi boschivi nell'area Mediterranea fornendo un servizio di previsione e monitoraggio degli incendi.

Gli incendi stanno diventando un problema serio nella regione Mediterranea, dal momento che nel 2022 ci sono stati più di 2700 incendi che hanno causato la perdita di oltre 800 000 ettari di area, segnando un trend che sta rapidamente peggiorando. Le iniziative più rilevanti in questo ambito sono intraprese dal programma Copernicus del JRC, in cui è stata proposta l'idea di utilizzare il remote sensing come strumento di rapid mapping per le squadre di soccorso in caso di disastri naturali come, appunto, gli incendi, ma l'approccio attuale a riguardo presenta ancora delle lacune. A questo proposito, la missione mira a soddisfare due bisogni principali: migliorare l'accuratezza delle previsioni di incendio e fornire uno strumento di monitoraggio e mapping ad alta risoluzione degli incendi quasi in tempo reale.

Ad oggi, le previsioni di incendio sono basate sul Fire Weather Index (FWI), un indice basato su dati meteorologici che non utilizza alcuna informazione riguardo allo stato della vegetazione. In questa tesi è quindi proposto di arricchire il FWI con il Fuel Moisture Content (FMC), un indice di remote sensing basato sulle bande SWIR e del visibile, che stima il contenuto d'acqua nella vegetazione, il chè è stato dimostrato migliorerebbe l'accuratezza delle previsioni di incendio. Da qui deriva una delle attività primarie che la costellazione dovrebbe svolgere: acquisire immagini nel visibile e in SWIR dell'area d'interesse con una frequenza di circa 10 giorni.

Per quanto riguarda il monitoraggio attivo, ad oggi è svolto dai pompieri che svolgono ispezioni in loco, pertanto ci possono volere molte ore per individuare e iniziare le operazioni di soccorso dopo che un incendio è iniziato. In questa tesi è presentata una costellazione satellitare con capacità di monitoraggio degli incendi in tempo quasi reale e capacità di mapping ad alta risoluzione. Da qui deriva la seconda principale funzione che la costellazione dovrebbe svolgere: scannerizzare l'area Mediterranea con una risoluzione temporale minore di un'ora, identificare le località degli incendi e mapparli con una GSD minore di 10 metri, infine inviare questi dati direttamente ai pompieri più vicini al luogo dell'incendio.

Una volta stabiliti questi obiettivi, sono stati valutati diversi mission concept e architetture, utilizzando gli strumenti di simulazione del pacchetto STK come strumento principale per identificare la configurazione ottimale della missione.

In questo contesto, diverse tecnologie e sfide di progetto sono evidenziate e fronteggiate, come la numerosità della costellazione e le soluzioni tecnologiche avanzate che la missione deve adottare per garantire le performance necessarie, in particolare riguardo al sistema di propulsione e al payload, dove è risultato inevitabile dover progettare uno degli strumenti ad hoc, siccome nessuno dei prodotti off-the-shelf rispetta i requisiti di misurazione che sono stati definiti.

Terminato lo studio tecnico della missione, la tesi si conclude con considerazioni riguardo il costo e il valore del servizio offerto dalla missione e riguardo le conquiste tecnologiche che, nei prossimi anni, potrebbero permettere di migliorare le prestazioni del servizio, o ridurne costo e complessità, considerevolmente.

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Introduction

The Mediterranean, with its timeless beauty, is one of the world's most iconic regions, celebrated for its climate, culture, and environmental diversity. However, in recent decades, the Mediterranean area has been plagued by a growing threat: forest fires. These natural disasters have devastated extensive areas of unique landscapes, endangering wildlife, local communities, and the ecosystem as a whole. The increasing frequency and intensity of these fires make the adoption of innovative and highly efficient preventive measures urgent.

It is in this context that this thesis finds its raison d'être. The aim of this work is to design a space mission dedicated to the surveillance and prevention of fires in the Mediterranean area, along with the preliminary design of a payload intended to be carried either on a microsatellite or on a constellation of microsatellites.

As just mentioned, wildfires in the Mediterranean are becoming a problem that is progressively more worrying, this is due to increasing occurrence of the phenomenon and due to the impact that wildfires have on multiple levels on the communities they affect and on the environment in general.

Meaningful numbers that can be taken into account to understand the extensiveness of the phenomenon are the number of wildfires and the surface of the burnt area. From 2006 to 2022, over 60 000 forest fires took place every year in the EU, burning, on average, half a million ha (nearly twice Luxembourg's area) [1]. The phenomenon is rapidly worsening in the last years, for example in 2022 in Europe the burnt area reached more than 800 000 ha, marking it the second worst fire season in Europe since we have official records (the worst fire season has been in 2017 and the third worst in 2021) [2].

These numbers make clear how urgent it is to implement highly efficient solutions in order to stop the diverging trend of wildfires and to limit the tragic consequences of this phenomenon, but why looking at satellites as a potential resolutive instrument? There are multiple reasons for that: primarily, it is possible to constantly observe a very large area with a limited number of satellites (while using on ground infrastructures would be way less efficient), furthermore, satellites allow to observe the same parameters on the same locations for a long time span, allowing a temporal analysis of the phenomenon and they also allow to perform some measurements that are just possible from the space (for example thermal or multispectral measurements), finally, satellites are not a standalone solution since it is very easy to design them so that they are integrable with other tools available either on ground or from already existing satellites.

In this thesis will be faced the problem of the design of a space mission aimed to perform efficient and effective wildfire prevention in the Mediterranean area. That means that it will be investigated what is the state of the art of remote sensing for fire prevention, so that it'll be possible to understand what are the gaps and the deficiencies in the system to date, and that it will be the starting point. The second step will be the understanding of what are the critical parameters that are important to be measured – and with what requirements in terms of resolution and revisit time - in order to provide helpful information to the authority that is in charge to manage emergencies in the location of the fire (e.g., civil protection in Italy). After that it'll be studied what is the best mission configuration to do what it is needed (e.g., is it better to have a single satellite or a constellation? In that case how many satellites are needed? What are the best orbits for this purpose?). When the preliminary design of the mission is done, it is finally possible to dedicate to the design of the payload, so it means understanding what are the technical specifications that the instruments must have to guarantee that the observation meets the requirements of the mission. In this phase it'll be also understood if some payload instruments that are available on the market have the right characteristics or if it is needed to design a custom instrument for the mission. The goal is to get to the end of the work having a catalogue of requirements for all the specialists that do the detailed design of the subsystems, and to have precise awareness of the data product that is possible to produce with this mission.

It is important to clarify that this thesis is not about a detailed design of the payload and that the investigation will be limited to what is feasible with microsatellites (with "microsatellite" is meant a spacecraft bus with dimensions around 500x500x500 mm and a maximum weight around 100 kg [3]). That is because large satellites are already available for the studied application with their advantages and their drawbacks, while microsatellites offer different features and opportunities that are yet to be explored.

1 – The wildfire problem in the Mediterranean

In this chapter the wildfire problem in the Mediterranean area will be examined more in detail. In particular, in this section the following will be shown:

- A more detailed overview of the tragic consequences of wildfires in the Mediterranean
- What are the characteristics of the Mediterranean region – in terms of vegetation, weather conditions and in general of fire vulnerability - that are meaningful to tackle the problem
- What is the state of the art, worldwide, of satellites devoted to Earth observation with the aim of fire prevention
- What has been done so far in the Mediterranean area to fight this tragic phenomenon and what is the approach used by in charge authorities to manage fire emergencies

1.1 – Wildfires trend and impact on the Mediterranean

As a first step it is important to have a deep understanding about how wildfires are affecting the Mediterranean region. In this section the damages produced by wildfires at different levels (economic, environmental etc) are shown.

Note for the reader: Most of the available data about wildfires in the Mediterranean area are collected and classified from the Joint Research Centre (JRC) of the European Union and are accessible through several instruments, such as the EFFIS' (European Forest Fire Information System) portal and the JRC's website where several periodic reports are published. Almost all the statistics about fires in the Mediterranean shown in this thesis are from these sources.

As already mentioned, this phenomenon is increasing in the last few years and it has always been a big issue for the affected countries. In *figure 1.1* it is possible to have a look at the impact of fires in terms of percentage of land loss [2].

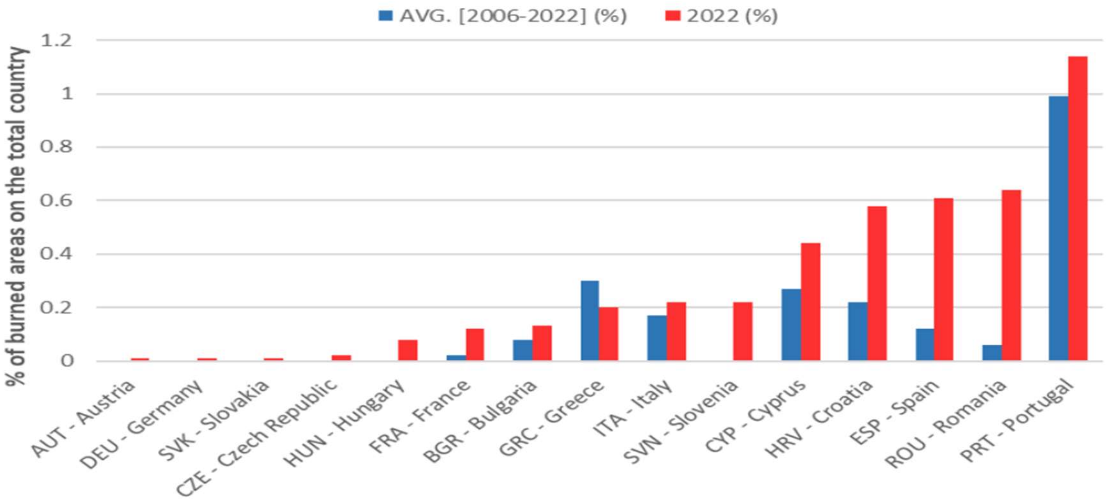


Figure 1.1 – % of land loss due to wildfires in 2022, EU countries

In *figure 1.2* it is possible to see the number of fires bigger than 30 ha compared to the annual average from 2006 to 2022 country by country [2].

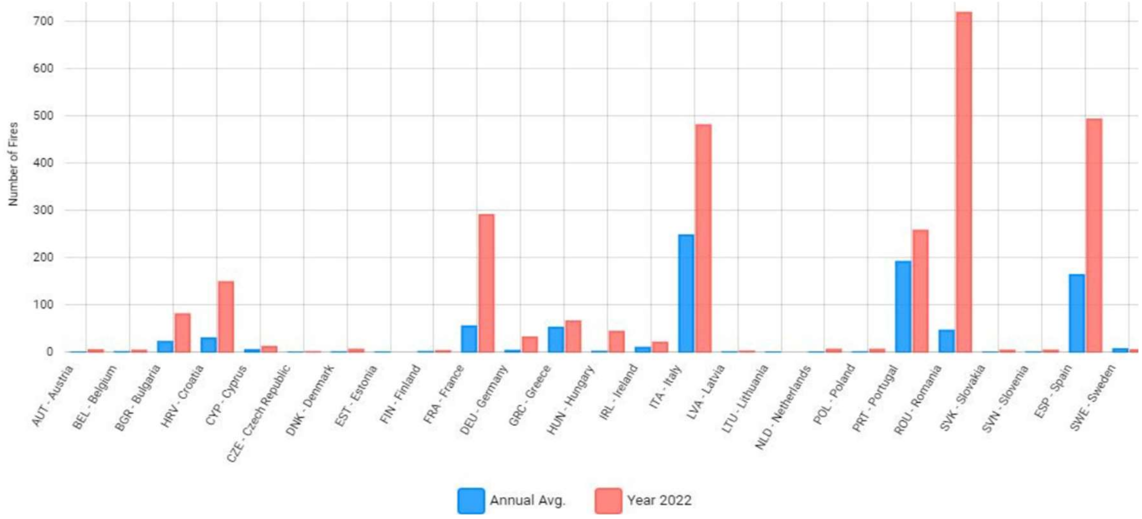


Figure 1.2 - number of fires bigger than 30 ha compared to the annual average from 2006 to 2022 in EU countries

In *figure 1.3* it is possible to see the cumulative number of fires/burnt area for the whole Europe during 2022 compared to average from 2006 to 2022 [2].

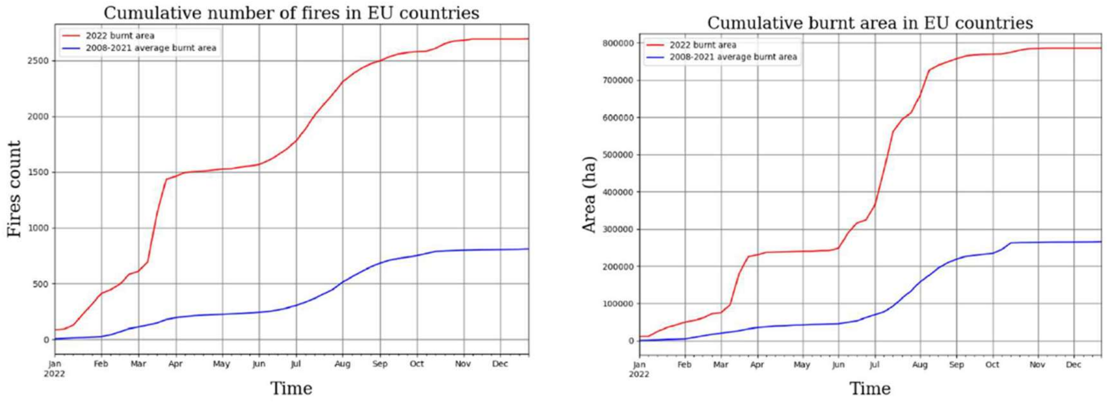
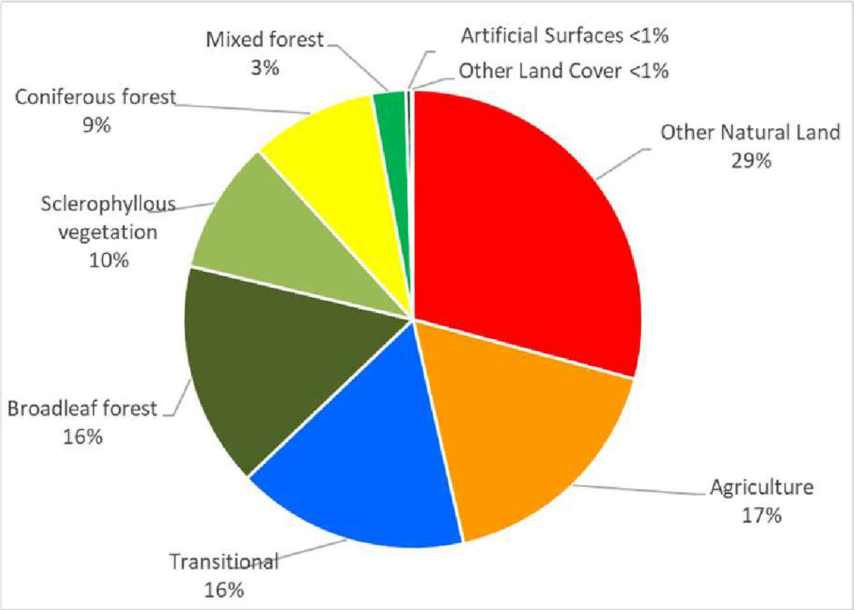


Figure 1.3 – Cumulative number of fires/burnt area in EU. 2022 vs 2006

An even more critical information is the type of land that is mainly affected by the phenomenon. In fact, in 2022, 44% of the burnt area was in protected areas belonging to the Natura2000 network [2] (a network of protected areas covering Europe's most valuable and threatened species and habitats [4]). It is easy to understand how severe is the damage produced by wildfires in this sense, endangering the existence of protected species of animals and vegetation that in some case mankind risks to lose forever.

Figure 1.4 – Land cover affected by wildfires



Other types of land covers affected by the wildfires are shown in *figure 1.4.*

From an economic point of view, the impact of wildfires is difficult to be assessed with accuracy. Direct damages from fires are estimated by JRC to be around 2 bln € per year [1], while GDP loss indirectly caused by fire events in 2022 is assessed to be from 13 to 21 bln € just for southern Europe [5] (please note that these predictions are not counting the long term consequences of fires that are yet to be fully understood).

From an environmental point of view, wildfires are one of the main causes of CO2 emissions in recent years. Furthermore, when a large green area is burnt, a double negative effect can be observed: if on one side the fire causes massive emissions, on the other side, when burning a green area, the environment is losing a tool to absorb CO2 in the future. To have an idea about CO2 emissions due to wildfires in Europe please look at *figure 1.5* [6].

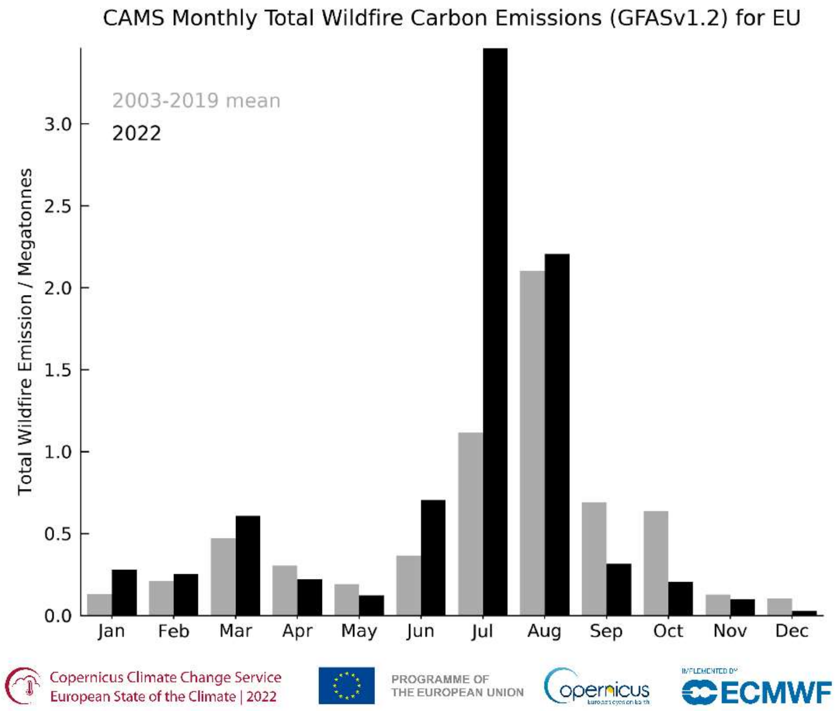


Figure 1.5 – CO2 emissions due to wildfires

The environmental impact of wildfires is not just limited to CO2 emissions. In fact, wildfires are also the cause of a severe worsening of air quality due to intense smoke plumes and particulate matter emissions and, during fire seasons, these emissions are likely to cause severe air pollution, with severe health impacts [7].

1.2 – The Mediterranean area

This paragraph is dedicated to the description of the main features of the Mediterranean area.

The most important information needed to characterize the fire prone behaviour of a certain area are: vegetation, weather conditions, social and economic context, urban settlement density and emergency management approach of the local in charge authority.

One aspect that increases the challenges in the monitoring of the Mediterranean area is the diversity that characterizes the area of interest.

The wide region that surrounds the Mediterranean Sea is characterized by variability of vegetation weather conditions (so certain regions have different type and concentration of fuel compared to others, and the diversity of conditions such as humidity, soil moisture, temperature, wind and precipitations makes more likely for a fire to propagate and last in certain regions compared to others).

Furthermore, certain areas have different economic context, so areas with a higher industrialisation and/or urban settlements density are more likely to experience fires due to human activity, while more rural regions can experience fires that are mainly caused by agriculture, wildlife, lighting strikes.

In certain areas the social context plays a very important role, because certain communities could have a more mature conscience about the risks related to wildfires. Therefore, they are more educated to behave in order to minimize it compared to other communities. Also, the potential role played by organized crime cannot be neglected as that could have particular interests in setting fires intentionally.

Last but not least, since the area of interest is very wide and spans over several different autonomous countries, it is important to investigate how fire events are managed by the in-charge authorities. Since the approach could be different from country to country, the requests in terms of data products could also be different.

1.2.1 – Vegetation in the Mediterranean

The most powerful tool available in order to understand the LULC (land use and land cover) in the Mediterranean area is the European Copernicus program that provides the CLC (Corine Land Cover) inventory, one of Copernicus' data products that has the objective to provide a complete mapping of the type of surface coverage in Europe and in the close regions [8].

The last update of the CLC inventory from 2019 gives this overview about the Mediterranean land cover [9].

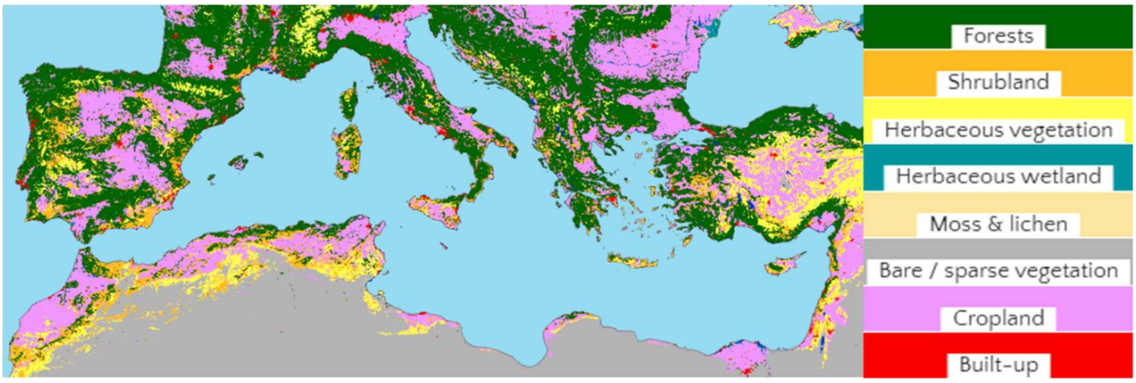


Figure 1.6 – Mediterranean area's land cover

From *figure 1.6* it is clear that most important types of vegetation that characterize the Mediterranean area are forests, shrubland, herbaceous vegetation and cropland. For this study the role played by herbaceous wetlands and moss & lichens cannot be neglected because they comprise a very small percentage of the Mediterranean area, while bare / sparse vegetation and built–up land cover can be excluded from this study because they are not affected by wildfires.

One of the very first steps in the design of the mission will be the understanding of the fire vulnerability of these four main types of vegetation and how it is possible to identify them through remote sensing and to assess their health status using optical sensors.

1.3 – Satellites for fire prevention

This paragraph is aimed to list all the most relevant satellite platforms that are available and used for fire prevention and fire monitoring.

Through the years, several actors – both public and commercial – have spent resources in order to develop solutions to the problem of Earth observation and monitoring, a general task to which the application of fire prevention belongs.

From NASA, is important to mention the Terra and Aqua satellites with their instruments MODIS and ASTER [10] [11], the GOES satellite network in cooperation with NOAA with their ABI instrument [12], the LandSat-9 satellite from the Earth observation LandSat series in cooperation with the U.S. Geological Survey with its OLI and TIRS instruments [13] and the Suomi NPP satellite with its VIIRS instruments [14].

From ESA, the Sentinel-1 and Sentinel-2 couples of satellites with their respectively active and passive sensors [15], the TerraSAR-X satellites in cooperation with the DLR [16] deserve to be mentioned.

From other public and private actors, deserve a mention the Himawari-8 and Himawari-9 satellites from JAXA with their AHI instruments [17], the GK2-A and GK2-B satellites from the Korean space agency [18] and the HOTSAT-1 mission from the SatVu company [19].

Clearly, many more missions could be mentioned in that list, but the purpose of this thesis is not a review of the state of the art of Earth observation's satellites, so the most meaningful ones are mentioned in order to understand what is the approach to fire prevention nowadays.

A summary of the main features of all the mentioned missions is shown in the table below.

Mission	Orbit	Instruments	Spatial resolution	Temporal resolution
Terra/Aqua	SSO	MODIS ASTER	250-1000 m 15-90m	2 days 2 days
GOES	GEO	ABI	2000 m	15 min
LandSat-9	SSO	OLI TIRS (temperature sensor)	20 m 100 m	16 days 16 days
Suomi NPP	SSO	VIIRS	750 m	12 hrs
Sentinel 1	SSO	C-SAR	5-40 m	12 days
Sentinel 2	SSO	MSI	10-20 m	2-3 days
TerraSAR-X	SSO	X-SAR	1-16 m	11 days
Himawari-9	GEO	AHI	500-2000 m	10 min
GK2-a	GEO	AMI	500-2000 m	10 min
HotSat-1	SSO	HotSat imager	3.5 m	mode dependent

Table 1.1 – Worldwide missions adopted in wildfires monitoring

From this quick analysis it is clear that there are two main types of mission for fire prevention. On one hand there are the ones using SSO that are capable of providing imagery with very high spatial resolution but with frequency of the observation on a specific location of the order of days. On the other hand, missions exploiting GEO orbits are capable of continuous monitoring of the area of interest, providing an update on imagery with a frequency of the order of minutes, however the observation has a spatial resolution that is way lower.

However, no GEO satellites are available for the task of fire prevention over the Mediterranean area, as the GEO satellites listed in *Table 1.1* are devoted to observation of the American and Asian continent.

Some of the listed missions use active sensors, in particular SAR in C and X band. These kinds of sensors are very interesting for this application because they are very reliable, since their functioning is not affected by low lighting conditions (for example, during night time) or by cloud coverage. Furthermore, their resolution is extremely high if compared to passive sensors. However, they offer different kinds of data since they do not really capture a picture of the target (for example, they do not offer any information about the spectral signature of the target). In the following chapters the suitability of these kinds of sensors for a microsatellite devoted to fire prevention will be further investigated.

1.4 – Current approach to the problem

This paragraph has the aim to discuss the current approach to wildfires prevention in the Mediterranean area and to highlight its weak points and lacks and its unsatisfied needs. This analysis is fundamental to understand what are the high-level requirements for the mission.

To date, the most important European authorities in the field of security, Earth observation, civil protection and weather forecasting are cooperating in the Copernicus program, that is the biggest European Earth observation and monitoring program and offers among its services the most powerful tools that all the countries in the Mediterranean area (the non-Europeans too) have to manage fire emergencies [20].

Copernicus is structured in six services, some of them (Land, Emergency, Climate Change) are directly or indirectly related to the problem of wildfires.

Copernicus has a very broad database that contains information about the land cover (so the vegetation), and it offers detailed temperature and weather forecasting. It also offers access to some portals strictly related to fires, namely EFFIS and GWIS, that use remote sensing and in situ data to provide short-term and long-term fire forecasting, monitoring of active fires and burnt area and statistics about the fire prone behaviour of the Mediterranean countries.

Another important service offered by Copernicus is the emergency management system, a service that can be triggered by authorised users (for example, a civil protection officer) when a natural or man induced disaster is occurring in a specific area (the service is guaranteed globally). When an activation of the system is triggered, the affected country is provided as soon as possible with a certain number of data products derived from remote sensing so that the civil protection or other in charge authorities in the area can intervene more effectively. Activations can also be aimed to pre-event risk assessment or to post-event damage evaluation.

This first analysis leads to the splitting of the general problem into three subproblems:

1. Pre-event risk analysis - to predict where and when a fire can occur. This can be done through the processing and the interpretation of

remote sensed images mixed with data from other sources like weather stations.

2. Active monitoring - to provide surveillance on the Mediterranean area in order to spot when a fire starts and to provide the firefighters with all the information needed to plan the intervention as soon as possible.
3. Post event damage assessment - once the fire is over, to scan the affected area in order to understand what is the damage resulting from the fire, what are the affected infrastructures and what is the recovery capability of the area.

These three subproblems are tackled independently, since the specific needs and the constraints are different. Now the three subproblems will be shortly analysed more in detail.

1.4.1 – Pre-event phase

As said, the pre-event risk analysis aims to produce forecasts about the fire risk in the Mediterranean area.

This part of the problem is tackled in several ways and there are several actors that interact in this panorama.

The contribution of satellites in that task is to collect as much data as possible on the area of interest so that it is possible to use them to make estimations and predictions. Remote sensing data are typically used to compute indices that are meaningful to describe a particular aspect of the observed area. Just to make an example, from remote sensing is possible to compute the health status of the vegetation that is well described by some indices that will be further described later. Furthermore, it is possible to understand the surface temperature or the soil moisture and a very large number of other parameters that can be used for fire prediction.

The standard approach is to choose a mathematical model (for example a machine learning model, a linear regression of some parameters or any other kind of model) that, taking in input a number of parameters about the conditions of the monitored area gives in output an index or a series or indices that quantify the fire risk.

This is also the approach used in the Copernicus program, indeed on the EFFIS portal are displayed data products like one in the figure below [21].

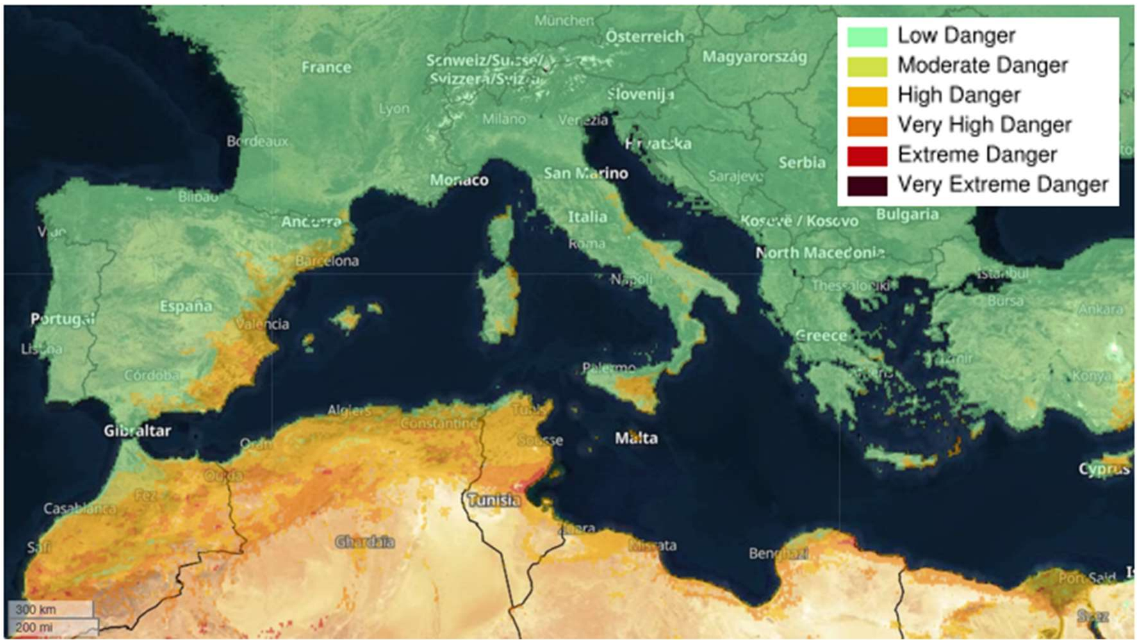


Figure 1.7 – FWI risk map from EFFIS

Clearly, the choice of both the mathematical model and the index to consider as well representative of the fire risk can take a lot of research and validation and goes beyond the topics dealt in this thesis.

What is important for this study is to understand what are the needs in this part of the problem. Hence, it is important to notice that this task is not time critical, since it is about forecasts that are weekly or more, but is data-centric, since the accuracy of the selected mathematical model depends directly on the data used to feed the model. From that logic it is clear that SSO missions perfectly fit these needs, indeed they provide data not very frequently, but the quality of the acquisition is very high and information that can be extracted from this kind of remote sensing is very various and accurate. The available satellites for the Mediterranean area accomplish this task proficiently, since are already available several high-resolution sensors and the approach used to date for fire forecasting is already performing quite good, so most of the effort in this thesis will be dedicated to the active monitoring and the post event phase. Nevertheless, in the following will be highlighted how the mission designed and presented in this thesis could contribute to this task as well as the others.

1.4.2 – Active monitoring phase

Active monitoring phase aims to provide to the local firefighters a set of data products that can help to fight the fire faster, safer, minimizing the damages and optimizing the employed resources.

So, the question that should lead the design process in this phase is “what do the firefighters need to know?”.

Firstly, there is a distinction between “fire detection” and “fire mapping” [22]. Fire detection is the first activity performed and consists in spotting the fire in a specific location, without mentioning any characteristic about the fire itself. Fire mapping is the activity that comes immediately after and consists in sizing the burning surface and estimating fire perimeter and other crucial features; what are the crucial features of interest to the fire fighters is not univocal but depends on the country where the fire occurs.

Fire detection is not something that the firefighters need from a satellite mission because this task is proficiently performed by the civilians, since almost all the wildfires are notified to the fire brigades through the unified emergency phone number of the country (e.g., in Italy it is 112) within two minutes after the fire ignition.

Immediately later, as said, comes the need for fire mapping. After the fire brigades receive a notification about a possible fire their approach is to send the closest team in the location for a live check – so they can understand if it is an actual fire or a false positive – and the rescue operations director of the team can make a first assessment and request the needed resources to intervene against the fire. In this phase the aid of satellite services can be beneficial because it can shorten the time needed to plan the intervention. So, the goal here is to select a small set of data products about the fire that are useful for the fire brigades and to deliver them in a time that is shorter than the time that would take to go physically on the location and check in person.

Now it is clear that GEO missions are better fitting the needs of this phase of the mission, since they allow a very quick data collection and delivery. The drawback of these missions is that the quality of the sensed data is worse – in terms of spatial resolution, for example – and the information that can be extracted from geostationary observation is less. Nevertheless, this phase of the mission does not require a huge quantity and an extremely high quality of the data since here the approach is not data-centric but time-critical.

On top of that, the available satellites to perform the task of fire monitoring on the Mediterranean area have a temporal resolution that is not compatible with the needs of this mission phase. Indeed, to date, when an activation is triggered the CEMS (Copernicus Emergency Management Service) is able to deliver data products in one day or more [23]. The conclusion that drew from that analysis is that major effort should be put in the design of this mission to fill the gap existing in particular in this mission phase.

One more thing to describe about the task of active monitoring is the list of data products that the mission aims to deliver. Clearly, every country's fire brigades have a different way to manage fire emergencies and usually this information is not public domain, so it is not easy to figure out precisely the list of needed data products. Anyway, some countries publish reports about their needs in the field of fire management, it is the case of Australia – that is one of the most advanced countries about fire management – that has identified some information considered crucial [24], namely:

- Type of fire (crown, surface or ground fire)
- Fire edge map
- Rate of change of the fire extent
- Direction and velocity of the flame front
- Fire intensity map
- Smoke plume dynamics

These can be considered high-level data products that can be derived from more basic characteristics of the fire and the environment in which it ignites. Indeed, these data products can be derived by the knowledge of the type, the concentration/distribution and the health status of the available fuel, as well as the slope and the wind speed. Some of this information is available on existing databases, does not change significantly over the time and said so will not be measured by this mission. This mission will measure the missing information that varies significantly over the time and that is needed to provide these data products.

1.4.3 – Post-event phase

The post event damage assessment, after a fire occurred in a certain location and once the emergency is over, aims to collect data from which to extract useful information about the damages caused by the disaster and to assess the recovery capability the location, maybe highlighting what the affected location and community need in this complex post-fire phase.

This phase of the mission is very similar to the pre-event one from an operational point of view. Indeed, this phase is not time-critical and data centric too, as well as the first one.

Another analogy with the first mission phase is that there are no evident lacks in the current approach that is adopted. Indeed, since the available missions for Earth observation over the Mediterranean are capable of very high-quality remote sensing, it is already possible to study with a high level of detail the affected region.

Nevertheless, in the following will be underlined some goals of opportunity that will arise from the design of the mission. Therefore, the mission will be designed putting major effort into the active monitoring phase, but once the mission architecture is fixed, a part of the mission study will be dedicated to understand how this mission can be used for that end too.

2 – Mission requirements

While the first chapter was intended to provide to the reader a deep knowledge of the problem that brought to the concept of the mission, from now on mission design with the aerospace standards for system engineering will be discussed.

The approach is based on the good practices and guidelines about system engineering presented in the Nasa SE Handbook [25].

This chapter is therefore aimed at producing a Science Traceability Matrix, that will be the blueprint for the further phases of the mission, such as the definition of technical requirements, concept of operations, and early mission timeline.

2.1 – Stakeholders needs analysis

In this paragraph the position of all the possible stakeholders of the mission will be analysed in terms of needs, values they can get from the mission, power and interest towards the mission.

2.1.1 – List of Stakeholders

The first step in understanding stakeholders' needs is having awareness of all the possible parties that could in some way play the role of a stakeholder. In the table below, all the stakeholders and the respective needs and values are listed.

Stakeholders	Needs	Values
1. Local Governments	N1.1: Protect local communities and infrastructures N1.2: Protect environmental heritage N1.3: Limit negative wildfires impact on economy and climate N1.4: Cooperate with rescue authorities	V1.1: Improve safety of population and local assets V1.2: Enhance tools provided to rescue authorities
2. JRC	N2.1: Contribute to Europe security offering useful services to the users N2.2: Fill gaps in the current remote sensing infrastructure	V2.1: Enrich Earth observation database V2.2: Expand Copernicus services catalogue

	N2.3: Support space industry, research and technological progress	
3. Space industry	N3.1: Set up a profitable and sustainable business by identification of services that can be sold to public or private entities N3.2: More advanced design solutions to improve remote sensing performances N3.3: Cut the cost of remote sensing operations	V3.1: Gain a leadership role in the field of fire emergency support V3.2: Improve know-how and technological solutions marketable to customers V3.3: Improve state of the art of remote sensing in terms of: temporal and spatial resolution, data management
4. Local communities	N4.1: Preserve environment, life quality and economic attractiveness of the area	V4.1: Provide awareness about fire risk and effects
5. Scientific community	N5.1: Support space industry and technological progress N5.2: Understand fire-prone behaviour markers N5.3: Elaborate mathematical models and algorithms useful to explain the wildfire phenomenon	V5.1: Provide up to date data about the phenomenon V5.2: Provide measurements in bands that are rare or highly requested (SWIR) V5.3: Provide data about the early stage of wildfires
6. Local firefighters or equivalent	N6.1: Shorten time needed for intervention planning N6.2: Improve daily resources allocation N6.3: Reduce incidence of false positive wildfire notifications	V6.1: Provide near real time fire detection and mapping V6.2: Provide a tool to identify smoke plume’s cause (fire/not fire)
7. Tourism industry	N7.1: Limit impact of wildfires on the touristic attractiveness of the area	V7.1: Provide fire prediction and notification allowing touristic activities adaption
8. Agribusiness industry	N8.1: Limit impact of wildfires on crops and agribusiness assets	V8.1: Imagery about fire exposure of the land V8.2: Prompt notification about fires affecting crops

Table 2.1 – Stakeholders’ needs and values

Table 2.1 highlights how the catalogue of possible stakeholders of a mission is very wide and various, since there are very different actors that could be interested or affected by the mission. The goal is to tailor the mission to the needs of the most relevant stakeholders and to keep in mind other possible needs to be fulfilled when will be the moment to identify the goals of opportunity of the mission.

2.1.2 – Stakeholders map

The next step is to evaluate for each stakeholder the relative interest and power, to identify the most influential ones, which may strongly support the mission. This analysis is summarized through a stakeholder mapping, which is divided into 4 different parts representing different categories. These areas can be classified as follow:

- Promoters: high power and high interest.
- Defenders: low power and high interest.
- Latents: high power and low interest.
- Apathetic: low power and low interest.

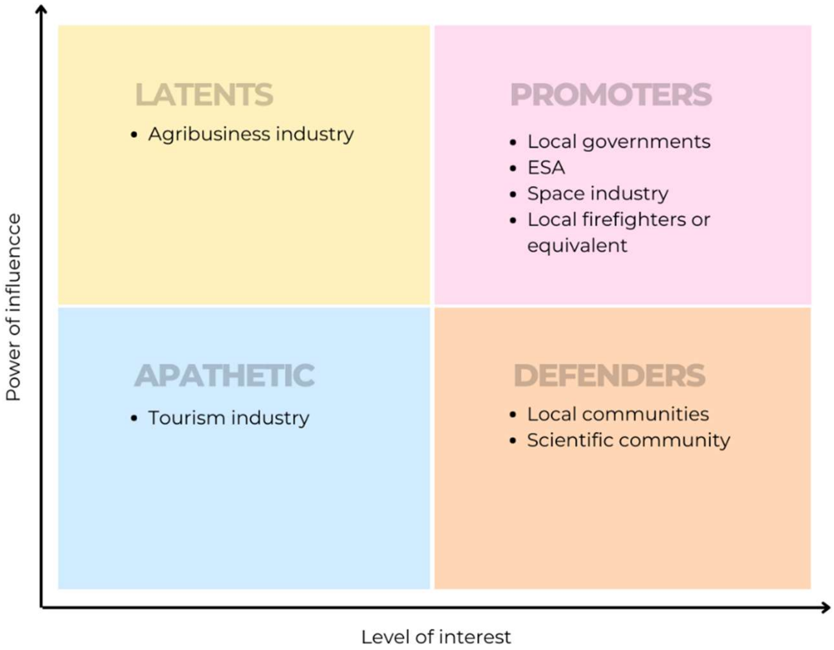


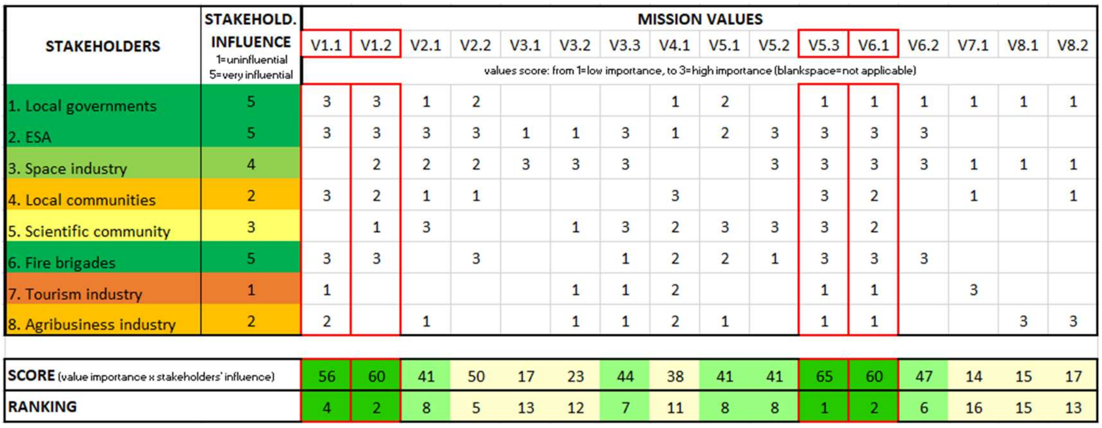
Figure 2.1 – Stakeholders' map

This analysis shows which are the most relevant stakeholders for the mission: local governments, ESA, local fire brigades and the space industry. In this list of stakeholders, there is one privileged stakeholder that shows the way for the others: the fire brigades. In the big picture, governments feel the need to curb the divergent trend of the wildfire phenomenon and have identified remote sensing as the best strategy to do so. There are two ways in which governments can do this: the first is to ask the ESA to allocate resources to the design of a mission such as the one that is the subject of this thesis; the second is to commission a private company to do it. Another possibility is for the space industry and ESA to work together to achieve the objective, as is the case with the Copernicus contributing missions. In any case, whoever is the technical entity carrying out the design (ESA, a private company or both) will have to tailor the mission to the needs of the service's most relevant user: the fire brigades. So, the four stakeholders have a unity of purpose and their needs and constraints are well represented by the fire brigade's ones, with small differences that have already been highlighted in the stakeholders' study.

2.1.3 – Quality function deployment

In this paragraph, the list of needs and values seen in paragraph 2.1.1 will be deployed in a quantitative way, so that all the potential values are assigned with a weight based on all stakeholders' needs and consequently the mission objectives can be retrieved (later translated into technical requirement)s and he mission statement can be formulated. This is done through a quality function that computes a score for every possible mission value simply multiplying a coefficient related to the stakeholder's influence with a coefficient related to value's importance for the stakeholder.

Table 2.2 – Quality function deployment



STAKEHOLDERS	STAKEHOLD. INFLUENCE 1=uninfluential 5=very influential	MISSION VALUES															
		V1.1	V1.2	V2.1	V2.2	V3.1	V3.2	V3.3	V4.1	V5.1	V5.2	V5.3	V6.1	V6.2	V7.1	V8.1	V8.2
		values score: from 1=low importance, to 3=high importance (blankspace=not applicable)															
1. Local governments	5	3	3	1	2				1	2		1	1	1	1	1	1
2. ESA	5	3	3	3	3	1	1	3	1	2	3	3	3	3			
3. Space industry	4		2	2	2	3	3	3			3	3	3	3	1	1	1
4. Local communities	2	3	2	1	1				3			3	2		1		1
5. Scientific community	3		1	3			1	3	2	3	3	3	2				
6. Fire brigades	5	3	3		3			1	2	2	1	3	3	3			
7. Tourism industry	1	1					1	1	2			1	1		3		
8. Agribusiness industry	2	2		1			1	1	2	1		1	1			3	3
SCORE (value importance x stakeholders' influence)		56	60	41	50	17	23	44	38	41	41	65	60	47	14	15	17
RANKING		4	2	8	5	13	12	7	11	8	8	1	2	6	16	15	13

This analysis shows how the mission objectives that need to be prioritized and that are driving the design are the ones circled in red and highlighted in dark green. Secondary objectives, highlighted in light green, are the ones not driving the design but that should be indirectly fulfilled even if with some performance degradation compared to the primary objectives. Finally, all the other objectives highlighted in light yellow, are not at all considered in the design process and will be analysed during the post-design phase as goals of opportunity.

As final result of the analysis, the mission aim is summarized by the following mission statement:

"To guarantee a satellite-based service of fire detection, mapping and forecasting, with the aim of providing a powerful tool to the fire brigades, the civil protections, and the governments; in order to improve safety of people, infrastructures and assets on the Mediterranean area against wildfires."

Consequently, primary mission objectives are defined as follows:

- To provide near real time fire detection and mapping
- To notify to the in-charge authorities with information about the fire extent, intensity and evolution as soon as possible
- To produce a database about the early stages of wildfires for operational and research purposes
- To make the service profitable, convenient and available for all the countries on the Mediterranean area

2.2 – Science traceability matrix

In this paragraph is built the science traceability matrix (STM) of the mission.

STM is a tool used in aerospace systems engineering "*to provide the overview of what a Mission will accomplish relative to high-level objectives […]. It provides a logical flow from these high-level objectives through mission objectives, science objectives, measurement objectives, measurement requirements, instrument requirements and spacecraft and system requirements to data products*" [26].

Please notice that the STM produced now is susceptible to changes in the further phases of mission and payload design. Now the goal is to link the mission objectives that came from the stakeholders needs analysis to the related technical requirements these mission objectives imply on the satellite platform.

The STM is shown in the table below and discussed in the following.

Science objectives	**Measurement objectives**	**Measurement requirements**	**Instrument**	**Instrument requirements**	**Data products**	**Mission requirements**
Active monitoring phase						
1. Detect fire in near real time	Measure temperature	Brightness temperature in one MWIR (3.8 to 4.2 µm) band Temporal res < 30 min Spatial res < 50 m Swath width > 100 km	Thermal imaging radiometer	Matrix detect. ≈ 4 Mp SNR t.b.d. FOV = 8 ° Lens: D>14 cm	Temperature of Mediterranean area, Fire spot real time detection	LEO ≈ 600 – 800 km

2. Map fire in near real time	Measure fire perimeter	Brightness temperature in SWIR (1.5 to 1.7 μm, 2.0 to 2.1 μm, 2.3 to 2.4 μm) Temporal res < 50 min Spatial res < 20 m Radiometric res = 8 bits Swath width > 10 km	Thermal imaging radiometer	Linear detect. ≈ 1x1000 p SNR t.b.d. FOV = 1 ° iFOV=0.002° Lens: D>30 cm	Fire perimeter map with intensity grade, Flame front velocity	Target pointing (max 40 ° off-nadir) LEO ≈ 600 – 800 km
	Measure fire intensity					
Pre-event phase						
3. Determine vegetation health status	Measure NDVI	Reflectance in NIR (0.8 to 0.9 μm) and VIS (0.6 to 0.7 μm) bands Temporal res < 10 days Spatial res < 500 m Radiometric res = 8 bits	Visual camera	Matrix detect. ≈ 1 Mp SNR t.b.d. FOV = 30 ° Lens: D>1 cm	NDVI and FMC computation, FWI enhancing and consequent weekly fire forecasting	Nadir pointing SSO ≈ 800 km
	Measure FMC	Reflectance in NIR (0.8 to 0.9 μm) and SWIR (1.4 to 1.7 μm) (same as above)	Visual camera	Matrix detect. ≈ 1 Mp SNR t.b.d. FOV = 30 ° Lens: D>1 cm		Nadir pointing SSO ≈ 800 km

Table 2.3 – Science traceability matrix

The mission objectives derived before directly imply three science objectives.

In the active monitoring phase, the science objectives of the mission are to detect and map the fire in (near) real time, providing to firefighters some information about the fire in the initial stage with a timing that can improve speed and effectiveness of fire rescue operations.

Fire detection algorithms are based on temperature measurements [27]. The latest standard used by the MODIS instrument is to use data in the 4 μm wavelength [28]. The goal is to detect a fire within 20 minutes after it reaches 1000 m^2. This requires a temporal resolution that does not exceed 30 minutes and a spatial resolution that does not exceed 50 m (assuming that the sensor is able to detect a fire when it covers on ground the equivalent area of a conglomerate of 3x3 pixels). In this application it is more important to maximize the swath width than the spatial resolution, so the swath width goal is set to 100 km (best achievable without degrading the spatial resolution). The approach to establish, now and in the following, instruments requirements respecting the given measurements requirements, is the one shown in the SMAD (Space Mission Analysis and Design) [29]. The measurements related to this science objective require a Nadir pointing (since the fire is not spotted yet, would be impractical to point the camera off Nadir blindly) and all the instruments requirements are computed for a generic low Earth orbit with an altitude between 600 and 800 km. Please notice this application is not dependent on lighting conditions, so there is no need to choose a sun-synchronous orbit and is possible to choose the orbit (later on in the design process) maximizing other parameters such as, for example, coverage.

Fire mapping is a science objective depending on what are the desired to be mapped features of the fire. Here the operational needs of the firefighters rule the design. Firefighters usually want to understand parameters known as flame depth (the horizontal distance between the fire front and the flame tail, represents the amount of fuel below the active fire and is an important parameter because is strictly related to the fire evolution) and flame length (the diagonal distance between the fire front and the flame tip, is important because include the vertical extent of the fire, so gives an awareness of the intensity of the fire and of the possible ignition of crown fires, that are considered more dangerous). Since it is not possible to deliver with precision such information, in this phase the measurement objectives are the fire perimeter and the fire intensity map that allow the firefighters to make roughly the same assumptions. It is important to notice that, combining such information with a DEM (digital evolution model) and with the knowledge of land cover type and wind (all these data are available from sources external to this mission), is possible to determine the direction and rate of expansion of the fire, a key information for intervention planning from fire brigades. Fire perimeter is usually understood through algorithms based on SWIR data either at 2.0 μm or at 2.4 μm [30], while fire intensity is understood thanks to the different profile of spectral emittance of bodies with different temperatures [31] and, since the range of temperature we are interested to observe is 500 K (smoldering fire), 1000 K (surface fire) and 1500 K (crown fire), the appropriate algorithm to determine fire intensity uses 1.5 to 1.7 μm, 2.0 to 2.1 μm, 2.3 to 2.4 μm SWIR bands [32]. After the first fire detection, it would be beneficial to provide the firefighters with updated fire mapping every 30 minutes, not exceeding 1 hour. While the spatial resolution is set to at least 20 meters because fire mapping requires a finer resolution than simply detecting it. In this operative mode target pointing is required, but since the fire needs to be spotted when it is really small, the swath width is not critical and is set 10 km (but probably way smaller would still be good). The type of detector that is more suitable here is a linear one so adjusting the scanning mode is possible to adapt the sensor to wildfires of different shapes and sizes. Again, since we are measuring emissivity, lighting conditions are not relevant and the required orbit is a general LEO.

In the pre-event phase, the mission objective is to improve accuracy and capability of fire forecasting, so that civil protection or equivalent authorities can better distribute resources and plan future operations. To date, the standard for fire forecasting is the FWI, an index based on weather data that quantifies if the weather conditions imply a high or low fire risk. It is important to mention that the FWI is not dependent on remote sensed data and does not contain any information about the conditions of the vegetation in a certain location. FWI is sampled on 8 km cells. To improve fire forecasting capability it is important to enrich the FWI with an index quantifying the health status of the vegetation, this can be the NDVI (normalised difference vegetation index) or even better FMC (fuel moisture content). FMC quantifies the water content in the leaves and branches that are the fuel for wildfires. The algorithm to determine FMC depends on the type of observed land cover. Anyway, it is possible to determine FMC in several ways, but many researchers claim that using SWIR data would increase the accuracy of the algorithm [33]. Several studies show how the biggest difference in reflectance of dry and green vegetation is dependent on the type of land cover but always lies in the 1.4 to 1.7 µm band [34]. Since the FWI is sampled on 8 km, spatial resolution of 500 m is a very good improvement on accuracy and detail of fire forecasting, the swath should be maximized and the measurement needs a sun-synchronous orbit. FMC content as a characteristic time dependent on how much precipitation occurred in a certain location, in general is possible to measure it once every 10 days or triggering the measurement when, in a certain location, there is a long period without precipitation.

2.3 – Mission requirements definition

Finally, it is possible to define a list of technical requirements, namely the technical requirements specification (TS), as recommended in the ECSS-E-ST-10-06C standard [35].

ID	Justification	Requirement	Traceability
FUN-01	STM-3	The mission shall acquire VIS, NIR and SWIR imagery of Mediterranean land cover to make fire forecasts.	Mission architecture - Payload
FUN-02	STM-1, STM-2	The mission shall acquire TIR imagery to detect and map fire spots	Mission architecture - Payload
FUN-03	SNA-N2.1	The mission shall cover an area of interest spanning longitudinal from Portugal to Turkey and latitudinal from northern Africa to northern Italy	Mission architecture - Orbits
FUN-04	SNA-V5.3	The mission shall be able to downlink raw imagery beside the final data product, with	Mission architecture –

		the purpose of creating a database about early stages of wildfires	Communication & ground system
MIS-01	Regulations*	Disposal time shall not exceed 5 years	ConOps
MIS-02	STM-1	The mission geometry shall ensure fire monitoring with temporal resolution smaller than one hour	Mission architecture - Orbits
MIS-03	STM-3	The mission geometry shall ensure consistent lighting condition for acquisitions related to the FMC product	Mission architecture - Orbits
PAI-01	STM-2	The fire mapping product shall be delivered to the end-user within 10 minutes after the acquisition	ConOps
PAI-02	SNA-V1.1, SNA-V1.2, SNA-V6.1	The active monitoring segment of the mission shall be operative without interruptions for the whole routine phase	ConOps
PAI-03	SNA-N3.1	The mission shall provide its services for at least 5 years	ConOps & Mission architecture - Orbits
PAI-04	STM-3	The FMC product shall be delivered to the end-user within one day after the acquisition	ConOps
INT-01	SNA-N3.3	The mission shall be compatible with at least 2 commercial launchers	Mission architecture – Spacecraft bus
OPS-01	SNA-N3.3	The mission shall consider the possibility of automation of the operations. Automatic tasking, data processing and downlink is preferred	Mission architecture - Operations
DES-01	SNA-N3.3	The mission shall use a space segment composed of off-the-shelf technologies and instruments, when possible	Mission architecture – Spacecraft bus

Table 2.4 – Mission requirements

*Refers to ESA Space Debris Mitigation Working Group’s ESSB-ST-U-007 Issue 1. [36]

This list of requirements will be used in the following chapter as a blueprint for the detailed mission design.

3 – Mission design

This chapter is related to the detailed design of the mission.

In the following will be developed a list of possible mission configurations, namely the concept of operations. Subsequently, for each mission concept, will be developed a corresponding mission architecture. Finally, the alternative architectures will be evaluated and the best mission concept and architecture will be identified, so that it is possible to identify consequent requirements for the subsystems.

The chapter’s roadmap is shown:

- Concept of operations
- Mission architectures
- Optimal architecture identification
- Subsystems’ requirements allocation

3.1 – Concept of operations

In this chapter we aim to identify the most suitable options in terms of data delivery, communication architecture, satellite tasking and control and mission timeline. So, here the objective is to understand alternative ways in which the mission could work, from data production to data delivery to the end-user, going through all the steps in the middle such as level of autonomy of the satellites, tasking, scheduling and control approach, data flow through the elements of the mission etc.

Six interesting mission concepts have been identified. Characteristics of them all are now shown:

- **MC1:** It is a mission with centralised and full autonomy to the satellites in the fire detection and mapping process, so it does not need the ground segment intervention for routine operations except for housekeeping data checks. The data processing is done on board and the data is downlinked in its end format directly to the end-user.
- **MC2:** It is a mission with centralised and full autonomy to the satellites in the fire detection and mapping process, but processing and delivering to the end-user of mission data is done by the ground segment.

- **MC3:** It is a non-autonomous mission in which scheduling and control is done by several users (distributed control) on the ground, that are in charge of tasking the satellite choosing its operations. Mission data processing is done on board and directly downlinked to the applicant.
- **MC4:** It is a non-autonomous mission in which scheduling and tasking are the responsibility of a central mission control (that manages the requests of several users). Mission data are processed on ground and subsequently transmitted to the users.
- **MC5:** It is a semi-autonomous mission in which the satellite tasking is hybrid: the mission works autonomously in the routine operations of fire detection, mapping and forecasting, until the central mission ground control sends tasking. Mission data are processed on board and sent directly to the end-user.
- **MC6:** It is a semi-autonomous mission in which the satellite tasking is hybrid: the mission works autonomously in the routine operations of fire detection, mapping and forecasting, until the central mission ground control sends tasking. Mission data are downlinked, processed and transmitted to the end-user by the ground segment.

A short summary of the considered mission concepts is shown in the table below.

ID	Level of autonomy	Central vs distributed control	On-board vs ground processing	Processing distribution	Data delivery to end-user
MC1	Autonomous	Central	On-board	Distributed	Direct
MC2	Autonomous	Central	Ground	Central	Indirect
MC3	Non-autonomous	Distributed	On-board	Distributed	Direct
MC4	Non-autonomous	Central	Ground	Central	Indirect
MC5	Semi-autonomous	Dual (on board and centralised on ground)	On-board	Distributed	Direct
MC6	Semi-autonomous	Dual (on board and centralised on ground)	Ground	Central	Indirect

Table 3.1 – Mission concepts

Since it is not handy to study in detail all these mission concepts, so now a trade-off is carried out to select the best for the mission needs.

3.1.1 – AHP analysis

The AHP (analytical hierarchy process) analysis is an instrument for decision making in the design of complex systems.

To lead this analysis, the most meaningful attributes to take into account need to be defined to best describe the effectiveness of the mission.

Here, the selected attributes are: reliability, production cost, data delivery time, operations cost, reconfigurability.

For each attribute, it is important to define a weight to quantify the relative importance of the attributes for the mission. To do so, a prioritization matrix is produced, in which the relative importance for all the possible pairs of attributes is displayed. Then a normalised sum is produced and the weight of each attribute is determined.

Table 3.2 – Mission concepts, AHP prioritisation matrix

Priortization Matrix	Reliability	Production cost	Data delivery time	Operations cost	Reconfigurability		Reliability	Production cost	Data delivery time	Operations cost	Reconfigurability		
Reliability	1	4	0,5	3	7		0,268	0,267	0,252	0,3	0,389		0,295
Production cost	0,25	1	0,143	0,5	1		0,067	0,067	0,072	0,05	0,056		0,062
Data delivery time	2	7	1	5	7		0,537	0,467	0,504	0,5	0,389		0,479
Operations cost	0,333	2	0,2	1	2		0,089	0,133	0,101	0,1	0,111		0,107
Reconfigurability	0,143	1	0,143	0,5	1		0,038	0,067	0,072	0,05	0,056		0,057

So, it is clear that data delivery time is the quality the mission should master, right before reliability, while for example reconfigurability is not the primary design driver. This is understandable as the timeliness of fire detection and mapping is the key in fire rescue operations. Furthermore, since the mission is employed to support safety critical operations on field, ithe offered service has to be reliable (so the firefighters can have full confidence on the data and warnings the mission will deliver). Meanwhile, reconfigurability is important – since it allows the mission to be adapted to changes in the user needs during the life cycle – but it is secondary to the other attributes considered.

Once the attributes' importance is known, it is necessary to quantify, for each mission concept, the compliance to each attribute. This compliance is expressed as a score in the figure below.

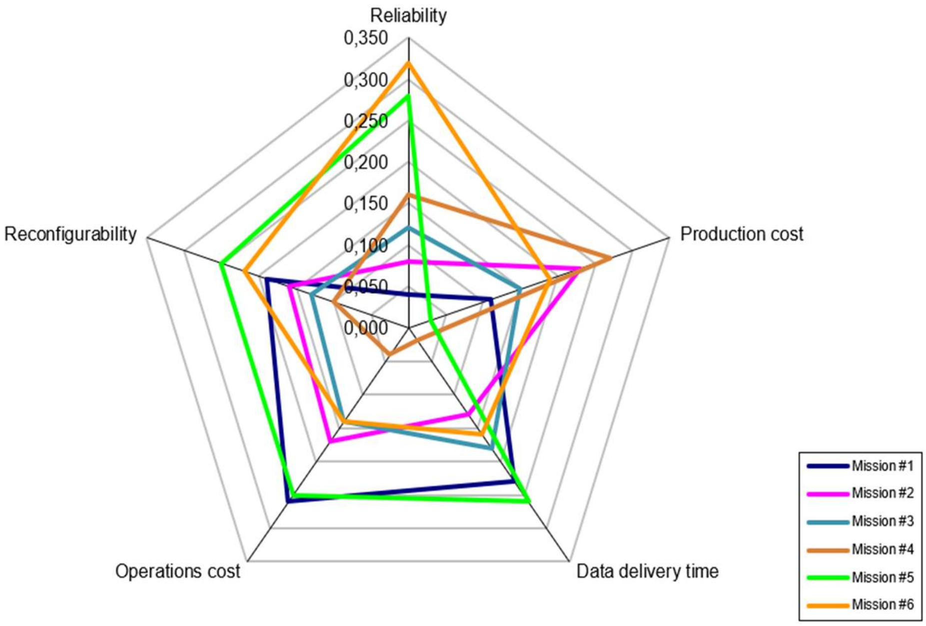


Figure 3.1 – Mission concept AHP

While, in the table below, to define the hierarchy between the considered mission concepts, it is computed the final score of each mission concept, obtained summing for each attribute the product between relative score and weight.

Summary	Reliability		Production cost		Data delivery time		Operations cost		Reconfigurability		**Final Score**
	Weighting	Score	Weighting	Score	Weighting	Score	Weighting	Score	Weighting	Score	
Mission #1	0,295	0,040	0,062	0,110	0,479	0,230	0,107	0,260	0,057	0,190	0,167
Mission #2	0,295	0,080	0,062	0,230	0,479	0,130	0,107	0,170	0,057	0,160	0,127
Mission #3	0,295	0,120	0,062	0,150	0,479	0,180	0,107	0,140	0,057	0,130	0,153
Mission #4	0,295	0,160	0,062	0,270	0,479	0,020	0,107	0,040	0,057	0,100	0,084
Mission #5	0,295	0,280	0,062	0,030	0,479	0,260	0,107	0,250	0,057	0,250	0,250
Mission #6	0,295	0,320	0,062	0,190	0,479	0,160	0,107	0,140	0,057	0,220	0,210

Table 3.3 – Mission concept, AHP scores

Now, it is clear the need to prioritize MC5 and MC6.

Actually, this analysis ignored an important fact. Indeed, a single analysis for pre-event and active monitoring phase has been conducted. Rigorously, this is right since these are both functions of the same mission, but was underlined several times how needs, requirements and even users in the two mission phases are strongly different. Said so, from now on it will be considered MC5 as the selected mission concept for the active monitoring phase, since it is the best concept to optimize data delivery time and is very reliable since it provides two different types of operations (autonomous and on demand). For pre-event phase instead, MC6 has been selected because these operations are not time critical, so mission data processing can be done on ground (it is more reliable, cheap and flexible) and dual control allows to acquire data needed for FMC determination both autonomously every 10 days and on demand when a certain location faces a shortage in precipitation.

In the following, this hybrid concept will be referred to as the **"final mission concept".**

3.1.2 – Final mission concept

Now the actual concept of operations is described. Here the goal is to split the mission in its fundamental phases and to describe in detail needs and constraints for each phase.

In the table below is shown the subdivision of the mission into stages.

Mission phase	Mission subphase	Purpose	Duration
LEOP	Launch	Launch, release and place sat(s) in the selected orbit(s)	6 hours
	Activation	First boot of vital subsystems	2 hours
	Detumbling and deployment	First attitude control and calibration, followed by solar panels deployment	4 hours
Commissioning	Subsystems checkout	Check and calibrate functioning of all subsystems in detail	1 week
	Maneuver 1	Transfer to operative orbit, constellation formation	3 days
	Payload checkout	Check and calibrate functioning of all payload instruments in detail	1 week
Routine phase	Routine operations	Fire forecasting, detection and mapping	5 years
EOL	DOM deployment	Deploy de-orbit mechanisms	1 day
	Passive disposal	Passivate satellite and slowly de-orbit	5 years

Table 3.4 – Mission timeline, general

In the following, every mission phase is studied in detail.

Launch and early orbit phase

Characteristics	Launch	Activation	Detumb and deploy

Initial condition	Sat(s) mounted on launcher	Sat(s)' subsystems are not initialised yet	Sat(s) is tumbling and appendices are undeployed
Final condition	Sat(s) separate from last launcher stage	All subsystems are activated and checked	Satellite is detumbled and in sun pointing
Environment	Low Earth orbit	Low Earth orbit	Low Earth orbit
Objectives	Inject sat(s) on target orbit and separate from launcher	First boot of most subsystems, get sat(s) ready for detumbling	Detumbling, appendices deployment, get sat(s) ready for checkout
Required I/F with other systems	Mechanical, electrical and data I/F with launcher	Data link with ground station network	Data link with ground station network
General description	Sat(s) are launched and released in target orbit	Sat(s) vital subsystems (power, comms, command & DH) are activated and checked	Sat(s) is detumbled, appendices are deployed, a stable safe mode is reached
Duration	6 hours	2 hours	4 hours
Constraints	-Environmental conditions -On orbit perturbation -Sat(s) relies on launcher's systems	-On orbit perturbation -Sat(s) is tumbling -Battery power supply only -Low degree of automation	-On orbit perturbation -Low degree of automation
Potential off-nominal events	-Failure during launch or separation -Wrong orbit injection	-Failure in data link establishing -Subsystems do not boot	-Failure in deployment mechanisms -Failure in AOCS

Table 3.5 – Mission timeline, LEOP

Commissioning phase

Characteristics	**Subsystems checkout**	**Maneuver 1**	**Payload checkout**
Initial condition	Sat(s) is in safe mode	Sat(s) in launch release orbit	Sat(s) is fully operative except payload
Final condition	Sat(s) is in safe mode but all subsystems are fully operative	Sat(s) in target orbit, constellation formed. Payload not active.	Sat(s)'s payload and subsystems are fully operative
Environment	Low Earth orbit	Low Earth orbit	Target LEO
Objectives	Test and calibrate all subsystems' functions	Constellation formation	Test and calibrate all payload's functions getting sat(s) ready for routine operations

Required I/F with other systems	Data link with ground station network	Data link with ground station network	Data link with ground station network
General description	Sat(s) subsystems are tested from low to highest level operative mode Payload is not activated yet	Sat(s) move from orbit resulting from launch to target orbits, so is possible to calibrate payloads on point	Payload instruments are calibrated and I/F with subsystems is checked
Duration	1 week	3 days	1 week
Constraints	-Low degree of automation -High number of available links needed	-Limited propellant -Time to complete maneuver -Maneuver's accuracy	-Medium degree of automation -High number of available links needed
Potential off-nominal events	-Unknown behaviour/performance of whatever instruments	- Failure in thrust vectoring/ thrust production	-Unknown behaviour/performance of payload instruments

Table 3.6 – Mission timeline, Commissioning

Routine phase

The routine phase is described differently from the other three. Since this phase is very long lasting and has a completely different structure and characteristics compared to the others, the table used for the first two phases would not fit it properly. So, here is described with a short text and the operative functioning of the routine operations is described in *figure 3.2*.

The routine phase should last at least 3 years and its objective is to maximize the production of fire forecasting, detection and mapping data products.

In the active monitoring phase, the satellites will implement a scanning mode so that, with the frequency established before (around half an hour), the whole area of interest is scanned in *fire detection mode*. As soon as a satellite detects a fire, it switches to *fire mapping mode* so it is able to produce fine imagery of the location affected by the fire. Once the proper imagery is collected, it is processed on board: it means georeferencing imagery, filtering the image so that cloudy and water pixels are excluded from the analysis, processing the remaining pixels to classify them for fire mapping and intensity, finally attaching the processed and “interpreted” image to an actual map of the location stored in the on-board database. Once the mapping is produced, the final data product (a graded map of fire and smoke plume with some data about the fire attached) is downlinked directly to the civil protection station closest to the fire and equipped with an adequate antenna (please notice the downlinked data here are very small since it is a simple map with very few metadata, this implies the required data rate is not very high and the downlink duration will be very short). The raw imagery, in the meanwhile, is compressed with a lossless algorithm and stored and will be downlinked to the ground segment when the satellite will pass over an operative ground station outside the area of interest (so it is not busy in the routine operations), so it is possible to produce a database with the original data for further and different processing on ground, in a later moment.

In the pre-event phase, the satellites will acquire at nadir while passing over the area of interest, collecting all data required to compute NDVI and FMC. Remember this mission phase requires sun-synchronous orbit, so there will be a long interval of time in which the satellite will overpass locations outside the area of interest. To exploit the satellite at its best, alternative application for the mission will be found and labelled as goals of opportunity. Since every sun-synchronous orbit ensures regular links with the poles, it will be easy to downlink raw data during links with a ground station properly located. There, the data packages are delivered to the JRC, so they can be processed and used to update the portals of fire forecasting.

In both active monitoring and pre-event phase, there is the possibility to receive tasking from the ground so is possible to check and map fires already spotted by the civil protection, as well is possible to compute NDVI and FMC of locations that are facing a shortage in precipitation with higher frequency on demand.

In this link, no interlink between different satellites appears necessary but this needs to be checked through an orbital analysis later on.

The figure below is a data flow diagram explaining extensively how data flows through components during routine operations.

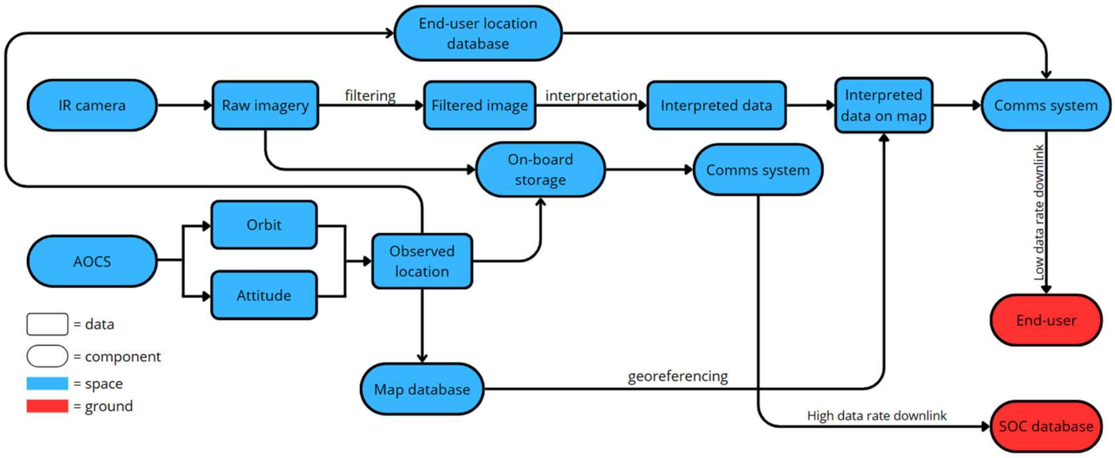


Figure 3.2 – Mission concept's routine phase data flow

End of life phase

Characteristics	DOM deployment	Passive disposal
Initial condition	Routine operations are over	Sat(s) is ready for deorbiting
Final condition	Sat(s) is ready for deorbiting	Sat(s) burn up in Earth's atmosphere
Environment	Low Earth orbit	Low Earth orbit, Earth's atmosphere
Objectives	Get sat(s) ready for safe and regulations compliant de-orbiting	Remove sat(s) from LEO in a controlled and safe way and within regulations terms
Required I/F with other systems	Data link with ground station network	Data link with ground station network
General description	De-orbit mechanism is deployed and the satellite is passivated	Sat(s) end its life deorbiting to Earth's atmosphere
Duration	1 day	5 years
Constraints	-Sat(s) subsystems are old and performances are degraded	-Sat(s) must burn up, not impact -Sat(s) position and state should be known for the whole maneuver
Potential off-nominal events	-DOM does not deploy	-Maneuver lasts longer than 5 yrs -Sat(s) reactivates -Sat(s) does not burn completely, thus impacts in unexpected location

Table 3.7 – Mission timeline, End of life

3.2 – Alternative mission architectures

In this paragraph will be defined the eight mission elements, namely: subject, payload, communication architecture, ground system, launch system, orbits, mission operations, spacecraft bus [37]. Among these elements, some are selected as the key tradables, so they are the ones on which the trade-off is performed, leading to the definition of the remaining ones. In the table below all the mission elements are listed and it is distinguished if they are considered key tradables or not in the following study. For each mission element, all the possible trades are listed.

Mission element	Key tradable	Possible trades/alternatives
Subject	No	The mission subject is fixed by the mission statement
Payload	Yes	Number of instruments, allocation of science goals on a different set of instruments
Spacecraft bus	No	Number of satellites, complexity and weight of subsystems
Orbit(s)	Yes	Which orbits are used? Just one orbit type can be used or a mix of many
Ground segment	Yes	Number of stations and their location. Are dedicated or existing stations used?
Mission operations	Yes	Level of autonomy for tasking and control, data processing and data delivery to the end user
Launch system	No	Using a dedicated launcher being its primary payload or not. Number of launches used to place sats in orbit
Communication architecture	No	Bands and equipment on ground and space segments needed to ensure data link

Table 3.8 – Mission elements

- **Orbits:** Mission geometry is chosen trying to accommodate several needs. In particular it is needed to choose orbits that make possible to fulfil measurement requirements, so here geostationary orbits are excluded (because would be impossible to have 10 m GSD from that distance) and for the purpose of FMC determination sun-synchronous orbits need to be selected. In the meanwhile, it is important to have enough satellites to meet the temporal resolution requirements, but they cannot be placed in too many different orbits because it is important to keep the number of launches and the orbital maneuvers needed for the constellation formations as low as possible. The following two options were considered:

1) Using Sun-synchronous orbits only, and the same satellites will be used for pre-event and active monitoring tasks.
2) Using few Sun-synchronous satellites for pre-event operations and a numerous constellation dedicated to active monitoring, exploiting LEO orbits different from Sun-synchronous ones that minimize revisit time.

The determination of the most suitable orbits is an extensive study and is now shown in a dedicated paragraph.

- **Payload:** Here what is fixed is the set of measurement requirements and science goals established in the STM. Anyway, these goals can be achieved in several ways, varying the allocation of measurement goals on a different set of instruments. Here two different payloads are considered feasible and compatible with the two different ideas about orbital configuration (for details about measurement requirements please refer to the science traceability matrix).
  1) Payload architecture 1 (PA1): fire detection, mapping and forecasting are allocated on three separate instruments. Respectively, a panchromatic-MWIR and two multispectral cameras.
  2) Payload architecture 2 (PA2): Fire detection is allocated on a panchromatic-MWIR camera, fire mapping and FMC computation are allocated on the same multispectral camera.

- **Spacecraft bus:** not a key tradable because the number of satellites directly comes as the minimum needed to respect temporal resolution requirements after orbit determination, while complexity and weight of the satellites depends on the payload and operations chosen.

- **Ground segment:** The number of ground stations used has to match the number of operations and the amount of information that, in nominal conditions, flow through the ground segment, with effective timing. So, since it has already been determined that, due to the strict time constraints of the mission, data processing will be on board and the downlink will be directly to the end user (this alleviates a lot the workload of the mission ground segment), if the mission is tasked and controlled fully autonomously, it is possible to have a small number of ground stations since they are used just for housekeeping operations. If such a large constellation is operated by only one ground station, this needs to be one dedicated ground station. If more than one ground station is used, it is possible to use already existing ground stations as customers. If it is chosen to have tasking and control coming from the ground segment, it will be necessary to use a numerous ground station network, so that it is possible to task the satellites timely. Three different alternatives are considered feasible:

1) 2 existing GS
2) 1 dedicated GS
3) Wide GSN (ground station network).

- **Mission operations:** Here the trade is really straightforward and has already been introduced:
  1) Autonomous tasking and control
  2) Non autonomous tasking and control.

- **Launch system:** not a key tradable because it is directly derived from the cheapest launch option after determining the target orbits and spacecraft bus weight.

- **Communication architecture:** not a key tradable because it is directly derived once the amount of generated data are known (only depending on the payload) and once orbits and ground segment are known.

3.2.1 – Mission orbital analysis

In the following section, it is determined which orbits can fulfil the mission requirements. Please remember that the main parameter driving the average revisit time is the total number of satellites employed, while the number of orbital planes influences the maximum revisit time (having more orbital planes allows to have a maximum revisit time very close to the average revisit time). Evidence about that will be provided during this study.

Sun-synchronous orbits: one option is to have every satellite placed in a sun-synchronous orbit, indeed some measurements have the explicit requirement to be taken from an SSO, while for the other measurements the orbit is not a requirement, so eventual an SSO or a different orbit could work anyway.

Since the average temporal resolution acceptable is 30 minutes, it will be necessary to have the satellites distributed on more than one orbital plane, creating what is called a Walker-star constellation pattern. Since it is necessary to have a dedicated launch for each orbital plane, it is important to minimize the number of orbital planes used. The initial guess used for the following analysis is that the optimum is with three orbital planes. Now it is important to understand how much the revisit time drops down if the number of satellites increases.

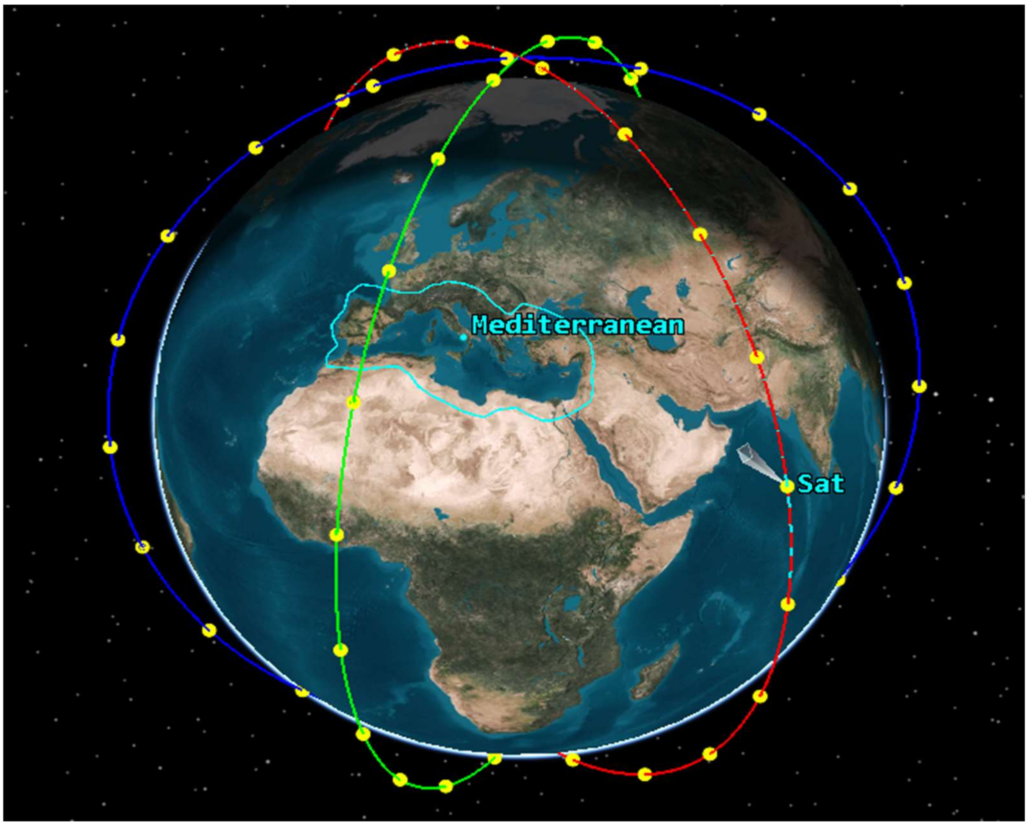


Figure 3.3 – Orbital analysis, SSO constellation

This scenario is modelled on STK®, where a coverage analysis over the Mediterranean area is run.

The revisit time provided by the sensor devoted to fire detection, the one on which the strict requirement on temporal resolution is defined, is computed; this sensor were modelled as a rectangular sensor with a 6° half aperture, whiskbroom scanning the underlying area with a 30° half aperture.

An iFOV = 12° is chosen to have a swath bigger than 100 km (as prescribed in the STM), while a FOV = 60° is chosen to have a GSD less than 50 m (as prescribed in the STM) in the worst case. This calculation was done taking as GSD reference value that of the optical payloads on the market that meet measurement requirements [38] (detailed analysis about off-the-shelf available payloads will be the subject of a dedicated paragraph). Since at nadir it is assumed $GSD = 37\ m$, off nadir:

$$GSD_\theta = \frac{GSD_{max}}{cos^2\theta} = \frac{37m}{cos^2(30°)} = 49.3\ m$$

At 30° off nadir it will be $GSD = 49.3\ m < 50\ m$.

In the following graph it is shown the average revisit time trend over the area of interest as the number of satellites per plane varies (the total number of satellites is simply obtained multiplying by three).

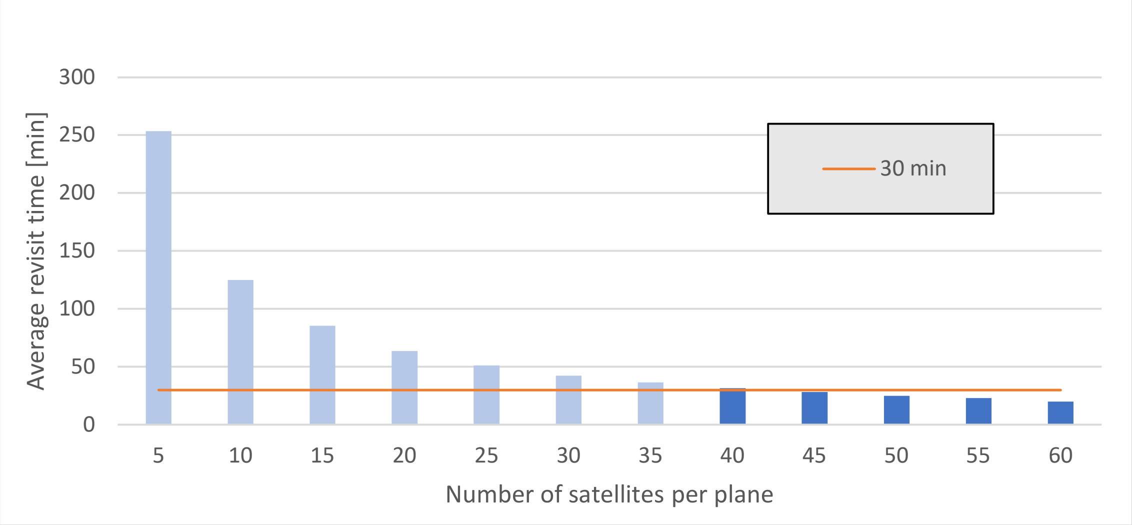


Figure 3.4 – Walker-star constellation, number of satellites

It is clear how the total number of satellites needed to meet the requirement on temporal resolution is very high, asin total 120 satellites are needed. However, it is important to notice how this figure of merit allows to establish not just nominal performances of the mission, but also what the mission could offer in the early stages of its life-cycle, when not all the satellites were deployed. Furthermore, if mission concepts including this kind of orbits will result advantageous on other aspects, this figure of merit allows to understand advantages and drawbacks of a potential negotiation of the temporal resolution requirement. To this end, it is now made the assumption of negotiating the requirement on temporal resolution to the point that now the new requirements is one hour (indeed, accepting a revisit time of 60 minutes it would be possible to cut 60 satellites off and this would be enormously cost effective), this assumption is possible since, as stated in paragraph 1.4.2, the current approach used by fire brigades takes several hours before actual rescue operations start, so having temporal resolution of 60 minutes instead of 30 would keep the mission worthy.

Having understood the total number of satellites needed in this mission configuration (60, holding all the assumptions just made), it is now important to define if the initial guess of three orbital planes as optimum makes sense or not. In the graph below it is shown the maximum revisit time trend over the area of interest as the number of orbital planes varies.

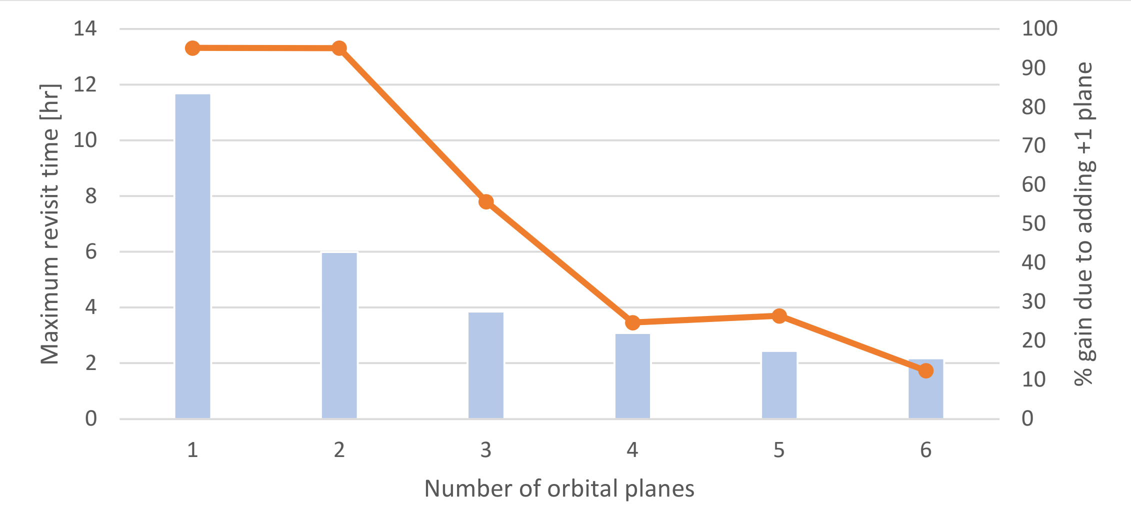


Figure 3.5 – Walker-star constellation, number of orbital planes

From this figure of merit, it is clear how the initial guess of optimum with three orbital planes is not the best, since with four planes there is an advantage of 30% in maximum revisit time compared to having three planes, while adding one more plane the trend flattens out. Therefore, it is assumed to have 60 satellites distributed on four orbital planes.

Anyway, the mission geometry related to a mission fully developed on Sun-synchronous orbits is summarised in the following table.

Constellation Walker-Star 98.6: 60/4/1			
# of satellites	60	altitude	550 km
# of orbital planes	4	inclination	97.8°

Table 3.9 – Walker-star constellation

The proper altitude was chosen ensuring to have a swath big enough as established in the STM matching typical aperture of payload components available on the market (this will be dealt in a dedicated paragraph), while inclination was chosen to have a Sun-synchronous orbit at that altitude.

Sun-synchronous and low Earth orbits combined: Another option, now fully investigated, is to have a mix of SSOs and LEOs. This can make sense because the only measurement requiring explicitly a Sun-synchronous orbit is related to the pre-event phase and is not time critical, while all other measurements, not requiring Sun-synchronous orbits, can be allocated on orbits that are more efficient in the optimisation of the revisit time over the number of satellites. So the idea is to have a dedicated launch, orbit and satellite (or maybe more than one) for the pre-event phase and a numerous constellation in a non-Sun-synchronous orbit with satellites dedicated to the active monitoring phase.

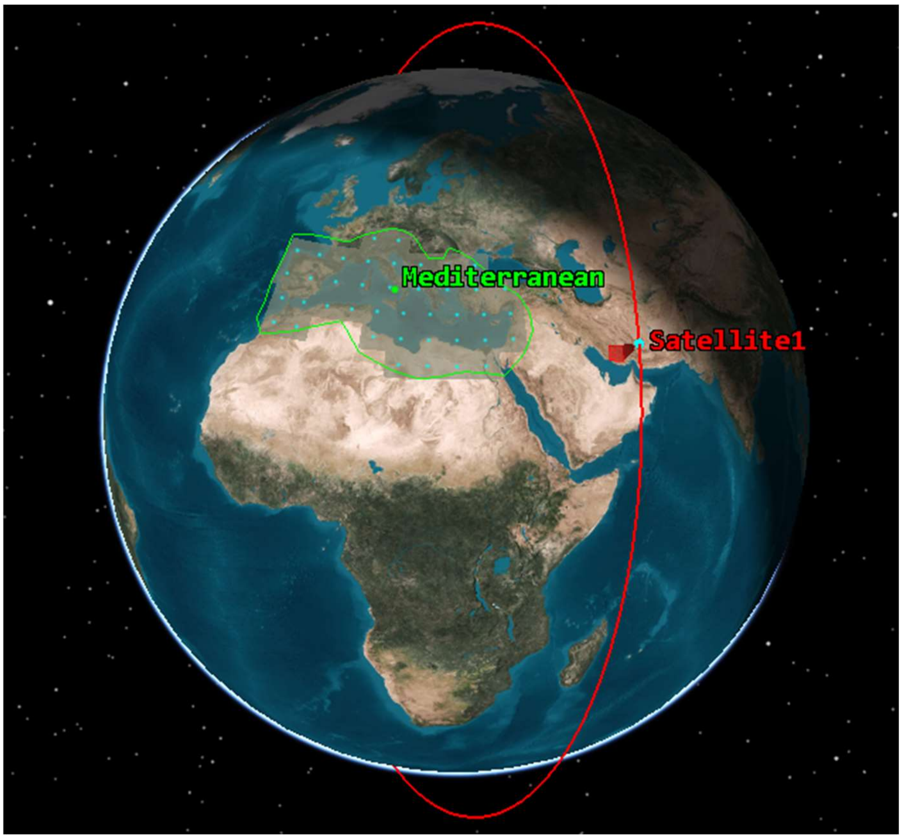
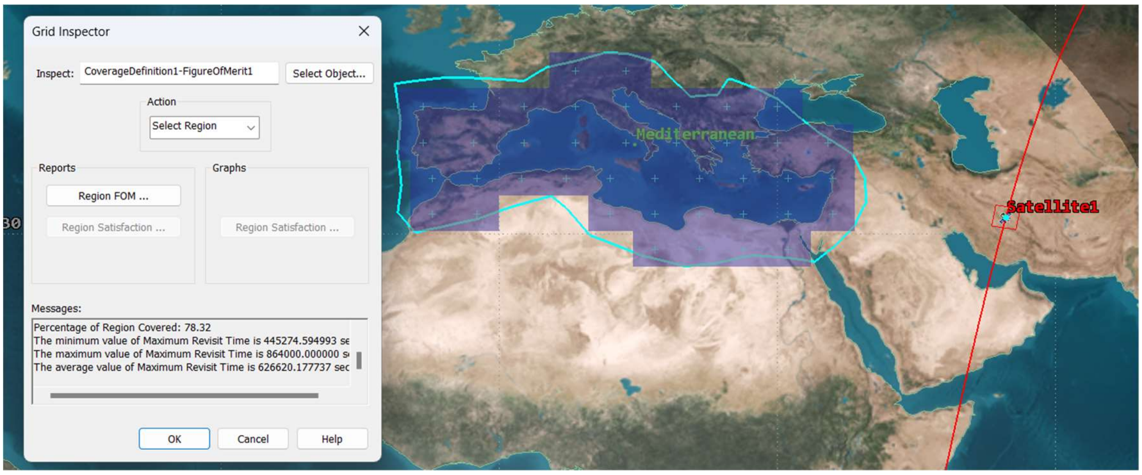


Figure 3.6 – Orbital analysis, pre-event

For the pre-event phase, the goal is to have at least one acquisition from a Sun-synchronous satellite in good lighting conditions (it is very important to ensure consistent and good lighting to have an accurate FMC computation), over the whole Mediterranean area with repetition frequency of no more than 10 days. This scenario is modelled in STK®, but the coverage is computed from a sensor with 9° fixed half aperture and pointing to Nadir from a Sun-synchronous orbit at an altitude of 550 km. Revisit time is computed counting the links that occur only in direct Sun (umbra and penumbra lighting conditions are excluded).

Here it is not needed to run a trade-off on the number of satellites and the number of orbital planes, since all requirements are met with just one satellite, as shown in the figure below.



Inspect: CoverageDefinition1-FigureOfMerit1

Action: Select Region

Messages:

```
Percentage of Region Covered: 78.32
The minimum value of Maximum Revisit Time is 445274.594993 se
The maximum value of Maximum Revisit Time is 864000.000000 s
The average value of Maximum Revisit Time is 626620.177737 sec
```

Figure 3.7 – Pre-event, revisit time & coverage

The figure above shows how with one single satellite in a Sun-synchronous orbit, it is possible to get an average revisit of about7 days, with a weekly coverage of more than 78% of the area of interest. So, if it is now possible to perform active monitoring with a number of satellites smaller than the previous orbital architecture, there will be a great advantage in terms of costs.

For the active monitoring phase, it is now selected a constellation on a Walker-delta pattern with orbital planes inclined of 45° (this choice is more efficient because now all the satellites do not fly over the poles, so it is possible to have a better temporal resolution on the Mediterranean area). The initial guess used for the following analysis is that the optimum is with two orbital planes. Now it is important to understand how much the revisit time drops down if the number of satellites increases.

This scenario is modelled on STK®, where a coverage analysis over the Mediterranean area is run.

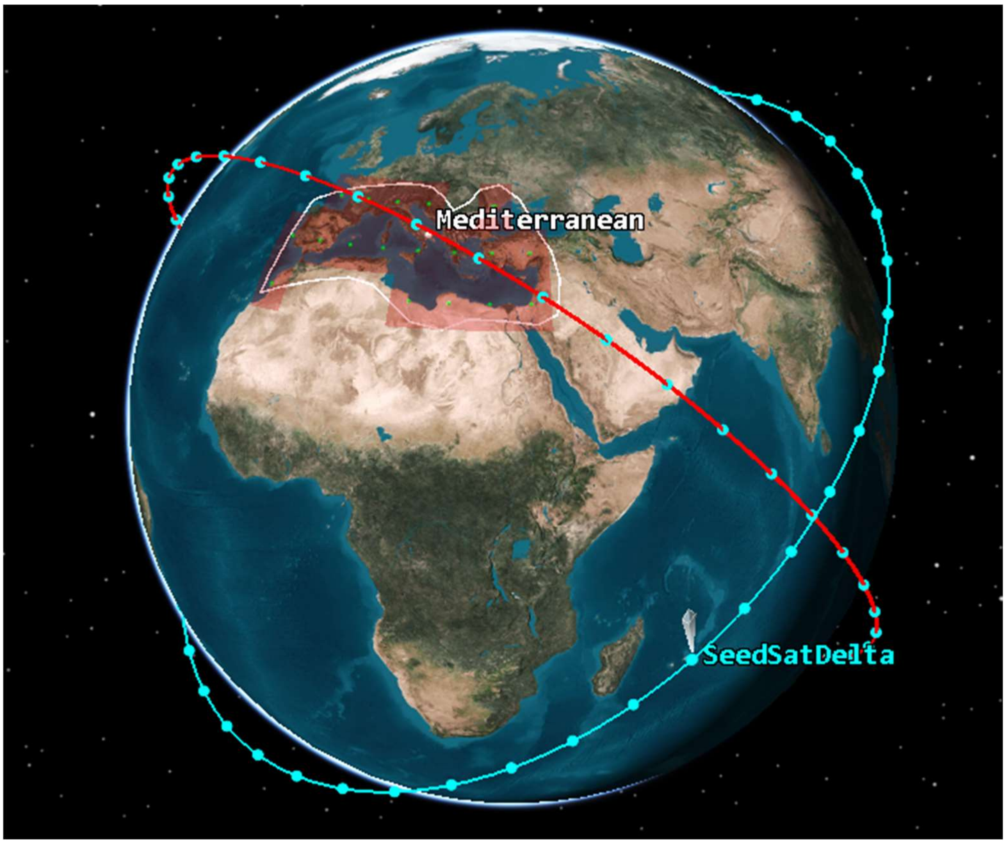


Figure 3.8 – Orbital analysis, walker-delta constellation

The coverage provided by the sensor devoted to fire detection, the one on which the strict requirement on temporal resolution is defined, is computed; this sensor were modelled as a rectangular sensor with an iFOV of 12°, whiskbroom scanning the underlying area with a 30° half aperture (these values are justified with the same logic explained in the previous orbital analysis).

In the following graph, it is shown the average revisit time trend over the area of interest as the number of satellites per plane varies.

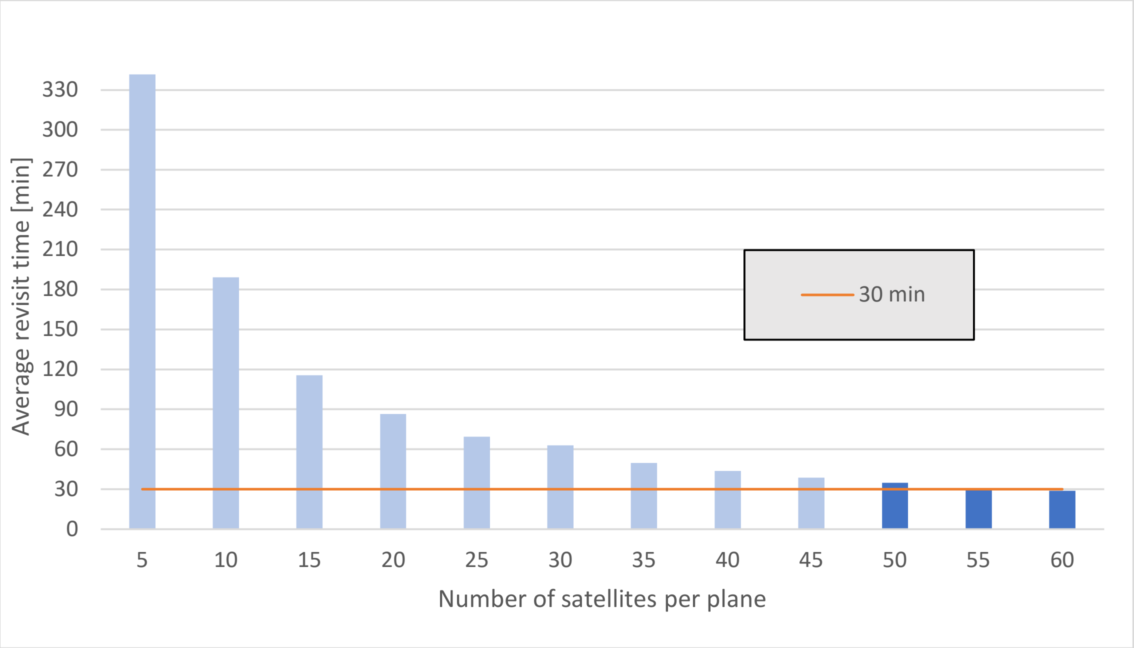


Figure 3.9 – Walker-delta constellation, number of satellites

This constellation provides better revisit time with respect to the number of satellites, indeed now it is possible to meet the 30 minutes requirement with a hundred satellites, while in the Walker-star constellation 120 satellites were needed. Once again, it is important to consider this figure of merit as meaningful of the performances of the constellation during the build-up phase of the mission, and again it is true that by slightly negotiating the 30 minutes requirement, it would be possible to have a big advantage in terms of cost. As before, it could be possible to identify a solution that achieves one hour revisit time with a reduced number of satellites (in this case 50), but for this constellation, 100 is selected as the number of satellites to take into account also a solution that perfectly meets the given requirements.

Having understood the total number of satellites needed in this mission configuration (100), it is now important to define if the initial guess of two orbital planes as optimum makes sense or not. In the graph below it is shown the maximum revisit time trend over the area of interest as the number of orbital planes varies.

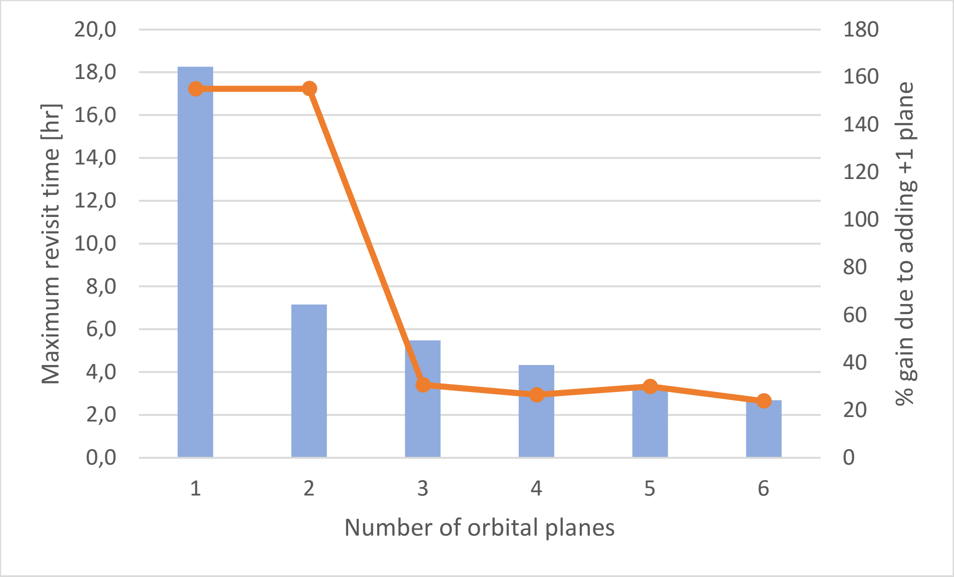


Figure 3.10 - walker-delta constellation, number of orbital planes

Applying the same criterion as before, the optimum about the number of orbital planes is found with three planes, since having three planes there is an improvement of over 30% in maximum revisit time, while adding one more plane the trend flattens out.

Anyway, the mission geometry related to a mission fully developed on Sun-synchronous orbits is summarised in the following table.

Constellation Walker-Delta 45: 99/3/1 (active monitoring)			
# of satellites	99	altitude	550 km
# of orbital planes	3	inclination	45°
1 SSO satellite (pre-event)			
# of satellites	1	altitude	550
RAAN	110°	inclination	97.8°
eccentricity	0	ω	N/A

Table 3.10 – Walker-delta constellation

The proper altitude was chosen ensuring to have a swath big enough as established in the STM, while the inclination was chosen as the one restricting the overpassed area the most without excluding the Mediterranean area.

It is important to make one observation about the two constellations discussed above. The main figure of merit used to assess them is the average revisit time, while the maximum revisit time is used as a secondary parameter but is not a constraining one. Strictly, this is wrong since having a high value of maximum revisit time means that the service is offered with some gaps, that is to say that some areas experience moments in which they are not observed by any satellite for some hours. Luckily, this can be neglected since more than 80% of total gaps are below the average revisit time, so the big gaps are a very uncommon contingency.

3.2.2 – Preliminary ΔV analysis

To these orbital configurations, is associated the following ΔV analysis. The premise to this analysis is the assumption that participating in a launch as part of a rideshare programme, satellites are likely to be released in a slightly different orbit compared to the target orbit. Furthermore, it is to be assessed the need to perform orbit maintenance maneuvers during the life-cycle, as well as the ΔV needed for deorbiting the mission when the disposal phase comes.

ΔV needed for orbit formation were estimated assuming to be launched in a rideshare programme and using the Keplerian parameters of SpaceX's next launches as a reference of the orbit in which the satellites could be released, then the orbital maneuvers requiredto movefrom the release orbit to the target orbit have been simulated on STK.

For orbit maintenance, it is preferred to avoid corrections maneuvers, if not strictly needed. To understand if it is necessary to do some propellant burns in this mission phase, it is important to understand how much the orbit is decaying due to orbit perturbations. For a preliminary design, the main responsible for orbit perturbation to take into account is the atmospheric drag, which is strongly dependent on satellite's ballistic coefficient:

$$C_B = \frac{m}{C_D A} \qquad (3.1)$$

Where:

- $m = satellite\ mass$. Since the estimated spacecraft bus mass, as will be dealt later in this chapter, it is around 15 kg, it is assumed in this part of the study to have 12U CubeSat [39].
- $C_D = satellite's\ drag\ coefficient$. For box shaped satellites it is usually very close to 2,2.
- $A = satellite's\ cross\ sectional\ area$. Since the hypothesis of 12U CubeSat holds, satellites dimensions are 20x20x35 cm, so $A = 0.04\ m^2$

So, $C_B = 272\ \frac{kg}{m^2}$

Once the ballistic coefficient is known, orbital decay depends on the altitude and on atmosphere variability. The relationship between those parameters is shown in the graph below, where it is displayed lifetime on orbit for three different values of ballistic coefficient and for each of them two curves show the two extremely different scenarios depending on atmosphere variability (due to magnetic and solar activity, such as other weather phenomena). This graph is shown for clarity of presentation, while the detailed theoretical study, used to compute the next results, is left as reference. [40]

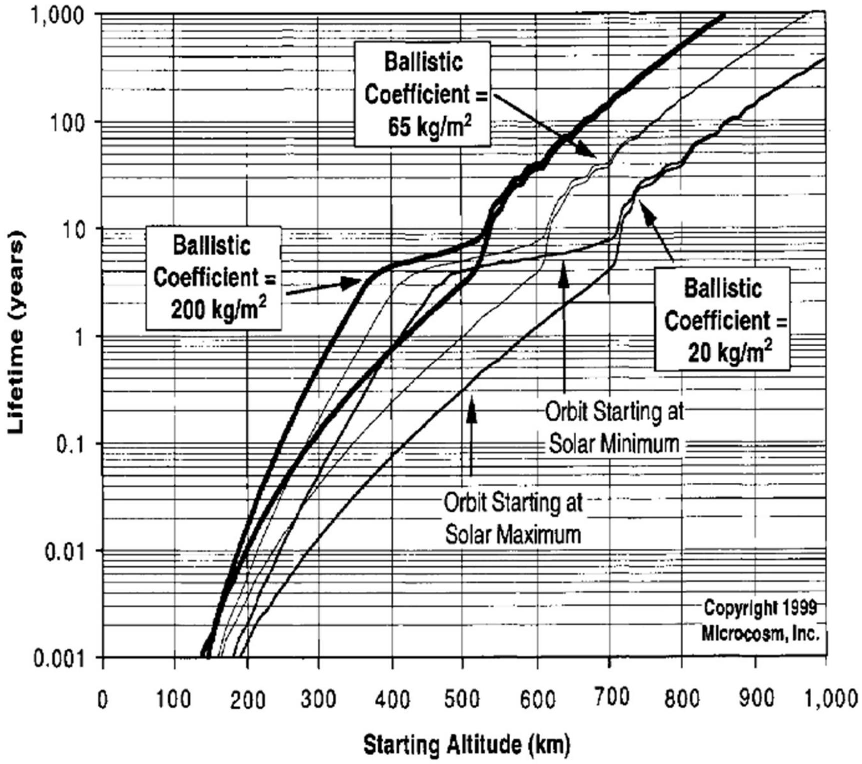


Figure 3.11 – Orbital decay time vs starting altitude and ballistic coefficient

Starting with an altitude of 550 km and considering the worst-case scenario related to the atmosphere variability, a satellite with these ballistic properties will have the following orbital decay:

$$\Delta h_{rev} = -\frac{2\pi\rho a^2}{C_B} \qquad (3.2)$$

This means $\Delta h \approx 10\ km$ over 5 years of routine operations, let's consider it acceptable for this mission (as the satellite decays, its instruments' swath gets smaller, so the temporal resolution gets worse, but 10 km in altitude variation cause a variation smaller than 5 minutes in constellation's revisit time, that is why it is acceptable). So, there is no ΔV budget allocated for orbit maintenance.

For deorbiting, there are two alternatives: when possible, a passive disposal using a de-orbit mechanism is preferred, otherwise it is needed to allocate a ΔV budget for a deorbiting maneuver. A DOM (De Orbiting Mechanisms) speeds up deorbiting by strongly decreasing the ballistic coefficient and deploying a film that increases the cross sectional area. It is easy to find off-the-shelf DOMs designed for CubeSats and nano/micro satellites in general. A typical DOM's film size is 500x500 mm [41].

Assuming to use such product, the satellite in the deorbiting phase would have

- $A = 0{,}25\ m^2$
- $C_B = 44\ \frac{kg}{m^2}$

Using graph at *figure 3.11* to determine deorbiting time in the worst-case scenario (solar minimum) once the DOM is deployed, it comes out that a passive disposal is possible in less than 5 years, and that means there is no ΔV budget allocated for that purpose.

So, for both possible mission geometries, here the ΔVs needed for these three tasks are shown: constellation formation, orbit maintenance, and deorbiting.

Orbit		**Orbit formation**	**Orbit maintenance**	**Deorbiting**	**Total ΔV**
SSO	per satellite	13 m/s	0 m/s	0 m/s	13 m/s
	per const.	780 m/s	0 m/s	0 m/s	780 m/s
LEO+SSO/ active monitoring	per satellite	6 m/s	0 m/s	0 m/s	6 m/s
	per const.	594 m/s	0 m/s	0 m/s	594 m/s
pre-event	one satellite	13 m/s	0 m/s	0 m/s	+ 13 m/s
					= 607 m/s

Table 3.11 - DeltaVs

An important step in the design is understanding how this ΔV budget reflects on the architecture in terms of amount of propellant and type of thrusters.

ΔV and propellant mass are correlated by the Tsiolkovsky equation [42]:

$$m_p = m_f \lfloor e^{\left(\frac{\Delta V}{I_{sp} g}\right)} - 1 \rfloor \qquad (3.3)$$

Where:

- $m_p = propellant\ mass$
- $m_f = spacecraft's\ final\ mass$
- $I_{sp} = specific\ impulse$, which only depends on the thruster type

Considering 4 kg as the maximum weight that can be allocated for the propulsion system plus the propellant mass, it is important to understand if common off-the-shelf thrusters designed for small satellites are capable to provide such performances within the weight and volume constraints.

From market research, it emerged that several products are largely capable to meet said requirements [43] [44]. Detailed equipment and subsystem sizing will be done later on this study, here it is enough to have understood that required performances are achievable.

Two examples using reference values from above mentioned products are now shown.

Assuming a final mass $m_f = 13\ kg$ and a maximum specific impulse $I_{sp} = 172\ s$ and having already derived a needed ΔV in the worst-case scenario equal to 13 m/s, it is possible to derive the needed propellant mass $m_p = 0.15\ kg$, that is far below the maximum tank capacity of this propulsion system ($0.7\ kg$) [43].

Assuming a final mass $m_f = 15\ kg$ and a maximum specific impulse $I_{sp} = 205\ s$ and having already derived a needed ΔV in the worst-case scenario equal to 13 m/s, it is possible to derive the needed propellant mass $m_p = 0.13\ kg$, that is far below the maximum tank capacity of this propulsion system ($4\ kg$) [44].

3.2.3 – Alternative mission architectures

Now the key-tradable mission elements have been chosen and alternatives have been identified for each of them:

- Payload: PA1, PA2
- Ground segment: 1 dedicated GS, 2 existing GS, 1 numerous GSN
- Mission operations: autonomous tasking & control, non-autonomous tasking & control
- Orbits: Walker-Star 97.8: 60/4/1, Walker-Delta 45: 99/3/1 + 1 SSO sat

All the possible mission architectures to trade-off are identified simply creating a tree with all the possible combinations of such elements and pruning the tree from unfeasible combinations.

This logical process is shown in the graph below:

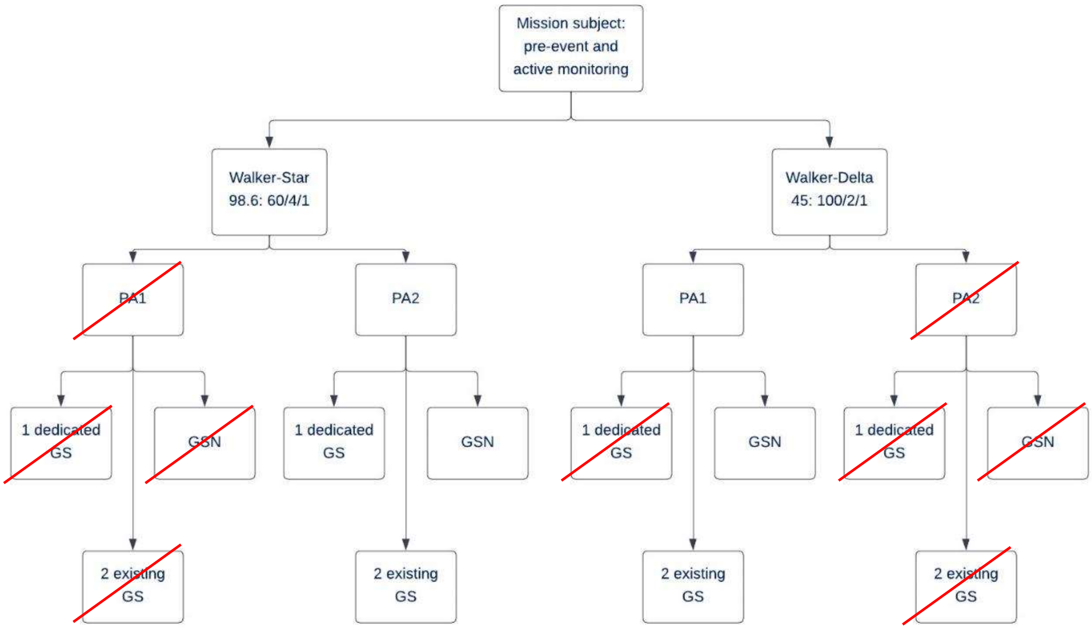


Figure 3.12 – Mission architectures tree pruning

The payload architecture 1 is not paired with the Walker-Star constellation because this would result inefficient: since all the satellites are equipped with the same instruments, it is better to reduce the number of instruments needed to do the mission, so the spacecraft bus will be lighter and smaller.

The payload architecture 2 is not paired with the other orbital configuration because in this architecture each science goal is allocated on a different instrument, so makes more sense to have a SSO satellite with one instrument only, since the only purpose of this satellite is fire forecasting, and the same holds for the Walker-Delta constellation.

Finally, in case the second orbital configuration is used, is not possible to have just one ground station, because to have decently frequent accesses with the SSO satellite it would be needed to place it at the poles, but this would make impossible for the Walker-Delta satellites to have links with it, since they do not fly at latitudes above 45° (basically, if this orbital configuration is used, at least two ground stations are needed, and at this point is no longer efficient to use dedicated ground stations, since splitting the mission workload on two ground stations, using two existing ones will be enough).

Tree in *figure 3.11* is the blueprint to figure out the following mission architectures:

- **Mission architecture 1:** consisting of a Walker-Star constellation with 60 satellites placed in Sun-synchronous orbits and distributed in four equally spaced orbital planes. These 60 satellites have the same spacecraft bus because they all host the same payload instruments: a panchromatic camera used for fire detection operating in MWIR with a swath bigger than 100 km and GSD smaller than 50 m and a multispectral camera used for fire mapping and FMC computation acquiring in RGB, NIR and SWIR with a GSD smaller than 10 m. This payload will take a mass per satellite around 15 kg to be accommodated. This mission architecture has the capability of full autonomy in tasking and control of routine operations so it is able to detect and map wildfires and downlink mapping products to the end users without any intervention from the ground segment. In this concept, the ground segment is used for housekeeping operations and to receive mission data, but just the ones related to the pre-event mission phase (once every 10 days), since all other mapping products are not supposed to pass through the ground stations. To this end, this mission architecture is served by one dedicated ground station at the North pole, since the workload for a single existing ground station also serving other missions would be too much.
- **Mission architecture 2:** consisting of a Walker-Star constellation with 60 satellites placed in Sun-synchronous orbits and distributed in four equally spaced orbital planes. These 60 satellites have the same spacecraft bus because they all host the same payload instruments: a panchromatic camera used for fire detection operating in MWIR with a swath bigger than 100 km and GSD smaller than 50 m and a multispectral camera used for fire mapping and FMC computation acquiring in RGB, NIR and SWIR with a GSD smaller than 10 m. This payload will take a mass per satellite around 15 kg to be accommodated. This mission architecture has the capability of full autonomy in tasking and control of routine operations so it is able to detect and map wildfires and downlink mapping products to the end users without any intervention from the ground segment. In this concept, the ground segment is used for housekeeping operations and to

receive mission data, but just the ones related to the pre-event mission phase (once every 10 days) since all other mapping products are not supposed to pass through the ground stations. To this end, this mission architecture is served by two existing ground stations: one at the North pole and one at the South pole, since the workload for a single existing ground station would be too much. The location of the ground stations is chosen to minimize time between two successive links (having one ground station at each pole would imply having one link every 45 minutes for each satellite).

- **Mission architecture 3:** consisting of a Walker-Star constellation with 60 satellites placed in Sun-synchronous orbits and distributed in four equally spaced orbital planes. These 60 satellites have the same spacecraft bus because they all host the same payload instruments: a panchromatic camera used for fire detection operating in MWIR with a swath bigger than 100 km and GSD smaller than 50 m, and a multispectral camera used for fire mapping and FMC computation acquiring in RGB, NIR and SWIR with a GSD smaller than 10 m. This payload will take a mass per satellite around 10 kg to be accommodated. In this mission architecture, tasking and control for routine operations are delegated to the ground segment, so no autonomy is expected for these tasks and that means these satellites are able to detect and map wildfires just once they receive specific commands about target pointing and functioning mode from ground. Then, acquired data are processed on board and mapping products are downlinked directly to the end users. This lack of autonomy makes the spacecraft bus less complex, thus lighter than the previous ones. In this concept, the ground segment is used for routine (science related) and housekeeping operations and, since the mission has to deliver promptly data to the end user after a data product is tasked, it is necessary to have a numerous ground station network all around the Mediterranean region serving the mission, so it is possible to send commands to the satellite shortly after a mapping is requested.
- **Mission architecture 4:** consisting of a Walker-Delta constellation with 99 satellites placed in 45° inclined orbits and distributed in three orbital planes plus a single nanosatellite placed in a Sun-synchronous orbit. The

payload architecture is composed of two instruments mounted on the 99 LEO satellites (a panchromatic camera used for fire detection operating in MWIR with a swath bigger than 100 km and GSD smaller than 50 m, and a multispectral camera operating in SWIR with a GSD smaller than 10 m) and one instrument mounted on the SSO satellite (a multispectral camera used for FMC computation operating in RGB, NIR, SWIR with a swath bigger than 200 km and a GSD smaller than 500 m). This payload will take a mass per satellite around 15 kg to be accommodated for the Walker-Delta constellation, while the SSO satellite will weigh around 5 kg. This mission architecture has the capability of full autonomy in tasking and control of routine operations so it is able to detect and map wildfires and downlink mapping products to the end users without any intervention from the ground segment. In this concept, the ground segment is used for housekeeping operations and to receive mission data, but just the ones related to the pre-event mission phase (once every 10 days) since all other mapping products are not supposed to pass through the ground stations. To this end, this mission architecture is served by two existing ground stations (since the workload for a single existing ground station would be too much): one ground station at the North pole is used to serve just the SSO satellite for raw imagery downlink, one ground station on the Mediterranean area is used to perform housekeeping operations for the whole mission.

- **Mission architecture 5:** consisting of a Walker-Delta constellation with 99 satellites placed in 45° inclined orbits and distributed in three orbital planes plus a single nanosatellite placed in a Sun-synchronous orbit. The payload architecture is composed of two instruments mounted on the 99 LEO satellites (a panchromatic camera used for fire detection operating in MWIR with a swath bigger than 100 km and GSD smaller than 50 m, and a multispectral camera operating in SWIR with a GSD smaller than 10 m) and one instrument mounted on the SSO satellite (a multispectral camera used for FMC computation operating in RGB, NIR, SWIR with a swath bigger than 200 km and a GSD smaller than 500 m). This payload will take a mass per satellite around 10 kg to be accommodated for the Walker-Delta constellation, while the SSO satellite will weigh around 5 kg. In this mission architecture, tasking and control for routine operations are delegated to the ground segment, so no autonomy is expected for these tasks and that means these satellites are able to detect and map wildfires just once they receive specific commands about target pointing and functioning mode from ground. Then, acquired data are processed on board and mapping products are downlinked directly to the end users. This lack of autonomy makes the spacecraft bus less complex, thus lighter than the previous ones. In this concept, the ground segment is used for routine (science related) and housekeeping operations and, since the mission has to deliver promptly data to the end user after a data product is tasked, it is necessary to have a numerous ground station network all around the Mediterranean region serving the mission, so it is possible to send commands to the satellite shortly after a mapping is requested.

All mission architectures are summarized in the tables below.

Mission architecture 1

Mission element	Description			
Spacecraft bus	# of sats	60	Each satellite has two cameras on board, an onboard computer powerful enough to allow for autonomous operations and propellant to guarantee $\Delta V \approx 13$ m/s	
	Mass	≈15 kg		
Payload	1. Panchromatic camera	- MWIR - Swath > 100 km - GSD < 50 m		Whiskbroom scanning, used for fire detection
	2. Multispectral imager	- RGB, NIR, SWIR - Swath > 10 km - GSD < 10 m		Target and nadir pointing, used for fire mapping and FMC computation
Mission operations	Autonomous tasking and control		Ground segment not involved in routine tasking & control, data processing and downlink	
Orbits	Walker-Star 97.8:60/4/1 @550 km constellation		- 1st maneuver: constellation formation (≈13 m/s) - No considerable station keeping needed - 2nd maneuver: passive deorbiting	
Ground segment	# of stations	1	One dedicated ground station at the North pole (for housekeeping and pre-event data reception only)	

Table 3.12 – Mission architecture 1

Mission architecture 2

Mission element	Description			
Spacecraft bus	# of sats	60	Each satellite has two cameras on board, an onboard computer powerful enough to allow for autonomous operations and propellant to guarantee ΔV≈13 m/s	
	Mass	≈15 kg		
Payload	1. Panchromatic camera		- MWIR - Swath > 100 km - GSD < 50 m	Whiskbroom scanning, used for fire detection
	2. Multispectral imager		- RGB, NIR, SWIR - Swath > 10 km - GSD < 10 m	Target and nadir pointing, used for fire mapping and FMC computation
Mission operations	Autonomous tasking and control		Ground segment not involved in routine tasking & control, data processing and downlink	
Orbits	Walker-Star 97.8:60/4/1 @550 km constellation		- 1st maneuver: constellation formation (13 m/s) - No considerable station keeping needed - 2nd maneuver: passive deorbiting	
Ground segment	# of stations	2	2 existing polar stations (at North and South pole) used for housekeeping and pre-event data reception only.	

Table 3.13 – Mission architecture 2

Mission architecture 3

Mission element	Description			
Spacecraft bus	# of sats	60	Each satellite has two cameras on board and propellant to guarantee ΔV≈13 m/s	
	Mass	≈10 kg		
Payload	1. Panchromatic camera		- MWIR - Swath > 100 km - GSD < 50 m	Whiskbroom scanning, used for fire detection
	2. Multispectral imager		- RGB, NIR, SWIR - Swath > 10 km - GSD < 10 m	Target and nadir pointing, used for fire mapping and FMC computation
Mission operations	Non-autonomous tasking and control		Ground segment does routine tasking & control. Autonomous data processing and downlink	

Orbits	Walker-Star 97.8:60/4/1 @550 km constellation		1st maneuver: constellation formation (13 m/s) No considerable station keeping needed 2nd maneuver: passive deorbiting
Ground segment	# of stations	>10	Ground station network on the Mediterranean area used for non-autonomous activities and prompt tasking

Table 3.14 – Mission architecture 3

Mission architecture 4

Mission element	Description			
Spacecraft bus	# of sats	100	99 constellation satellites with two cameras, one onboard computer powerful enough to allow autonomous operations and propellant to guarantee ΔV≈6 m/s. One SSO satellite with a single camera, no processing or autonomous operation capability on board and propellant to guarantee ΔV≈13 m/s	
	Mass	≈15 kg		
Payload	1. Panchromatic camera		MWIR Swath > 100 km GSD < 50 m	Whiskbroom scanning, used for fire detection. Mounted on LEO sats
	2. Multispectral imager		SWIR Swath > 10 km GSD < 10 m	Target pointing, used for fire mapping. Mounted on LEO sats
	3. Multispectral imager		RGB, NIR, SWIR Swath > 200 km GSD < 500 m	Nadir pointing, used for FMC computation. Mounted on SSO sat
Mission operations	Autonomous tasking and control		Ground segment not involved in routine tasking & control, data processing and downlink	
Orbits	Walker-Delta 45:99/3/1 @550 km constellation		1st maneuver: constellation formation (6 m/s) No considerable station keeping needed 2nd maneuver: passive deorbiting	
	1 SSO @550 km, 97.8° inclination		1st maneuver: constellation formation (13 m/s) No considerable station keeping needed 2nd maneuver: passive deorbiting	
Ground segment	# of stations	2	1 polar station used to receive raw pre-event data and 1 station on the Mediterranean used for housekeeping	

Table 3.15 – Mission architecture 4

Mission architecture 5

Mission element	Description			
Spacecraft bus	# of sats	100	99 constellation satellites with two cameras and propellant to guarantee $\Delta V \approx 6$ m/s. One SSO satellite with a single camera and propellant to guarantee $\Delta V \approx 13$ m/s	
	Mass	≈10 kg		
Payload	1. Panchromatic camera		MWIR Swath > 100 km GSD < 50 m	Whiskbroom scanning, used for fire detection. Mounted on LEO sats
	2. Multispectral imager		SWIR Swath > 10 km GSD < 10 m	Target pointing, used for fire mapping. Mounted on LEO sats
	3. Multispectral imager		RGB, NIR, SWIR Swath > 200 km GSD < 500 m	Nadir pointing, used for FMC computation. Mounted on SSO sat
Mission operations	Non-autonomous tasking and control		Ground segment does routine tasking & control. Autonomous data processing and downlink	
Orbits	Walker-Delta 45:99/3/1 @600 km constellation		1st maneuver: constellation formation (6 m/s) No considerable station keeping needed 2nd maneuver: passive deorbiting	
	1 SSO @550 km, 97.8° inclination		1st maneuver: constellation formation (13 m/s) No considerable station keeping needed 2nd maneuver: passive deorbiting	
Ground segment	# of stations	>10	Ground station network (Mediterranean + polar areas) used for non-autonomous activities and prompt tasking	

Table 3.16 – Mission architecture 5

In the tables above, the mass per satellite was estimated considering that 30% of the spacecraft bus (fuel excluded) is occupied by payload instruments for autonomous missions and 40% for non-autonomous missions. To this mass is added the mass of fuel needed to guarantee a proper ΔV. The payload mass used as reference for this calculation is taken from off-the-shelf products; this topic is not discussed in detail now because it is the matter of one of the next paragraphs.

3.2.4 – Trade-off on mission architectures

Once the five alternative mission architectures are identified, it is important to choose which key FoMs (figures of merit) to take into account in order to perform a trade-off on the five alternatives to identify the Mission Architecture baseline.

The FoMs selected for this study are:

- **Temporal resolution**: time needed to deliver data products to the end user. It is related to revisit time (depending only on the orbital configuration) and time needed to collect, process and downlink data to the end user. Shorter time elapsing to accomplish these operations means better temporal resolution, so it is related to a higher score.
- **Cost**: amount of costs associated with the mission design and manufacturing and to launch complexity. Features implying higher cost are: higher orbits with different orbital planes, high number of satellites, heavier and more complex spacecraft bus. Low cost is better, so it is related to a higher score.
- **Operations**: amount of cost and complexity of all the activities required on ground (and onboard to perform the mission). Autonomy in tasking and control of the mission (like on-board processing), as well as a small number of ground stations, imply lower intervention from ground that is better, so it is related to a higher score.
- **Data quality**: effectiveness of information contained in data products. Higher compliance with measurement requirements (in terms of spectral bands, GSD, swath) implies better data products. Higher data quality is better, so it is related to a higher score.
- **ΔV**: total variation of space segment velocity to maintain the desired mission geometry. Low delta V is better because the mission is simpler and there is more volume available for the payload since the quantity of propellant required is lower. Low delta V is related to a higher score.

Based on these FOMs, an AHP is used to perform the trade-off.

At first, for each attribute or FOM, it is important to define a weight to quantify their relative importance for the mission. To do so, a prioritization matrix is produced, in which the relative importance for all the possible pairs of attributes is displayed. Then a normalised sum is produced and the weight of each attribute is determined.

Prioritization Matrix	Temporal resolution	Data quality	Cost	ΔV	Mission operations		Temporal resolution	Data quality	Cost	ΔV	Mission operations	
Temporal resolution	1	2	3	5	7		0,46	0,496	0,456	0,385	0,389	0,437
Data quality	0,5	1	2	3	5		0,23	0,248	0,304	0,231	0,278	0,258
Cost	0,333	0,5	1	3	4		0,153	0,124	0,152	0,231	0,222	0,176
ΔV	0,2	0,333	0,333	1	1		0,092	0,083	0,051	0,077	0,056	0,072
Mission operations	0,143	0,2	0,25	1	1		0,066	0,05	0,038	0,077	0,056	0,057
	2,176	4,033	6,583	13	18		1,000	1,000	1,000	1,000	1,000	1,000

Table 3.17 – Mission architecture, AHP prioritization matrix

Once attributes’ relative importance is known, the next step is to quantify, for each mission architecture, compliance to each attribute. Said compliance is expressed as a score in the figure below.

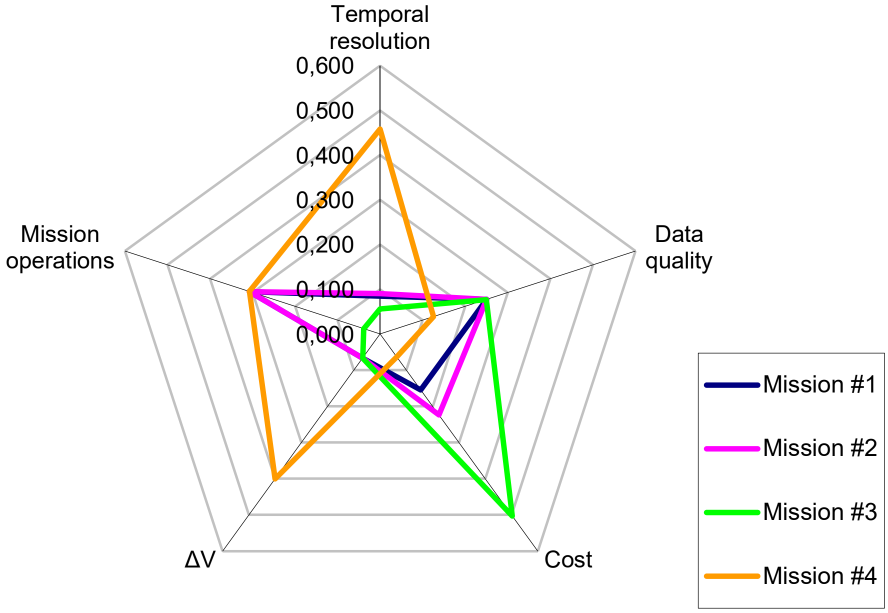


Figure 3.13 – Mission architectures AHP

Knowing the compliance of each mission architecture to each attribute and knowing the relevance of each attribute, it is possible to produce a weighted normalised sum of the scores obtained by each mission architecture.

Summary	Temporal resolution		Data quality		Cost		ΔV		Mission operations		**Final Score**
	Weighting	Score	Weighting	Score	Weighting	Score	Weighting	Score	Weighting	Score	
Mission #1	0,437	0,085	0,258	0,250	0,176	0,154	0,072	0,067	0,057	0,308	0,151
Mission #2	0,437	0,091	0,258	0,250	0,176	0,223	0,072	0,067	0,057	0,308	0,166
Mission #3	0,437	0,056	0,258	0,250	0,176	0,502	0,072	0,067	0,057	0,038	0,185
Mission #4	0,437	0,459	0,258	0,125	0,176	0,063	0,072	0,400	0,057	0,308	0,290
Mission #5	0,437	0,310	0,258	0,125	0,176	0,057	0,072	0,400	0,057	0,038	0,209

Table 3.18 – Mission architectures, AHP results

From the table above, it is possible to understand the results of the trade-off: the mission architecture baseline needs to be mission architecture 4.

4 – Payload design

This chapter is aimed to design the payload that matches the mission architecture selected in the previous chapter. Here the approach is to skim the existing off-the-shelf products to understand if there are payload instruments available on the market that meet the mission requirements, otherwise there will be the need to design a custom one.

The selected mission architecture requires three different instruments to be identified, so the same analysis is repeated three times for each instrument.

In the table below there is a list of off-the-shelf thermal cameras compatible with a 12U CubeSat frame [45].

Product	Producer	Mass [g]	Volume [mm³]	GSD [m]	Swath [km]	Bands
HyperScout 2	Cosine	1800	200x200 x50	330	280	VIS, NIR (up to 50) TIR (up to 3)
Digital Earth sensor	Sitael	400	126x71x52	10000	400	8-14 µm (PAN)
iSIM-90 (single channel)	Satlantis	4000	308x114 x100	1.65	13	VIS to SWIR (up to 4)
iSIM-90 (dual channel)	Satlantis	6000	308x216 x115	1.65	26	VIS to SWIR (up to 8)
Chameleon imager	DragonFly	1600	100x100 x215	8.7	11.2	SWIR (up to 4)
Mantis imager	DragonFly	500	100x100 x65	16 (PAN) 32 (MS)	32	VIS to SWIR (up to 6)
Drago-1	IACTEC	1040	89x92x137	300*	190	SWIR (up to 2)
Drago-2	IACTEC	1160	96x96x170	50*	32	SWIR (up to 2)
HSI-100	BST	5600	262x221 x131	40 -VIS 100 -SWIR	50	VIS to SWIR (up to 30)
T-Scout	Cosine	1800	95x95 x160	60	62	8-14 µm (up to 2)
22 mm cluster	Kairo Space	2400	200x91 x91	37	114	VIS to SWIR (up to 32)

22 mm camera	Kairo Space	1100	221x74 x91	37	125	VIS to SWIR (up to 6)
ECAM-IR1**	Malin SSS	330	78x58x63	/	/	8-14 µm (up to 2)

Table 4.1 – Payloads off-the-shelf

** before super-resolution augmentation algorithm*

*** GSD and swath are negotiable*

4.1 – Instrument 1

In this paragraph the goal is to select the first of the three instruments used in the selected mission architecture. Said instrument is a panchromatic camera operating in MWIR with a swath > 100 km and a GSD < 50 m at an altitude of 550 km.

From *Table 4.1* it is possible to notice that a MWIR sensor is not common. That is probably because in this wavelength there are fewer applications than SWIR and LWIR.

Anyway, for this sensor there will be the need to design a custom one, since none of the off-the-shelf instruments is satisfying, but it is still possible to give a look at the existing products matching the needed GSD and swath to have an awareness about mass, volume and power budget.

Below, *Table 4.1* is retrieved, highlighting whether an instrument meets the given requirements:

Product	Producer	Mass [g]	Volume [mm^3]	GSD [m]	Swath [km]	Bands
HyperScout 2	Cosine	1800	200x200 x50	330	280	VIS, NIR (up to 50) TIR (up to 3)
Digital Earth sensor	Sitael	400	126x71x52	10000	400	8-14 µm (PAN)
iSIM-90 (single channel)	Satlantis	4000	308x114 x100	1.65	13	VIS to SWIR (up to 4)
iSIM-90 (dual channel)	Satlantis	6000	308x216 x115	1.65	26	VIS to SWIR (up to 8)
Chameleon imager	DragonFly	1600	100x100 x215	8.7	40	SWIR (up to 4)

Mantis imager	DragonFly	500	100x100 x65	16 (PAN) 32 (MS)	32	VIS to SWIR (up to 6)
Drago-1	IACTEC	1040	89x92x137	300*	190	SWIR (up to 2)
Drago-2	IACTEC	1160	96x96x170	50*	32	SWIR (up to 2)
HSI-100	BST	5600	262x221 x131	40 -VIS 100 -SWIR	50	VIS to SWIR (up to 30)
T-Scout	Cosine	1800	95x95 x160	60	62	8-14 µm (up to 2)
22 mm cluster	Kairo Space	2400	200x91 x91	37	114	VIS to SWIR (up to 32)
22 mm camera	Kairo Space	1100	221x74 x91	37	125	VIS to SWIR (up to 6)
ECAM-IR1	Malin SSS	330	78x58x63	/	/	8-14 µm (up to 2)

Table 4.2 – Instrument 1 search

KairoSpace's instruments 22 mm cluster and 22 mm camera are perfectly meeting requirements on swath and GSD, while Drago-1 from IACTEC could get close to the desired GSD depending on the super-resolution algorithm, and ECAM-IR1 from Malin SSS could be a very good option if the customisation capability offered by the manufacturer allow to achieve a good trade-off between GSD and swath.

In the table below it is possible to analyse more in detail the technical specifications of these instruments.

Instrument	Mass [g]	Volume [mm^3]	GSD [m]	Swath [km]	Power [W]	Bit depth
Drago-1	1040	89x92x137	300*	190	5.5	14 bit
22 mm cluster	2400	200x91x91	37	114	12-48	8-14 bit
22 mm camera	1100	221x74x91	37	125	12	8-14 bit
ECAM-IR1	330	78x58x63	/	/	8.75	12 bit

Table 4.3 – Instrument 1, best options

From this table it is possible to select the KairoSpace instrument 22 mm camera as the first instrument (as reference for the massand power budget), because it is lighter, smaller and less power consuming than other alternatives, while in the future Drago-1 could turn out to be a new best option if the state of the art of the GSD will get to 50 m.

Still holds the need to design a custom instrument with specifications similar to the selected one, but operating in MWIR.

4.2 – Instrument 2

In this paragraph the goal is to select the second of the three instruments used in the selected mission architecture. Said instrument is a multispectral camera operating in at least three SWIR wavelengths, with a swath > 10 km and a GSD ≈ 10 m at an altitude of 550 km.

From *Table 4.1* it is possible to notice that several off-the-shelf SWIR sensors are available. That is probably because several applications exploit this wavelength.

Below, *Table 4.1* is retrieved, highlighting whether an instrument meets the given requirements:

Product	Producer	Mass [g]	Volume [mm³]	GSD [m]	Swath [km]	Bands
HyperScout 2	Cosine	1800	200x200 x50	330	280	VIS, NIR (up to 50) TIR (up to 3)
Digital Earth sensor	Sitael	400	126x71x52	10000	400	8-14 µm (PAN)
iSIM-90 (single channel)	Satlantis	4000	308x114 x100	1.65	13	VIS to SWIR (up to 4)
iSIM-90 (dual channel)	Satlantis	6000	308x216 x115	1.65	26	VIS to SWIR (up to 8)
Chameleon imager	DragonFly	1600	100x100 x215	8.7	11.2	SWIR (up to 4)
Mantis imager	DragonFly	500	100x100 x65	16 (PAN) 32 (MS)	32	VIS to SWIR (up to 6)
Drago-1	IACTEC	1040	89x92x137	300*	190	SWIR (up to 2)
Drago-2	IACTEC	1160	96x96x170	50*	32	SWIR (up to 2)
HSI-100	BST	5600	262x221 x131	40 -VIS 100 -SWIR	50	VIS to SWIR (up to 30)
T-Scout	Cosine	1800	95x95 x160	60	62	8-14 µm (up to 2)

22 mm cluster	Kairo Space	2400	200x91 x91	37	114	VIS to SWIR (up to 32)
22 mm camera	Kairo Space	1100	221x74 x91	37	125	VIS to SWIR (up to 6)
ECAM-IR1**	Malin SSS	330	78x58x63	/	/	8-14 µm (up to 2)

Table 4.4 – Instrument 2 search

It is possible to notice how three different instruments are meeting the given requirements, namely: Satlantis' iSIM90 single channel and dual channel, and DragonFly's Chameleon imager.

In the table below it is possible to analyse more in detail the technical specifications of these instruments.

Instrument	Mass [g]	Volume [mm^3]	GSD [m]	Swath [km]	Power [W]	Bit depth
iSIM-90 single ch.	4000	308x114 x100	1.65	13	25	8-12 bit
iSIM-90 dual ch.	6000	308x216 x115	1.65	26	30	8-12 bit
Chameleon imager	1600	100x100 x215	8.7	11.2	5-7	8 or 10 bit

Table 4.5 – Instrument 2 best options

From this table it is clear how the best option is the Chameleon imager, since it is perfectly meeting all requirements being very light, small and power consuming.

Instruments 1 & 2 are the ones mounted on the 99 small sats of the constellation, so now there is a precise estimate of the payload mass for these satellites and that allows to do a better estimate of the total mass of the small satellites.

Since the payload mass will be the total mass of instruments 1 & 2, it will be 3.4 kg. Assuming the payload mass being 30% of the total spacecraft mass (as stated in the SMAD and mentioned before), it will be around 12 kg. To this value must be added the wet mass of the propulsion stage that, from the assumptions made in chapter 3.2.2 of this thesis, is around 2.5 kg, plus 0.5 kg of fuel. Finally, the total wet mass of each of the 99 LEO satellites of the constellation is about 15 kg. It is still assumed to fit the spacecraft bus in a 12U CubeSat configuration, but the mass per satellite is now adjusted and can be now used for budgeting purposes.

4.3 – Instrument 3

In this paragraph the goal is to select the third of the three instruments used in the selected mission architecture. Said instrument is a multispectral camera acquiring in RGB and at least in one NIR and one SWIR wavelengths, with GSD < 500 m and swath > 200 km, at an altitude of 550 km.

From *Table 4.1 it* is possible to understand how none of the available instruments provide acquisition both in VNIR and SWIR with such a large aperture, but there is one that gets really close. Indeed, Cosine's HyperScout-2 provides acquisition in VNIR and in thermal infrared with proper GSD and swath, the only problem is that the band offered in TIR is not in the right wavelength. It is possible to assume that this problem is solvable since on the manufacturer's website it is declared that the spectral bands given in the datasheet are customisable on demand.

So, this instrument is selected and here its technical specifications are shown.

Instrument	Mass [g]	Volume [mm^3]	GSD [m]	Swath [km]	Power [W]	Bit depth
HyperScout -2	1800	200x200 x50	330	280	12	8-12 bit

Table 4.6 – Instrument 3 best option

5 – Mission Cost

In this chapter a detailed cost analysis of the mission is performed and the possible positive economic impact of the mission on the Mediterranean wildfire problem is analysed. These two information give an awareness about the economic value of the mission itself.

The mission cost is modelled using a parametric approach, so it is identified one or more cost drivers for each mission area and those are used as inputs of a mathematical model that gives as output a cost estimate for the specific mission area.

The mathematical model here adopted is the one used in the SMAD, that is a summary of the SSCM from The Aerospace Corporation [46].

The only cost of the mission area that was not derived with the parametric model is the launch cost, since the exact pricing is publicly available on providers' websites.

5.1 – Methodology

A cost estimate is possible using Cost Estimate Relationships (CERs), which are formulas relating a cost driver to the cost estimate.

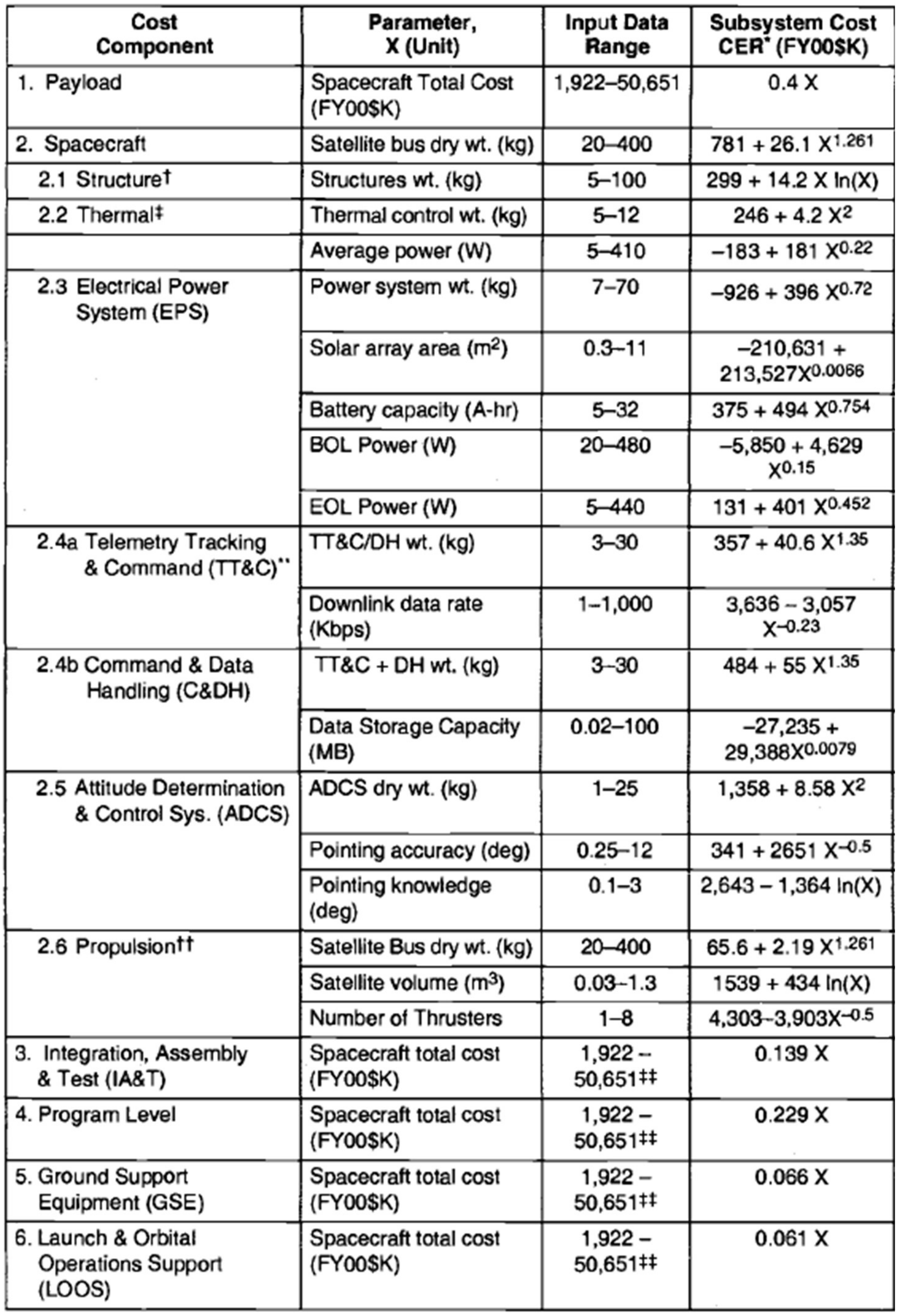
The model provides results is FY00$K (thousands of dollars referred to the fiscal year 2000).

The model computes total cost for RDT&E (research, development, test & evaluation) plus TFU (theoretical first unit).

RDT&E is considered a non-recurring cost, that means it is not dependent on the number of satellites or flight units used in the mission (if mission is supported by one satellite or by a large constellation, RDT&E has the same value since the cost of research and development is paid just once).

TFU is the cost necessary to fly the first flight unit once the RDT&E spending phase is over, and comprises cost for assembly, labour, material, equipment related to the manufacturing and launch phase. This is considered a recurring cost since the total cost for the mission (apart from RDT&E costs) depends on the number of satellites or flight units needed for the mission accomplishment.

To compute the total mission cost, the TFU must be multiplied with the learning curve, so the total cost to manufacture hundred satellites is not simply hundred times TFU, because the higher the number of satellites, the lower will be the average manufacturing cost per satellite (that is true because labour gets more productive as the employees' experience grows, materials and assets are cheaper if acquired in bigger quantities and in general because system level duties are performed more efficiently if the production is larger). This concept will be dug deeper in a dedicated paragraph later on.



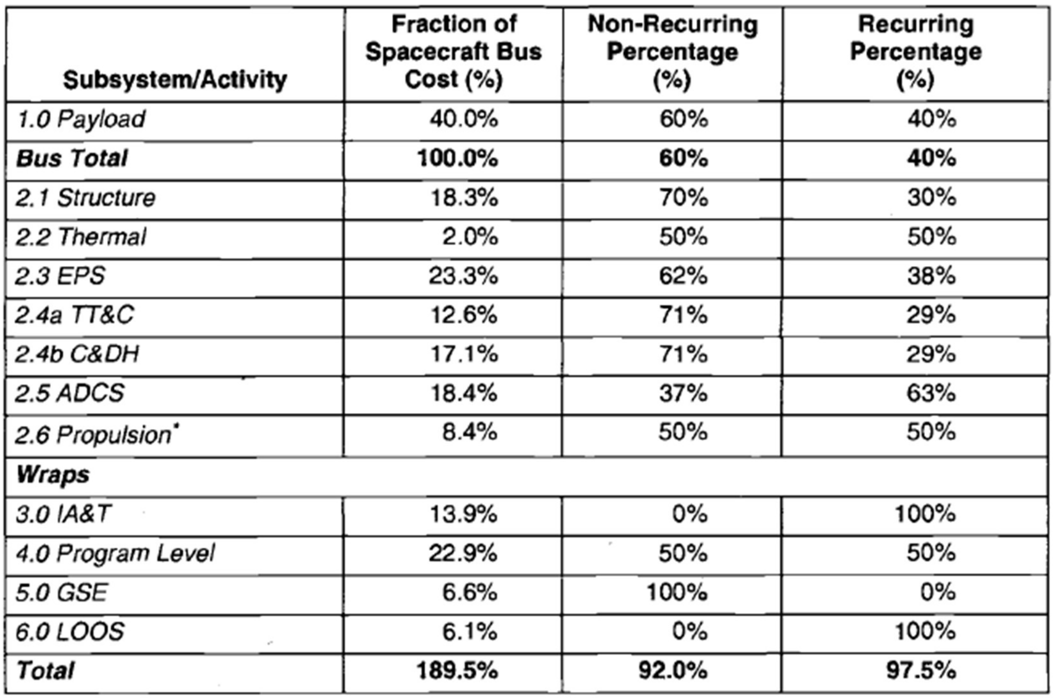
Cost Component	Parameter, X (Unit)	Input Data Range	Subsystem Cost CER* (FY00$K)
1. Payload	Spacecraft Total Cost (FY00$K)	1,922–50,651	$0.4\,X$
2. Spacecraft	Satellite bus dry wt. (kg)	20–400	$781 + 26.1\,X^{1.261}$
2.1 Structure†	Structures wt. (kg)	5–100	$299 + 14.2\,X\ln(X)$
2.2 Thermal‡	Thermal control wt. (kg)	5–12	$246 + 4.2\,X^2$
	Average power (W)	5–410	$-183 + 181\,X^{0.22}$
2.3 Electrical Power System (EPS)	Power system wt. (kg)	7–70	$-926 + 396\,X^{0.72}$
	Solar array area (m²)	0.3–11	$-210{,}631 + 213{,}527X^{0.0066}$
	Battery capacity (A-hr)	5–32	$375 + 494\,X^{0.754}$
	BOL Power (W)	20–480	$-5{,}850 + 4{,}629\,X^{0.15}$
	EOL Power (W)	5–440	$131 + 401\,X^{0.452}$
2.4a Telemetry Tracking & Command (TT&C)**	TT&C/DH wt. (kg)	3–30	$357 + 40.6\,X^{1.35}$
	Downlink data rate (Kbps)	1–1,000	$3{,}636 - 3{,}057\,X^{-0.23}$
2.4b Command & Data Handling (C&DH)	TT&C + DH wt. (kg)	3–30	$484 + 55\,X^{1.35}$
	Data Storage Capacity (MB)	0.02–100	$-27{,}235 + 29{,}388X^{0.0079}$
2.5 Attitude Determination & Control Sys. (ADCS)	ADCS dry wt. (kg)	1–25	$1{,}358 + 8.58\,X^2$
	Pointing accuracy (deg)	0.25–12	$341 + 2651\,X^{-0.5}$
	Pointing knowledge (deg)	0.1–3	$2{,}643 - 1{,}364\ln(X)$
2.6 Propulsion††	Satellite Bus dry wt. (kg)	20–400	$65.6 + 2.19\,X^{1.261}$
	Satellite volume (m³)	0.03–1.3	$1539 + 434\ln(X)$
	Number of Thrusters	1–8	$4{,}303 - 3{,}903X^{-0.5}$
3. Integration, Assembly & Test (IA&T)	Spacecraft total cost (FY00$K)	1,922 – 50,651‡‡	$0.139\,X$
4. Program Level	Spacecraft total cost (FY00$K)	1,922 – 50,651‡‡	$0.229\,X$
5. Ground Support Equipment (GSE)	Spacecraft total cost (FY00$K)	1,922 – 50,651‡‡	$0.066\,X$
6. Launch & Orbital Operations Support (LOOS)	Spacecraft total cost (FY00$K)	1,922 – 50,651‡‡	$0.061\,X$

Table 5.1 - SSCM, From SMAD: Mission cost modelling (Table 20-6)

In the table above CERs for small satellites are shown. These CERs are applicable for input data 25% above and below the given data range. It is important to notice that this model gives just a rough estimate and that it has been elaborated in 1996, while in the last two decades small-sats space missions became enormously more efficient and cheaper, so the results of this analysis are considered to consistently overestimate the real mission cost (but it is still helpful to have an idea of the order of magnitude of it).

Since the table above gives an estimate for the development and manufacturing of one spacecraft and since this mission has a large constellation of 99 identical satellites, it is important to split the total cost of each of the six mentioned cost elements into RDT&E and TFU, so it is possible to make separate analysis for these two different types of cost.

This is done through the application to the following recurring and non-recurring factors:



Subsystem/Activity	Fraction of Spacecraft Bus Cost (%)	Non-Recurring Percentage (%)	Recurring Percentage (%)
1.0 Payload	40.0%	60%	40%
Bus Total	**100.0%**	**60%**	**40%**
2.1 Structure	18.3%	70%	30%
2.2 Thermal	2.0%	50%	50%
2.3 EPS	23.3%	62%	38%
2.4a TT&C	12.6%	71%	29%
2.4b C&DH	17.1%	71%	29%
2.5 ADCS	18.4%	37%	63%
*2.6 Propulsion**	8.4%	50%	50%
Wraps			
3.0 IA&T	13.9%	0%	100%
4.0 Program Level	22.9%	50%	50%
5.0 GSE	6.6%	100%	0%
6.0 LOOS	6.1%	0%	100%
Total	**189.5%**	**92.0%**	**97.5%**

Table 5.2 – Recurring factors, From SMAD: Mission cost modelling (Table 20-9)

Once the total cost for RDT&E and for mission manufacturing is computed, the total mission cost is obtained adding ground segment & mission operations costs and launch cost.

Applying this model to the mission object of this thesis, the following results are derived:

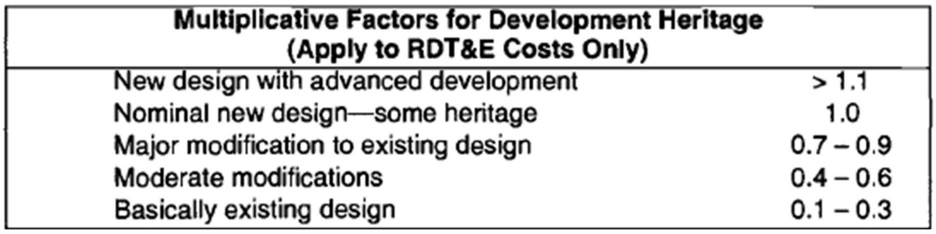
Cost component	Parameter X	Input data value	Subsystem cost [FY00$K]	RDT&E cost [FY00$K]	TFU cost [FY00$K]
Spacecraft bus	Satellite bus dry weight	15 [kg]	1541	925	616
Payload	Spacecraft bus cost	1541 [FY00$K]	616	370	246
IA&T*	Spacecraft bus cost	1541 [FY00$K]	214	0	214
Program Level	Spacecraft bus cost	1541 [FY00$K]	352	176	176
GSE**	Spacecraft bus cost	1541 [FY00$K]	102	102	0
LOOS***	Spacecraft bus cost	1541 [FY00$K]	94	0	94
Total			**2919**	**1573**	**1346**

Table 5.3 – RDT&E and TFU cost modelling

*Integration, assembly and test; **Ground support equipment; ***Launch & orbital operation support;

5.2 – RDT&E cost modelling

RDT&E costs are the ones computed in *Table 5.3* after applying a heritage factor, namely a coefficient adjusting research and development costs according to the level of heritage the mission has from already existing space missions. A mission relying on a completely new design has zero heritage, so the corresponding factor is higher; a mission that replicates an existing design has a great heritage, so the corresponding factor is lower. For commercial missions the heritage factor is 0.8, while the other contingencies are shown in the table below:



Multiplicative Factors for Development Heritage (Apply to RDT&E Costs Only)	
New design with advanced development	> 1.1
Nominal new design—some heritage	1.0
Major modification to existing design	0.7 – 0.9
Moderate modifications	0.4 – 0.6
Basically existing design	0.1 – 0.3

Table 5.4 – Heritage factors, From SMAD: Mission cost modelling (Table 20-8)

For this mission is considered a heritage factor equal to 0.8, so:

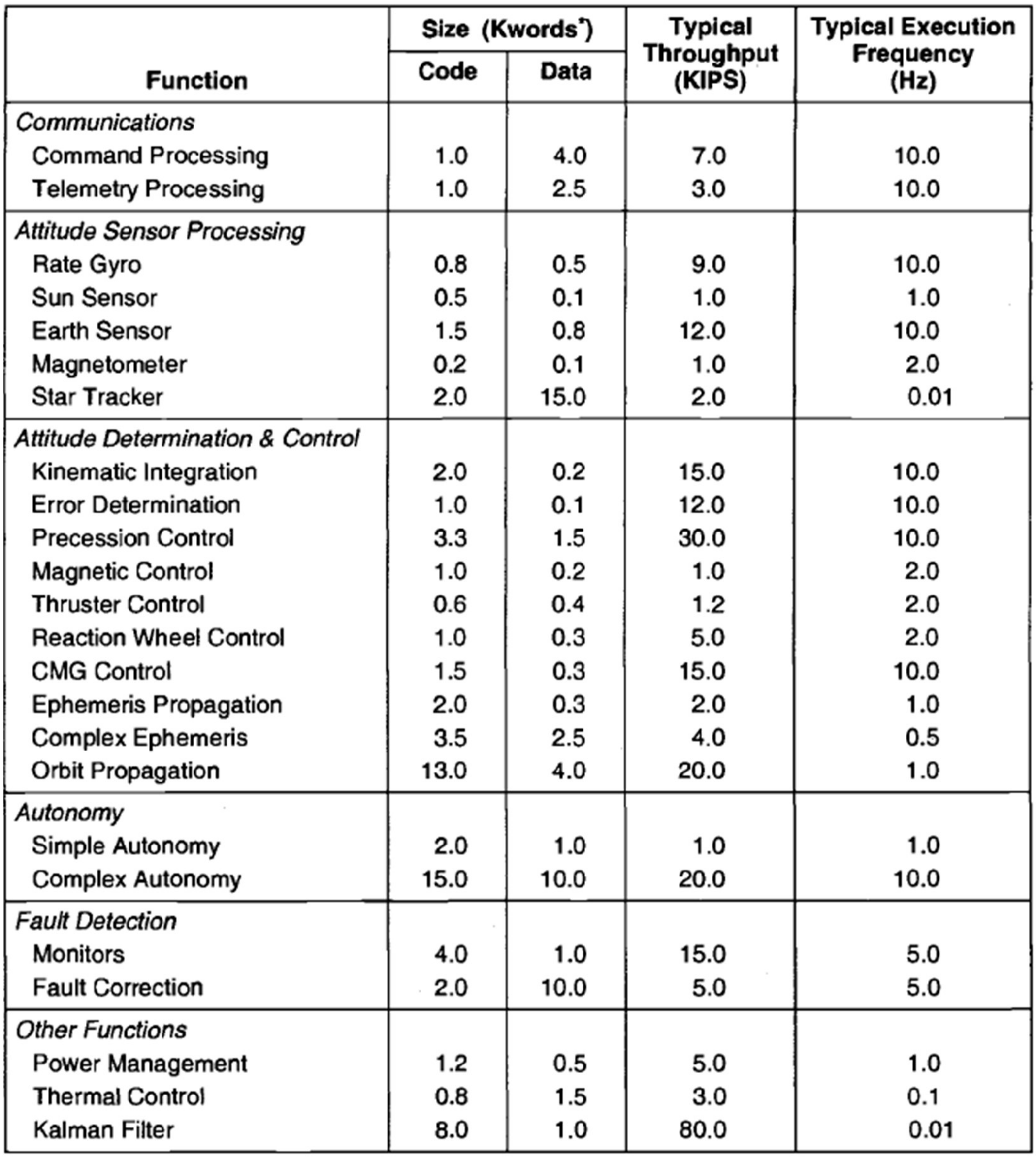
$$RDT\&E = 1573 * 0.8 = 1258\ FY00\$K$$

Furthermore, cost for RDT&E comprises software production, validation and maintenance (updates). Software cost depends on number of lines of code, on the programming language in which is written, as follows:

$$onboard\ software\ [FY00\$K] \qquad 435\ x\ KLOC*$$

*Thousands of lines of code

The extent of the software depends on the number of assembly instructions requested to the onboard computer by each satellite subsystem, so it depends on the complexity of the satellite bus. Typical values are in the table below.

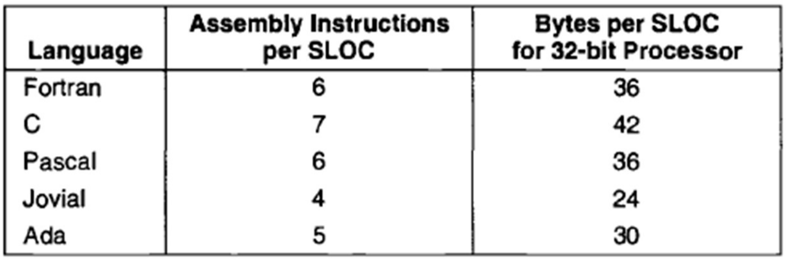


Function	Size (Kwords*)		Typical Throughput (KIPS)	Typical Execution Frequency (Hz)
	Code	Data		
Communications				
Command Processing	1.0	4.0	7.0	10.0
Telemetry Processing	1.0	2.5	3.0	10.0
Attitude Sensor Processing				
Rate Gyro	0.8	0.5	9.0	10.0
Sun Sensor	0.5	0.1	1.0	1.0
Earth Sensor	1.5	0.8	12.0	10.0
Magnetometer	0.2	0.1	1.0	2.0
Star Tracker	2.0	15.0	2.0	0.01
Attitude Determination & Control				
Kinematic Integration	2.0	0.2	15.0	10.0
Error Determination	1.0	0.1	12.0	10.0
Precession Control	3.3	1.5	30.0	10.0
Magnetic Control	1.0	0.2	1.0	2.0
Thruster Control	0.6	0.4	1.2	2.0
Reaction Wheel Control	1.0	0.3	5.0	2.0
CMG Control	1.5	0.3	15.0	10.0
Ephemeris Propagation	2.0	0.3	2.0	1.0
Complex Ephemeris	3.5	2.5	4.0	0.5
Orbit Propagation	13.0	4.0	20.0	1.0
Autonomy				
Simple Autonomy	2.0	1.0	1.0	1.0
Complex Autonomy	15.0	10.0	20.0	10.0
Fault Detection				
Monitors	4.0	1.0	15.0	5.0
Fault Correction	2.0	10.0	5.0	5.0
Other Functions				
Power Management	1.2	0.5	5.0	1.0
Thermal Control	0.8	1.5	3.0	0.1
Kalman Filter	8.0	1.0	80.0	0.01

Table 5.5 – Flight software throughput, From SMAD: Spacecraft computer system (Table 16-13)

Summing the instructions required by the highlighted functions, it is possible to derive that the software throughput is ≈ 250 KIPS (thousands of instructions per second).

Conversion from assembly instructions to lines of source code depends on the programming language.



Language	Assembly Instructions per SLOC	Bytes per SLOC for 32-bit Processor
Fortran	6	36
C	7	42
Pascal	6	36
Jovial	4	24
Ada	5	30

Table 5.6 – Programming language influence, From SMAD: Spacecraft computer system (Table 16-14)

Assuming to have the software written in C, the onboard software will be ≈ 36 KLOC long, so

$$onboard\ software\ [FY00\$K] = 435\ x\ KLOC = 15\,660\ FY00\$K$$

The heritage factor applies to the software cost as well, since it is part of the RDT&E cost. Since software for CubeSat can be largely recycled by existing missions, the heritage factor here is 0.4, so:

$$onboard\ software\ [FY00\$K] = 15\,660 * 0.4 = 6264\ FY00\$K$$

5.3 – TFU cost modelling

TFU cost is derived from *Table 5.3,* then the learning curve is applied to obtain the production cost, so:

$$Production\ cost = TFU * L$$

Where:

$$L = Learning\ curve = N^{B}$$

$$N = number\ of\ flight\ units$$

$$B = 1 - \frac{ln\ ln\ [100\%/S]}{ln\ 2}$$

$$S = curve\ slope$$

The curve slope S represents the percentage reduction in cumulative average cost when the number of production units is doubled. For example: if S = 95% and the first unit costs $1 million, then doubling the number to 2 units reduces the average cost of both to 95% of the first unit. Thus, the two units cost \$1.9 million. The second unit cost is \$0.9 million.

For less than 10 units, a 95% learning curve slope is recommended to be applied. Between 10 and 50 units, a 90% learning curve and 85% for over 50 units is appropriate.

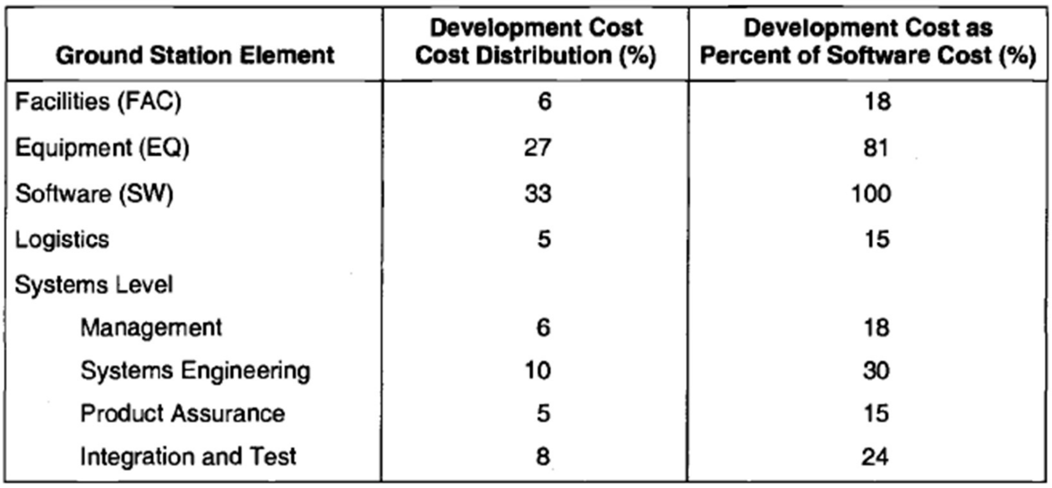
Since here the flight units are 100, S = 85%, so:

$$B = 1 - \frac{ln\, ln\left[\frac{100\%}{S}\right]}{ln\, ln\, 2} = 0.766$$

$$Production\ cost = 1346 * 100^{0.766} = 45720\ FY00\$K$$

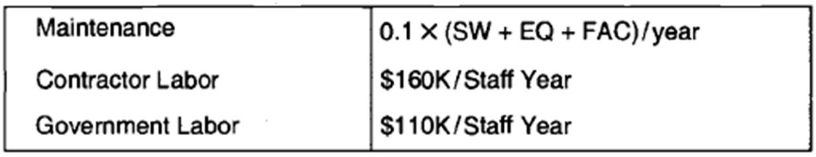
5.4 – Ground segment & operations cost modelling

In this study, ground segment and operations costs are modelled as functions of the software cost, as shown in the tables below:



Ground Station Element	Development Cost Cost Distribution (%)	Development Cost as Percent of Software Cost (%)
Facilities (FAC)	6	18
Equipment (EQ)	27	81
Software (SW)	33	100
Logistics	5	15
Systems Level		
Management	6	18
Systems Engineering	10	30
Product Assurance	5	15
Integration and Test	8	24

Table 5.7 – Ground segment cost modelling, From SMAD: Mission cost modelling (Table 20-11)



Maintenance	0.1 × (SW + EQ + FAC)/year
Contractor Labor	\$160K/Staff Year
Government Labor	\$110K/Staff Year

Table 5.8 – Operations cost modelling, From SMAD: Mission cost modelling (Table 20-12)

Cost element	Cost per year [FY00\$K]	Overall cost [FY00\$K]
Ground segment		
Facilities	N/A	1127
Equipment		5073
Logistics		940

System level		5450
Total	**12590**	
Operations		
Maintenance	1246	6232
Labor*	2400	12000
Total	**3646**	**18232**

Remembering the mission is supposed to last 5 years and software is supposed to cost 6264 FY00$K, for this mission holds:

Table 5.9 – Ground segment & operations cost

*Assuming to have 15 contractor employees operating the mission

5.5 – Launch cost modelling

Nowadays space industry launchers have become way cheaper than the past.

This is also true thanks to rideshare programs, in which smaller payloads can participate in launches organised for bigger spacecrafts, namely the launcher primary payload.

On one hand being a secondary payload in a rideshare program allows for low cost launches, on the other hand it implies that the launch is not tailored to mission needs in terms of launch window, interfaces and orbit injection.

To date, the cheapest launch provider is SpaceX, which with its Falcon 9 has the capability to launch to a wide variety of low Earth orbits (SSO, Polar, inclined orbits) and has several launch windows available due to the high number of launches in schedule.

The SpaceX rideshare program allows secondary payloads to be launched with a minimum fare of 300000 $ for a payload mass up to 50 kg, then an additional fee of 6000 $/kg is applied [47].

In this mission there is the need to launch 99 sats in three separate launches to form the walker delta constellation, so:

$$One\ launch\ cost = 33\ satellites * 15\frac{kg}{satellite} * 6000\frac{\$}{kg} = 2970\ FY20\$K$$

This cost has to be multiplied times three launches, then there is an additional launch for the SSO satellite, that would cost 300 FY00$K, so:

$$Launch\ cost = 3 * 2970 + 300 = 9210\ FY20\$K$$

Please notice these costs are in FY00$K because the pricing is referred to nowadays inflation.

In the table below the cost analysis is summarised and converted in FY20$K.

Cost element	FY00$K	FY20$K
RDT&E	7522	11456
Production cost	45720	69631
Ground segment	12590	19174
Operations	18232	27767
Launch	9210	14026
Total	**93274**	**142054**

Table 5.10 – Overall mission cost

In conclusion, according to the described parametric model, the mission is expected to cost no more than 142 M $.

5.6 – Mission profit potential

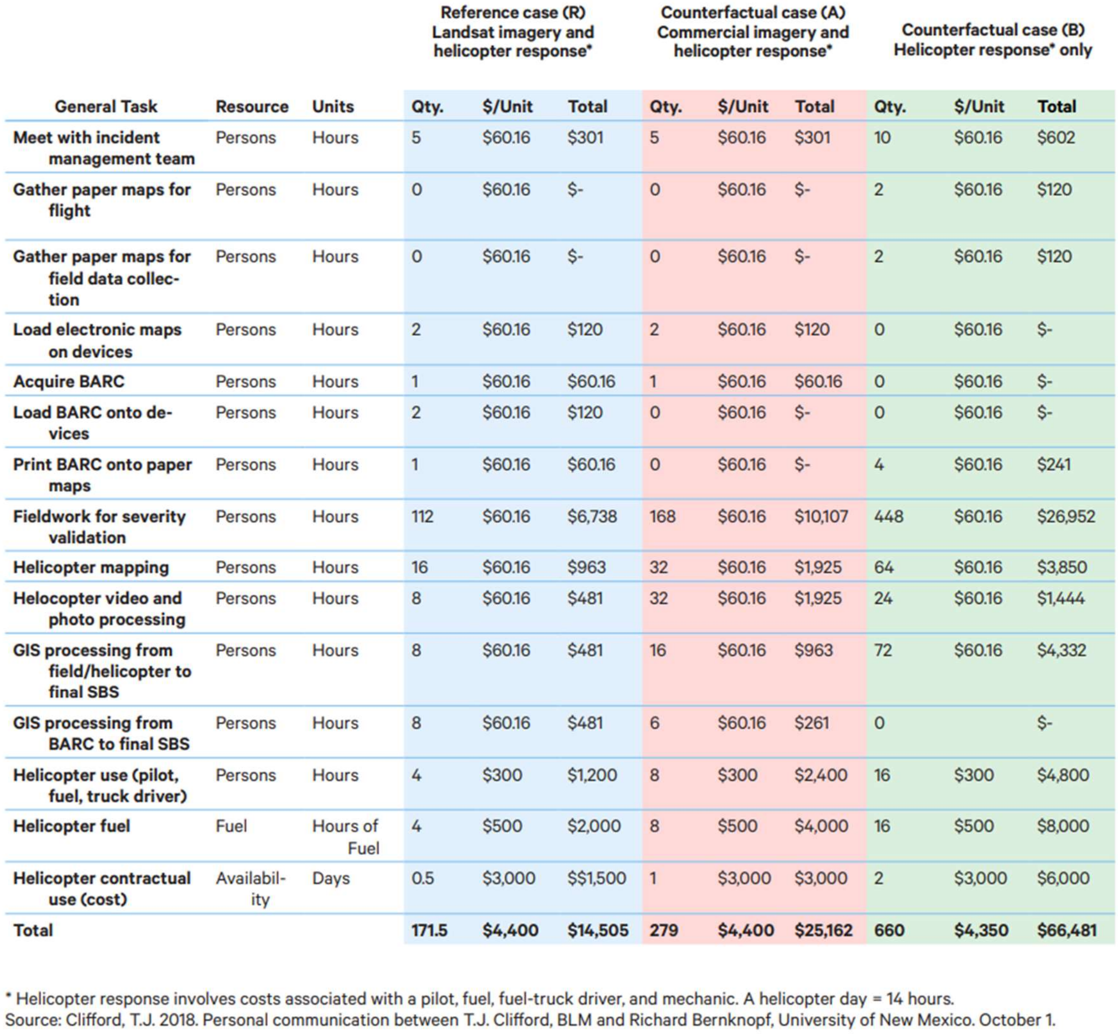
In this paragraph it is described how the utilization of this satellite-based service in the Mediterranean area could have a positive impact economically, justifying its cost.

As already described, the mission would operate in two tasks: fire forecasting and fire monitoring.

About fire forecasting, it is difficult to quantify how much could be saved thanks to an improved forecasting capability. It is enough to understand that fire forecasts are used to produce a daily fire danger bulletin, that is used to identify danger zones on the territory so in each zone certain resources in terms of vehicles and people are deployed. Improving fire forecasts would mean improving efficiency of these mechanisms, so would have a positive economic effect.

About fire monitoring, it is easier to make an estimation.

In chapter 1, the current fire-fighting process has been described, so it is important to make a comparison between how much it costs to perform fire-fighting operations in the traditional way and how much it would cost to do so with the aid of satellite imagery. This comparison is possible considering fires occurred outside the Mediterranean area, for example as shown in the table below [48].



General Task	Resource	Units	Reference case (R) Landsat imagery and helicopter response*			Counterfactual case (A) Commercial imagery and helicopter response*			Counterfactual case (B) Helicopter response* only		
			Qty.	$/Unit	Total	Qty.	$/Unit	Total	Qty.	$/Unit	Total
Meet with incident management team	Persons	Hours	5	$60.16	$301	5	$60.16	$301	10	$60.16	$602
Gather paper maps for flight	Persons	Hours	0	$60.16	$-	0	$60.16	$-	2	$60.16	$120
Gather paper maps for field data collection	Persons	Hours	0	$60.16	$-	0	$60.16	$-	2	$60.16	$120
Load electronic maps on devices	Persons	Hours	2	$60.16	$120	2	$60.16	$120	0	$60.16	$-
Acquire BARC	Persons	Hours	1	$60.16	$60.16	1	$60.16	$60.16	0	$60.16	$-
Load BARC onto devices	Persons	Hours	2	$60.16	$120	0	$60.16	$-	0	$60.16	$-
Print BARC onto paper maps	Persons	Hours	1	$60.16	$60.16	0	$60.16	$-	4	$60.16	$241
Fieldwork for severity validation	Persons	Hours	112	$60.16	$6,738	168	$60.16	$10,107	448	$60.16	$26,952
Helicopter mapping	Persons	Hours	16	$60.16	$963	32	$60.16	$1,925	64	$60.16	$3,850
Helocopter video and photo processing	Persons	Hours	8	$60.16	$481	32	$60.16	$1,925	24	$60.16	$1,444
GIS processing from field/helicopter to final SBS	Persons	Hours	8	$60.16	$481	16	$60.16	$963	72	$60.16	$4,332
GIS processing from BARC to final SBS	Persons	Hours	8	$60.16	$481	6	$60.16	$261	0		$-
Helicopter use (pilot, fuel, truck driver)	Persons	Hours	4	$300	$1,200	8	$300	$2,400	16	$300	$4,800
Helicopter fuel	Fuel	Hours of Fuel	4	$500	$2,000	8	$500	$4,000	16	$500	$8,000
Helicopter contractual use (cost)	Availability	Days	0.5	$3,000	$$1,500	1	$3,000	$3,000	2	$3,000	$6,000
Total			**171.5**	**$4,400**	**$14,505**	**279**	**$4,400**	**$25,162**	**660**	**$4,350**	**$66,481**

* Helicopter response involves costs associated with a pilot, fuel, fuel-truck driver, and mechanic. A helicopter day = 14 hours.
Source: Clifford, T.J. 2018. Personal communication between T.J. Clifford, BLM and Richard Bernknopf, University of New Mexico. October 1.

Table 5.11 – Fire operations cost: traditional approach vs satellite-based approach, [48]

This table shows cost elements and total cost of the operations needed to extinguish a large wildfire in three cases: without satellite aid (traditional way), using Landsat imagery (open source, so imagery is free), using commercial imagery (imagery is not free).

The comparison shows that using satellite imagery aid to traditional fire-extinguishing operations can save around 50000 $ per big fire event.

As stated in the introduction, in 2022 in the Mediterranean area more than 2700 big fire events (wildfires larger than 30 ha) were recorded, so having such a service as a tool for the fire brigades and if it were systematically used in the fire-fighting approach, would result in savings of135 M $ per year (while the total cost of the mission for 5 years of operations would be for sure less than 142 M $).

Beside this big economic advantage, there is the social and environmental one to avoid the loss of assets due to burnt areas and there is an improvement in air quality and life quality for the citizens.

6 – Conclusions

This thesis had the objective to provide a preliminary mission design for the described mission and to identify a set of high-level requirements as guidelines for the successive lower-level design phases.

The most important system design drivers have been identified, such as number of satellites, orbits, payload instruments, measurement requirements, time constraints, etc.

Today’s space technology is already mature enough to develop the mission to its accomplishment, but performances could be highly improved or cost considerably cut with some progress in the state of the art of strategic equipment.

The most important contingency to mention about that, it is related to off-the-shelf payload instruments. First of all, the lack of TIR cameras for small satellites must be tackled because cameras are not available in all the needed spectral bands (in particular in the MWIR and LWIR). In second place, most of the available cameras have a very good GSD, often oversized for many applications, but there are very few cameras offering acquisition with a large aperture: having a big swath is a key feature in time critical applications, because if the observed area is larger, it is easy to cover whole area of interest in a shorter time. So, having the chance to pick a very large aperture imager on the market (even if there is some loss in GSD), would allow to meet the temporal resolution requirement with a reduced number of satellites (which, in chapter 5, has resulted being one of the most relevant cost elements).

Acknowledgments

I moved to Turin on 25th September 2018 and at that time I was a kid used to never having any responsibilities and spending his days taking everything as a game, I leave this university today, 10th April 2024 and I have profoundly changed in my body and in my soul, but I remember everything about what happened in between.

I remember mine and my dad's tears as we went to the airport for the first time.

I remember my mother's pride after the first 30 mark.

I remember the winter sessions taking all the exams on the first call because I wanted to celebrate Valentine's Day with Greta.

I remember the summer sessions taking all the exams on the first call, because I couldn't stand seeing the photos of the others at the seaside while I was still studying.

I remember the beers at jumping, the breakfasts with Pino, the films at Lux, the Sanremos with Fede.

I remember how nice it was to come back for the holidays and drive the 127, go to the bar with my friends, or go out to dinner with my girlfriend.

I remember waking up at 5 am to study, I remember falling asleep on books at 3 am.

I remember failing my very first exam which made me think I had chosen a faculty that was too difficult for me.

I remember that, after that rejection, I studied so hard that I never again had anxiety before an exam, until the last exam, where I remember that anxiety came back to keep me company, perhaps to remind me where I started from.

As said, I remember everything, and all these memories make me think that in the end it was a really nice trip.

A nice tortuous journey during which I lived in three countries (Italy, Germany and Calabria), I saw a pandemic, I was a janitor, a private teacher and an Erasmus student, I took 37 exams, and all these things that happened were more beautiful because while they were happening, I had loved ones with me to share them, and whom I would like to thank.

Thanks to my parents, thank you because you allowed me to study and above all to do it peacefully, thank you because you saw my study as your priority as well as mine and this gave me strength and made me acquire that responsibility that I lacked when I moved to Turin.

Thanks to my mother for her sweetness and her thousand kindnesses.

Thanks to my dad for teaching me to see things clearly and understand how the world works.

Thanks to my sister, because you are the first stabilizing element in my private life, because when everything was shaking and it was easy for us to fall apart you always kept the bar straight and gave me balance.

Thanks to my grandmother Assunta, because you are a magnificent character and I think you should have your own show on Rai 1. Thank you because you are the simplest and most genuine person I know and every time I see you, I smile.

Thanks to my beautiful Greta, because you make me have fun, relax, learn. Thank you because every time I leave, we count together the days until we see each other again, and when I come back to you, we count together the days we can enjoy. Thank you for listening to me even when others would be bored.

Thanks to Pino, because you are the most reliable person in my life in Turin, there is not a time that I needed you and you weren't there. Thank you because if I don't call you for more than three days, on the fourth day I have the mathematical certainty that we will go for a coffee.

Thanks to my friends, because you make life as fun and enjoyable as ice-cold beer in summer or the first slice of capocollo of the season. Sometimes I think friendship is underrated, but maybe that's because most people aren't as good at choosing friends as I am.

Thanks to my grandmother Peppina, who unfortunately never got to see me graduate. If you are looking at me now, thank you because when this path seemed too difficult for me you have always been an example of determination, wisdom and integrity, which motivated me to keep pushing.

Thanks to the land in which I was born and from which I left, and which inspired my thesis. I hope that my work can one day contribute to making you a better place so that those who, like me, miss you, can find fulfilment without having to abandon you.

To conclude, thanks to me, because I have never given up and because in this journey I have learned consistency, because as an actor who I respect very much once said:

“Dreams without goals are just dreams and only fuel disappointment. Along the way to achieving your dreams, you must apply discipline but, more importantly, consistency. Because without commitment you will never start, but without consistency, you will never finish."

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"I sogni senza obiettivi sono solo sogni e alimentano solo delusione. Lungo la strada per realizzare i propri sogni, bisogna applicare disciplina ma, ancora più importante, costanza. Perchè senza impegno non inizierai mai, ma senza costanza, non finirai mai".

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