Mission and System Architecture for an Operational Network of Earth Observation Satellite Nodes

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Abstract

Nowadays, constellations and distributed networks of satellites are emerging as clear development trends in the space system market to enable augmentation, enhancement, and possibilities of new applications for future Earth Observation (EO) missions. While the adoption of these satellite architectures is gaining momentum for the attaining of ever more stringent application requirements and stakeholder needs, the efforts to analyze their benefits and suitability, and to assess their impact for future programmes remains as an open challenge to the EO community. In this context, this paper presents the mission and system architecture conceived during the Horizon 2020 ONION project, a European Union research activity that proposes a systematic approach to the optimization of EO space infrastructures. In particular, ONION addressed the design of complementary assets that progressively supplement current programs and took part in the exploration of needs and implementation of architectures for the Copernicus Space Component for EO.

Among several use cases considered, the ONION project focused on proposing system architectures to provide improved revisit time, data latency and image resolution for a demanding application scenario of interest: Marine Weather Forecast (MWF).

A set of promising system architectures has been subject of a comprehensive assessment, based on mission analysis expertise and detailed simulation for evaluating several key parameters such as revisit time and data latency of each measurement of interest, on-board memory evolution and power budget of each satellite of the constellation, ground station contacts and inter-satellite links. The architectures are built with several heterogeneous satellite nodes distributed in different orbital planes. Each platform can embark different instrument sets, which provide the required measurements for each use case.

A detailed mission analysis has then been performed to the selected architecture for the MWF use case, including a refined data flow analysis to optimize system resources; a refined power budget analysis; a delta-V and a fuel budget analysis considering all the possible phases of the mission. This includes from the correction of launcher injection errors and acquisition of nominal satellite position inside the constellation, orbit maintenance to control altitude, collision avoidance to avoid collision with space debris objects and end-of-life (EOL) disposal to comply with EOL guidelines.

The relevance of the system architecture selected for the MWF has been evaluated for three use cases of interest (Arctic sea-ice monitoring, maritime fishery pressure and aquaculture, agricultural hydric stress) to show the versatility and the feasibility of the chosen architecture to be adapted for other EO applications.

Keywords: Earth Observation, Mission Architecture, System Architecture, Constellation, Small Satellites, Marine Weather Forecast, Federated Satellite Systems

1. Introduction

Two trends have recently emerged in space systems and could even further strengthen in the future: small satellites, with the development of key modularization and miniaturization technologies, and the deployment of constellations and distributed networks of satellites. It is paramount for Europe to properly analyze those trends and determine whether or not they could provide advantages for Earth Observation systems. To address those challenges, the Horizon 2020 ONION project (Operational Network of Individual Observation Nodes), completed at the beginning of 2018, investigated the distribution of spacecraft functionalities into multiple cooperating nodes, leveraging on the emerging fractionated and federated satellite system concepts [1]. In the case of Federated Satellite Systems (FSS) conventional spacecraft establish a network to exchange resources (such as bandwidth and computing power) for mutual benefit. It bridges a gap between traditional space distributed systems, such as constellations, and novel approaches, such as fractionated spacecraft [2], in terms of component uniformity and independency. The baseline of the ONION concept consists of augmenting current mission profiles, like the Copernicus Space Component for Earth Observation and Earth Explorer missions, with missing observation bands, increasing data resolution, improving coverage and revisit time, reducing data latency, augmenting mission lifetimes and ultimately sharing the capabilities across multiple spacecraft platforms. To reach its objective, the project followed the steps listed below.

1) **Survey and analysis of stakeholders and end user needs** [3] in the Earth observation field and identification of **technological gaps** [4]. A quantitative methodology has been applied to select 10 promising use cases that emerge from the combination of pressing needs and technological gaps: climate for ozone layer and ultraviolet assessment, land for basic mapping, risk assessment, marine for weather forecast, atmosphere for weather forecast, fishing pressure, land for infrastructure status assessment, sea ice monitoring, agriculture (hydric stress), natural habitat & protected species monitoring, and sea ice melting emissions.
2) Identification of current **infrastructure technological gaps** in meeting user needs, based upon the measurements, instruments and mission components of the EO value chain [5]. The identified technological areas for improvement served as support for the following system requirements generation.
3) Survey of **fractionated and federated technology state of the art** with the identification of key enabling technologies to fill the identified technological gaps.
4) Formulation of **system requirements** for a cost-effective space-based Earth observation infrastructure, based on identified use cases and available technologies. System requirements include spectral bands, spatial and temporal resolution, coverage and data latency.
5) Identification of **architecture concepts** that can fill the gaps identified in the observation requirements analysis, including pre-selection of sensors, orbits, satellite mass classes and ground station network architectures.
6) Selection of a **reference architecture**, by means of a systems architecting methodology that optimizes the constellation design and the allocation of instruments. This methodology has two stages.
   a) First, an exhaustive, multi-attribute, tradespace exploration process evaluates architectural trends resorting to Pareto-optimality concepts and the definition of qualitative criteria. Based on the findings in the tradespace exploration, which comprised thousands of potential architectures, the space of solutions is reduced to a small subset of the most promising designs.
   b) This reduced set is then thoroughly analyzed with refined mission and system simulations in order to select the most optimal architecture in accordance to the elicited system requirements.
7) **Detailed analysis of the architecture selected**, comprising payload, platform, mission and ground segment.
8) Assessment of the **relevance of the selected architecture** with respect to other use cases identified at the beginning of the project.

The ONION User Advisory Board recommended to focus on the selected use case (Marine Weather Forecast) and to perform an end-to-end analysis with the aim of showing ONION's added value and its link to the existing and planned Copernicus infrastructure. After the completion of the analysis of the MWF use case, also the agricultural hydric stress use case has been analyzed, with the aim of deriving a general and generic concept regarding the benefits of ONION.

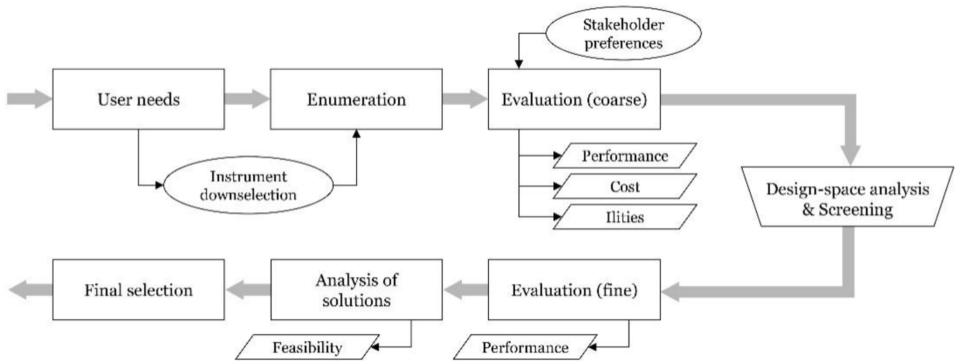


Fig. 1. Architecting methodology based upon tradespace exploration and coarse-fine evaluation.

This paper presents the findings that resulted from the last stages of the ONION project, namely, steps 6), 7) and 8). The paper is organized as follows: Section 2 provides a brief overview of the generic architecture optimization process and summarizes the multi-attribute tradespace exploration methodology (step 6a). Section 3 defines the MWF use case and its elicited system requirements. Section 4 highlights the most relevant observations in the design-space exploration for this particular use case and summarizes the trends that allowed the pre-selection of 28 candidate solutions (step 6b). Section 5 details the mission and system analysis workflow conceived in ONION to evaluate the reduced set of candidates (step 7). Section 6 explores in detail the specific characteristics of the optimal solution. Finally, Section 7 assesses its versatility with other use-cases in ONION (step 8), and Section 8 concludes with final remarks.

2. A framework to architect EO satellite systems

The architecting of space systems is a discipline concerned with the identification and optimization of early design decisions; often in Pre-Phase A studies. Architecting frameworks produce high-level system descriptions in the form of a set of design recommendations that guide engineering teams to ultimately attain the delivery of expected value. As much as systems architecting studies are focused in the exploration of the space of alternatives (rather than only in the finding of a single optimal solution), the design of complex architectures, like satellite constellations, has often adopted this paradigm as one essential tool to systematically evaluate the tensions that exist among decision variables and to find the best combinations of architectural choices [6]. In that sense, distributed satellite missions may present multiple decision variables that oftentimes produce very large and non-convex solution landscapes that are hard to explore and optimize.

This section introduces an architecting framework aiming at the optimization of satellite constellations for the compendium of mission cases and stakeholder needs identified in [3]. The goals of this architecting framework are threefold. On the one hand, it explores constellation designs that are characterized both by their orbital configuration and their instrument allocation. While the selection of potential spaceborne instruments was carried out in separate studies [7], the framework was conceived to allocate feasible configurations across all satellite nodes without restricting homogeneity, i.e. constellations are allowed to encompass multiple different satellite designs. Simultaneously, the selection of a certain instrument configuration assigns the selection of satellite platforms of different classes. Facilitating the generation of heterogeneous constellations (i.e. the combination of traditional spacecraft designs with single-instrument, small-satellite platforms) was posed as an essential feature to allow for the evaluation of impact that small-satellite technologies could pose in future European EO programs.

Secondly, this architecting methodology is focused on the simultaneous optimization of multiple system attributes, thus allowing the formulation of the architecting process as a generic Multi-Objective Optimization (MOO) problem [8]. Tradespace exploration is adopted as the quantitative tool to support this process, thus facilitating the analysis of Pareto-dominance, the identification of coupling between decisions, or the location of areas of unfeasibility [6]. Several works have leveraged tradespace methodologies to architect satellite systems [9], both for communications (e.g. [10, 11, 12, 13]), as well as in Earth Observation missions (e.g. [14, 15]).

As it is common in architecting studies, the benefit or value delivered by each of the enumerated architectures is evaluated through numerical scores that aggregate (and often normalize) multiple attributes of the system [16]. The mission requirements elicited during the first steps of the project identified three performance metrics as the most relevant figures to quantify stakeholder satisfaction in ONION, namely, revisit time, spatial resolution, and latency. The aggregation of these three metrics yields a numerical score that determines how well the architecture satisfies the multiple objectives of the mission.

However, in the architecting of systems it is also frequent to observe, evaluate, and optimize non-tangible properties, the so-called qualitative attributes, like flexibility, reliability, evolvability, versatility, etc. [17] These qualitative aspects of a system, often generalized under the term 'ilities', identify additional properties that are not the primary functional requirements of a system's performance but present wider impact in the system after it has been put to initial use [6]. In fact, the very value proposition of Distributed Satellite Systems (DSS) is often articulated through ilities [18]. They capture some of the functional qualities and emergent capabilities of complex system-of-systems that DSS also aim at exploiting [19]. Thus, the third goal of this architecting framework is the incorporation of such qualitative attributes as downstream influences in the design process, in order to guide the optimization towards solutions that excel in functional performance as well as in their qualitative traits.

The definition and analysis of ilities in architecting studies has been demonstrated in previous works [20, 17, 21, 22, 23] in which they are proposed as complementary criteria during the analysis of the space of solutions. One of the differentiating characteristics of this architecting methodology is the explicit incorporation of numerical evaluations of ilities in the formulation of architectural figures of merit. While stakeholder preferences are usually encoded as weights that prioritize functional metrics, this framework proposes to integrate a weighted aggregation of ilities as part of the final score. Thus, preferences over qualitative properties are also systematically considered in the decision process. The complete formulation of architectural figures of merit and qualitative attributes has been previously discussed in [24] and is out of scope in this paper.

Fig. 1 illustrates the processes proposed as part of this tradespace exploration framework, where some of them correspond to the steps enumerated in Section 1 above. The evaluation of user needs encapsulates the vast majority of initial activities in the ONION project. For the sake of generality, these can be described here as the definition of stakeholders, and the elicitation of their needs in the form of system requirements. In Earth observation systems, these requirements can be formulated as the set of Earth monitoring parameters and their relative performance attributes. The functional characteristics of these measurements (e.g. minimum ground sampling distance, accuracy, etc.) facilitate the selection of instruments that could be embarked in the constellations. These aspects will be explored in detail for the MWF use case in Section 3.

2.1. Enumeration of architectural candidates

Upon the definition of user expectations, the architecting process identifies the set of decision variables and their allowed values. Six of them were considered during the application of this framework in ONION, as listed in Table 1. Note that these decision variables are always tied to the definition of satellite constellations, since they were the most suitable architectural concept throughout the project.

Table 1. Decision variables.

Decision variable	Values
Orbital altitude	{500, 650, 800} km
Walker pattern	Delta, Star
# orbital planes	Specific to use case
# satellite units (total)	Specific to use case
Satellite platform class	Heavy, medium, small
Instrument configuration	Specific to use case

While some values were valid to all use cases, others can only be determined with the specific needs of the use case (e.g. possible constellation sizes are chosen considering the expected revisit times). Once all possible values are set, the enumeration of possible

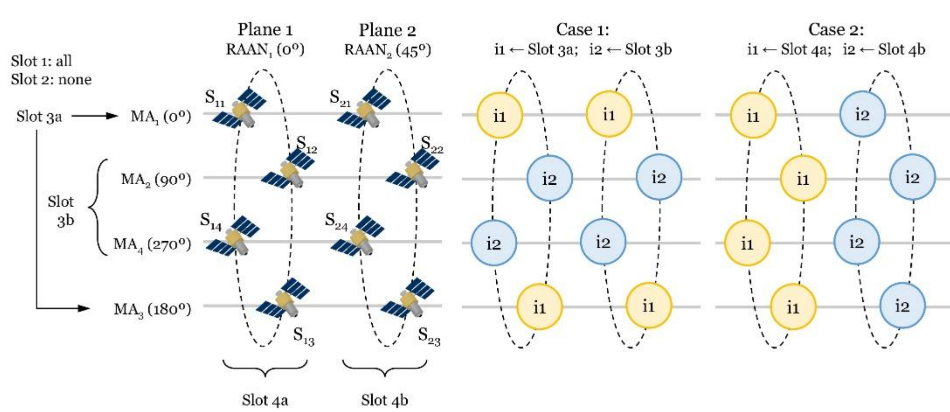


Fig. 2. Generation of constellation slots for the structured assignment of instrument configurations to satellite units.

combinations yields the set of candidate architectures. It is worth noting that two enumeration variables are intrinsically related: instrument configurations specify mass and power requirements for the platform and thus force the selection of one of the alternatives and not any other. Three archetypical platform classes were defined based on available technologies and satellite buses. Heavy satellite platforms are assumed to have a 600 kg dry mass (approximately 200 kg of payload capacity). This kind of platform is generally consolidated for conventional MEO constellation designs. One particular example of this type of platform is Surrey's SSTL-600 (600 kg dry mass, 200 kg payload capacity, 450 W of peak power). Medium platforms present dry masses of around 160 kg (~50 kg dedicated to payload capacity). Examples include: OHB's TET-X (120 kg/50 kg, 160 W peak); Surrey's SSTL-150 (153 kg/50 kg, 100 W); or Sierra Nevada's SN-50 (50–100 kg, 245 W at BOL). Small platforms are assumed to be similar to nano-satellite classes of 3U to 12U, and payload capacity of 1 to 10 kg. Representative manufacturers of include ISIS' 6U bus (6 kg, 10 W average), GomSpace's 6U platform (4–6 kg, 12 W peak), or Tyvak's TRESTLES 6U and 12U (3-13 kg, payload peak power 180 W, solar arrays peak power 40W, 60W, or 120W).

Noteworthy, the cardinality of the allowed value sets in Table 1 hinders a full factorial exploration and forces to limit the number of solutions to tractable sizes. Therefore, the enumeration of constellation configurations reduces the number of candidates by constraining the combinations of instrument allocation. Once the constellation geometry is determined (i.e. altitude, number of planes and nodes, and Walker pattern), the framework computes a finite number of constellation "*slots*." Each slot encompasses a subset of identical satellites based upon the structure of the constellation. Fig. 2 shows the slots that would be generated for a constellation of 8 satellites and 2 planes. The figure also shows two of the multiple cases for the allocation of instruments when two configurations are available (*i1* and *i2*). A combinatorial sub-routine generates all cases exhaustively, eliminating redundant solutions and maintaining the final number of architectures to tractable amounts [25].

2.2. Coarse-fine evaluation

As stated above, the goal of this architecting methodology is to explore the design space in order to observe global trends, areas of unfeasibility or coupling between decisions. Performance metrics need to be computed to obtain the aggregated figures of merit with which compare sets of architectures and analyze the effects of certain decision variables. In spite of the efforts to reduce the solution space, the enumeration process often yields several thousand unique architectures. While ilities and cost estimates are computed with analytical models, revisit times and data download latencies are computed with simulation tools that implement a coarse-fine strategy. In order to cope with the necessary enumeration of large design spaces, an initial coarse evaluation process employs custom simulation and analysis tools that have been tailored for large architectural sets and require lower computational resources. Following the recommendations in [9], these tools compute performance values with models of moderate fidelity: energy and data budgets are not considered in the simulation of coverage, downlink, and inter-satellite communications. However, these tools still provide performance figures of enough fidelity to accurately capture how value-deriving variables affect the overall utility or score of each solution. The coarse evaluation process essentially computes performance in best-case scenarios (i.e. without on-board resource constraints) and, therefore, provides an optimistic estimate for performance figures. A small subset of candidate architectures is pre-selected based on the globally observed trends and is then analyzed in detail to find the optimal design.

Rather than trimming the solution set with an arbitrary threshold on architectures figure of merit, this framework proposes to identify regions of optimality and to carefully select a small set of designs that still present some variations. The guidelines to perform the screening of candidates are summarized as follows:

- ***Score:*** pre-selected solutions should not present low ranks. Solutions need to be close to the highest scoring architecture.
- ***Diversity, similarity and proximity:*** the subset needs to include designs that *differ* in a few design characteristics in order to provide meaningful alternatives during the second evaluation process. The pre-selection shall consider changes to decision variables to produce solutions that are *similar* to the one with highest score. When identifying alternative values for design variables, the solutions need be similar to the ones of architectures with high figures of merit. Drastic changes in design choices should be avoided, i.e. non-adjacent values in the variables' option set (Table 1) can be considered only if their distances within the set are relatively short.
- ***Avoid falling into new exploration:*** prune choices in which multiple decision variables are changed simultaneously.
- ***Pareto efficiency:*** include non-dominated designs presenting higher scores if they fulfill the guidelines above.
- ***Expert insight:*** rely upon human and expert judgment to include additional specific architectures, if necessary.

The second analysis process, applied only to the pre-selected set, and the tools required computing performance metrics of higher fidelity are presented in detail in Sections 5 and 6.

3. Marine Weather Forecast: Use Case and Requirements

After an analysis of stakeholders' needs [3] and technological gaps [4] in the European EO infrastructure, the Marine Weather Forecast (MWF) use case has been selected, based upon a quantitative assessment methodology, as representative of classes of requirements that call for complex satellite architectures to which the ONION contribution might be beneficial. Details on the identification of the EO measurements gaps (spatial resolution, revisit time, precision and temporal continuity, data latency) in the time frame from 2020–2030, to complement the Copernicus space infrastructure, can be found in [4].

In the recent years, global warming has induced a number of companies in the shipping, oil and gas or fishing industries to consider extending their operations to the North. With the decline of sea-ice, the Northern routes are bound to become effective alternatives to the Suez Canal with an increasing number of transits. Interesting applications cover Oil and Gas offshore operations and fisheries on Polar Regions (above 60º latitude North) [26].

The associated measurements and corresponding system requirements are summarized in Table 2. Both threshold (T) and goal (G) values are reported. Higher priority is given to the first 4 measurements, i.e. ocean surface currents, wind speed over sea surface, significant wave height and dominant wave direction.

To design the ONION system architecture complying at best with the list of requirements coming from user needs, a tradespace exploration has been performed considering:

- several constellation configurations (i.e. multiple number of satellites, distribution in number of planes, Walker pattern),
- orbit altitudes (500 km, 650 km and 800 km),
- platform masses and sizes: small, medium and heavy,
- instruments, and
- ground stations.

The output of the survey of possible instruments able to provide the required measurements for MWF [7] is a list encompassing: Global Navigation Satellite Systems-Reflectometry (GNSS-R), Optical Imager with Visible (VIS), Near-Infrared (NIR) and Thermal Infrared (TIR) bands, Radar Altimeter in Ka band, Microwave Radiometer (MW) with W, X, Y, K and Ka bands, Synthetic Aperture Radar (SAR) in Ku and C band and SAR in X band (SAR-X).

4. Design space exploration and architectural trends

This section briefly summarizes the main results from the application of the architecting methodology to MWF and it shows how the exploration of the design space led to the pre-selection of a small subset of architectures.

Table 2. Measurements and system requirements for the MWF use case

MWF Use Case Measurement	Spatial Resolution [km]	Revisit Time [h]	Data Latency [min]
Ocean surface currents *	25 (T) / 1 (G)	24 (T) / 6 (G)	60 (T) / 6 (G)
Wind speed over sea surface *	10 (T) / 1 (G)	24 (T) / 3 (G)	60 (T) / 6 (G)
Significant wave height *	25 (T) / 1 (G)	12 (T) / 3 (G)	60 (T) / 10 (G)
Dominant wave direction *	15 (T) / 1 (G)	12 (T) / 3 (G)	60 (T) / 6 (G)
Sea surface temperature	20 (T) / 1 (G)	24 (T) / 3 (G)	60 (T) / 5 (G)
Atmospheric pressure	25 (T) / 1 (G)	24 (T) / 3 (G)	60 (T) / 5 (G)
Sea-ice cover	12 (T) / 0.01 (G)	24 (T) / 3 (G)	60 (T) / 10 (G)

* Priority Measurement

The revisit time and spatial resolution requirements of MWF suggested to consider 11 constellation sizes of {4, 6, 8, 10, 12, 17, 21, 25, 33, 40, 48} satellites. The enumeration considered geometries of {2, 3, 4, 6, 8} orbital planes. With the selected instruments, spacecraft could embark up to 12 instrument configurations. Each instrument configuration combined compatible technologies that satisfy one or more measurements of the use case with varying performances (i.e. ground sampling distance is determined both by the actual instrument and the orbital altitude). Based on the cardinality of decision variable sets and the enumeration constraints explained in Section 2, the space of solutions was populated with 5586 unique designs that where generated from 219 constellation geometries.

Coarse performance simulation, the estimation of costs and the evaluation of qualitative traits allowed to compute architectural scores and to study global design trends. Fig. 3 shows the trade space where each architecture is represented in terms of its cost and score. The red line represents the Pareto frontier and connects all the Pareto-optimal (i.e. non-dominated) solutions. Oftentimes, this analysis is carried out using aggregated scores (utility or figure of merit) and cost (monetary or otherwise). In ONION, Pareto-dominance was assessed with the aggregated architectural figures of merit ("score" in Fig. 3 vertical axis) which encompass and prioritize the evaluated performance metrics and ilities in accordance to the elicited needs of this use case. Pareto-optimal architectures are those that present an efficient trade-off in the displayed attributes (aggregated figure of merit and monetary cost). Among the non-dominated architectures with higher figure of merit, one could identify solutions with 4, 8 and 16 satellites distributed in 2 or 4 planes. In all cases, these designs combined heavy spacecraft embarking the SAR-X and/or the optical imager, with medium or small satellites complementing the architecture with additional payloads.

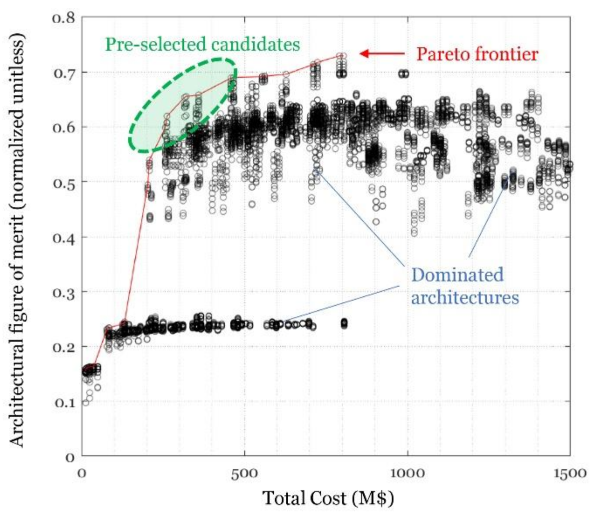


Fig. 3. Tradespace representation for the architectures enumerated in the MWF use case. Note that for the sake of clarity, the plot only shows the bulk of architectures and does not show points above $1,500M.

However, non-dominated designs are not necessarily the optimal choices. As a matter of fact, architecting studies require additional criteria and/or strategies to select optimal designs. In ONION, the selection strategy was focused on the evaluation of performance and mission analysis carried out for the pre-selected candidates, as detailed in the sections that follow.

The pre-selection was guided by a careful inspection of differences and similarities among solutions of higher ranks. The analysis of coarse performance metrics, detailed in [27], showed that amongst the 100 solutions of highest score the SAR-X and the Optical imager were critical to provide acceptable spatial resolutions and revisit times for some of the measurements of this use case. Due to their mass and power requirements, these instruments can only fly in heavy platforms, which also present a significant cost compared to medium and small satellite designs. Small and medium platforms are posed as critical elements to architect these systems, as observed in the Pareto frontier. Nevertheless, inspecting the characteristics of designs clustered below 0.3 scores in Fig. 3 revealed that architectures that only encompass small and medium platforms were insufficient to satisfy the requirements of the use case.

Fig. 4 shows additional information of the space of solutions that was instrumental to select candidate designs. The plot represents an interpolated surface that intersects at the maximum architectural scores for each constellation geometry. Iso-score curves are projected in the surface to ease the analysis of the plot and highlight the effects of constellation sizes in architectural scores. The clear identification of plateaus for sizes larger than 24 satellites suggests that these designs are worsened by excessive cost and/or some of the ilities modeled in this case [27]. The green markers locate the most promising regions of the design space.

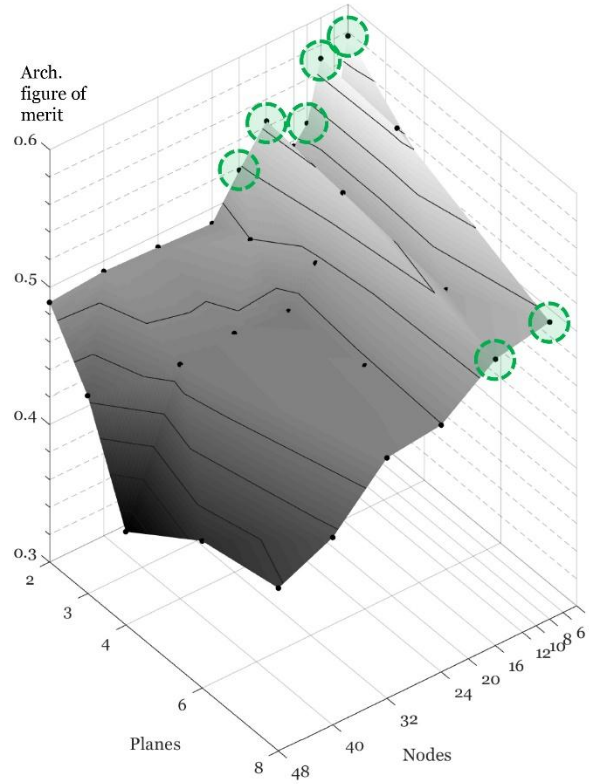


Fig. 4. Global trends. Plot shows the surface of maximum architectural scores for each constellation configuration in the planes-nodes space.

The pre-selection of candidate architectures considered architectures of high ranks that were located within these regions. 28 solutions were selected, including 8 non-dominated designs. In terms of architectural score, these solutions represented the best 4.3% and ranged from 1st to 241st in rank. While the vast majority of these architectures orbit in LEO at 800 km, a few of the selected cases also included lower altitudes. The Walker pattern did not impact their performance and both Delta and Star constellations were selected in the reduced set. Finally, it is important to note that all the designs encompassed 2, 4 or 8 heavy spacecraft, and were always complemented by, at least, the same number of medium or small platforms. Some cases include both, and present instrument allocations that favor revisit times. Further details on the characteristics of this subset of designs can be read in [27].

5. MWF Architecture Selection

The 28 pre-selected architectures for the marine weather forecast use case have been subject of a complete chain of analyses that employs refined models to evaluate several key parameters as revisit time and data latency of each measurement, on-board memory evolution and power budget of each satellite of the constellation.

For each architecture the workflow presented in Fig. 5 has been followed, where the analysis modules are represented by red circles, the inputs are in blue, internal outputs are in white and the most important outputs used later to select the winning architecture are in green. The steps followed are detailed hereafter.

Architecture characteristics (orbit altitude, number of planes, number of satellites, constellation distribution, platform types and instruments) are loaded and platforms are distributed into planes and inside each plane following a defined slot allocation criterion.

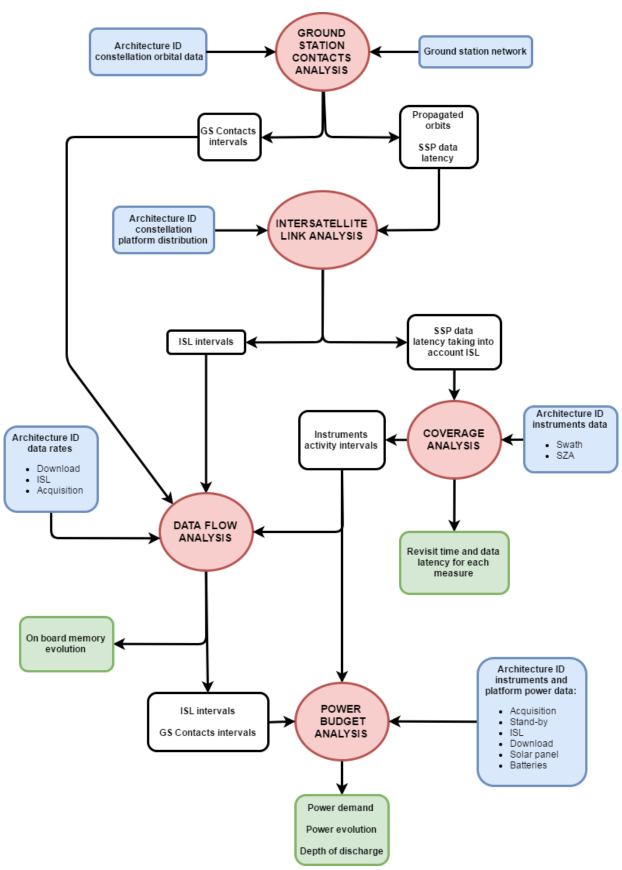


Fig. 5. Detailed analysis for pre-selected architectures workflow.

Depending on the instruments embarked on each platform, the Local Time at Ascending Node (LTAN) distribution among the different orbital planes is selected, in order to guarantee the best illumination conditions for both observations and platform solar panels.

Orbits are considered to be Sun-synchronous, frozen and repeating, and they are propagated during an entire repeating period (in the order of 1 month) with a time step of 10 seconds.

Visibility intervals with ground station (GS) network are computed considering visibility constraints such as minimum elevation angle. This analysis defines the ground station contact intervals, used in data flow, power budget and Sub-Satellite Point (SSP) data latency analyses. In order to minimize the data latency, the GS network, composed by Svalbard (78ºN, 15ºE) and Inuvik (68.4ºN, 133.7ºW), has been chosen to guarantee one contact per orbit for all the orbital altitudes considered (Fig. 6).

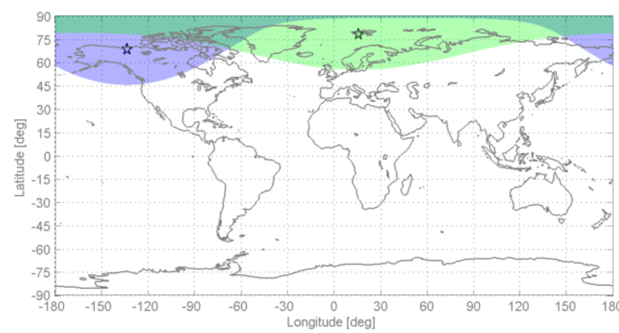


Fig. 6. Visibility areas for a 800 km SSO orbit considering a GS network with Svalbard (green) and Inuvik (blue), 5º Min Elevation Angle.

Inter-Satellite Link (ISL) analysis is devoted to establish unidirectional communications between pairs of spacecraft in order to reduce the latency of the data sent by the transmitting satellite when the receiving one is in contact with a ground station. In addition to that temporal restriction, the inter-satellite link is also constrained by visibility (considering maximum inter-satellite distance constraints for each platform type and minimum grazing altitude) and platform restrictions (the two platforms must set up compatible and available links). Fig. 7 shows the ISL configuration for heavy platforms. For example, the maximum ISL distance for small platforms has been set to 400 km, while no ISL distance constraints are imposed in the case of medium and heavy platforms. The ISL analysis produces as output the ISL sending and receiving time events, used in the data flow analysis, and the SSP latency with ISL, used to estimate the overall data latency.

SSP data latency is calculated taking into account contacts with the ground stations and ISL.

For each measurement (Table 2 for MWF) the coverage analysis computes the **revisit time** and the **data latency**, which are two fundamental outputs of the detailed architecture analysis. Maximum revisit time and maximum data latency are compared with the use-case requirements to rank the pre-selected architectures. This computation is based on the instruments characteristics (instrument swath and acceptable maximum Sun-zenith angle) and on the area of interest (for the MWF use case: sea and oceans at latitudes above 60ºN, as shown in Fig. 8). Geographic distribution of revisit time and data latency is computed for each measurement separately, taking into account only the instruments generating that specific measurement. Fig. 9 shows an example of maximum and average revisit time maps.

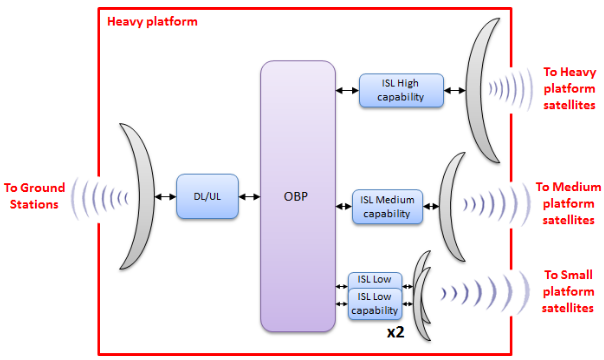


Fig. 7. ISL configurations for heavy platforms.

Fig. 8. Marine Weather Forecast use-case area of interest in white inside the orange box.

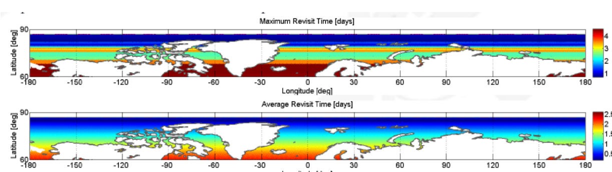


Fig. 9. Example of ocean currents maximum and average revisit time maps.

Given the instruments acquisition data rate, platform download rate, intervals of instrument activity coming from the coverage analysis, the ground station contacts and ISL connections, it is possible to estimate the **mass memory evolution** for each platform and assess its feasibility in terms of data accumulation and maximum on-board mass memory needed. Fig. 10 presents an example of mass memory evolution.

Finally, the last stage of the detailed analysis is the **power budget** computation, which models platform's solar panels and battery. It computes the platform power demand profile considering different consumptions during different modes, including stand-by, payloads acquisition intervals, GS contact and ISL communications in order to compare it with the power production profile and retrieve the battery depth of discharge (DoD) evolution (as shown in Fig. 11).

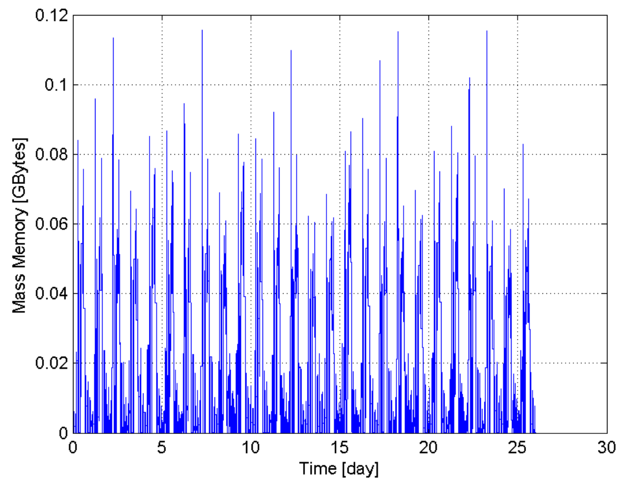


Fig. 10. Example of mass memory evolution.

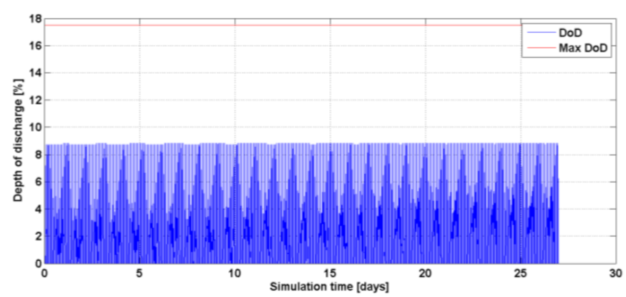
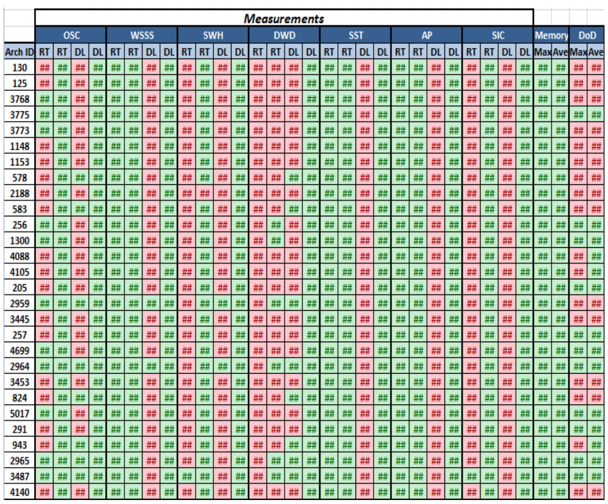


Fig. 11. Example of depth of discharge evolution.

The entire process is highly automated. About 5 hours are needed to run a single architecture on a desktop computer.

Results of the analysis over the 28 pre-selected architectures are summarized in Fig. 12, where green boxes represent compliancy with requirements, while red boxes represent non compliancy.

General considerations can be extracted on the results. Data flow and on-board data handling are not critical points in any of the selected architectures. This is due to the fact that the area of interest is not very vast, data can be downloaded once per orbit and the download data rate is high enough to guarantee no data is accumulated on-board. Due to ISL range limitations on small platforms and to the reduced available time to perform ISL (only when a platform is already in contact with a ground station), the connectivity of the constellation is poor most of the times. Maximum data latency is about one orbital period (around 90 min), thanks to one contact per orbit with the ground station network. Because of ISL constraints, ISL does not help to improve maximum data latency, however the average data latency benefits of the constellation connectivity. Maximum revisit time for the less demanding measures is in general accomplished, however when the requirement goes below few hours, few architectures are able to fulfil it. To improve revisit time, the number instruments delivering data for that measurement, should be increased, both on the same orbital plane and on more orbital planes. The most critical aspect is the power budget. Because of the many orbital planes to consider, the illumination conditions are different from plane to plane and a unique design for the power subsystem is not able to provide enough power to the spacecraft. The DoD often reaches values well above the maximum acceptable value, drastically reducing the batteries cycle life.



	Measurements																															
	OSC				WSSS				SWH				DWD				SST				AP				SIC				Memory		DoD	
Arch ID	RT	RT	DL	DL	RT	RT	DL	DL	RT	RT	DL	DL	RT	RT	DL	DL	RT	RT	DL	DL	RT	RT	DL	DL	RT	RT	DL	DL	Max	Ave	Max	Ave
130	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##
125	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##
3768	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##
3775	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##
3773	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##
1148	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##
1153	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##
578	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##
2188	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##
583	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##
256	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##
1300	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##
4088	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##
4105	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##
205	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##
2959	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##
3445	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##
257	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##
4699	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##
2964	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##
3453	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##
824	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##
5017	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##
291	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##
943	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##
2965	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##
3487	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##
4140	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##	##

Fig. 12. Evaluation results on the 28 pre-selected architectures.

Among the 28 pre-selected architectures for the marine weather forecast use case, almost all the combinations including medium platforms should be discarded because their depth of discharge profiles always reach unfeasible values of 100%. Among the remaining constellations architecture, the one complying the most with revisit time and data latency requirements has been selected (3487 in Fig. 12).

The resulting winning architecture for MWF is a constellation of **16 nodes equally distributed in 8 orbital planes at about 800km altitude**: 8 heavy platforms embarking SAR-X and Optical payloads and 8 small platforms with GNSS-R antenna. Fig. 13 shows a graphical representation of the constellation. Main characteristics of the selected payloads are summarized in Table 3. Each instrument provides relevant measurements for one or many parameters required by the MWF use case, as shown in Table 4.

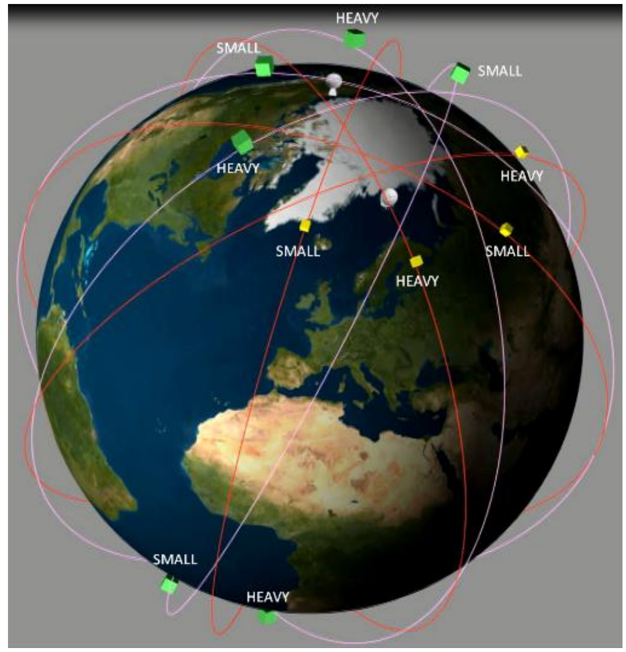


Fig. 13. 3D visualisation of the ONION constellation for MWF use case.

Table 3. Selected payloads for the MWF use case and characteristics.

Selected Payload	GNSS-R	Optical (VIS/NIR/ TIR)	SAR-X
Reference	CYGNSS [28]	MetopC AVHRR/3	Severjanin-M [29]
Field of Regard [deg]	35	55.4	-
Incidence Angle [deg]	-	-	25-48
Mass [kg]	2	31	150
Power [W]	12	27	1000
Data rate [Mbit/s]	0.2	0.5	10

6. MWF Final Design

A thorough mission analysis has been performed considering the MWF winning architecture.

6.1 Coverage and Revisit Time Analysis

Revisit time is defined as the time interval between two recurrent measurements on the same target, based upon the set of instruments capable to perform such measurement. Table 5 reports statistics on the maximum and average revisit time for each measurement of the MWF use case considering the selected architecture.

Values can be compared with the requirements in Table 2: in orange the revisit time that comply with threshold requirements, but not with goal requirements, in green revisit time that comply with goal requirements. Average revisit time is always lower than the goal requirement, while for some measurements the maximum revisit time is above the goal value, but still below the threshold.

Table 4. Mapping between payloads and measurements for the MWF use case.

MWF Measurement	GNSS-R	Optical (VIS/NIR /TIR)	SAR-X
Ocean surface currents			✓
Wind speed over sea surface	✓		✓
Significant wave height	✓		✓
Dominant wave direction			✓
Sea surface temperature		✓	
Atmospheric pressure		✓	
Sea-ice cover	✓	✓	

Table 5. Maximum and average revisit time (RT) for MWF with the selected architecture.

MWF Measurement	Max RT [h]	Ave RT [h]
Ocean surface currents	**7**	**2.1**
Wind speed over sea surface	**2.5**	**0.7**
Significant wave height	**2.5**	**0.7**
Dominant wave direction	**7**	**2.1**
Sea surface temperature	**11**	**0.5**
Atmospheric pressure	**11**	**0.5**
Sea-ice cover	**2.5**	**0.4**

6.2 Data Latency Analysis

In this analysis data latency is defined as the time interval from the acquisition of the data by the instrument to the download to an available ground station, including data transfer between satellites thanks to the ISL. It represents the "space-segment" data latency and it does not include the latency due to data transfer, processing, archiving and cataloguing on ground. The implemented ISL model is simplified and it does not take into account ISL protocol time effects, access to the medium and queue effects.

The relative geometry of the satellites in the ONION constellation does not allow small platforms to communicate with ISL because the inter-satellite distance when a small platform is downloading is always longer than 400 km. With the current and near future technology, ISL can be exploited only for heavy platforms.

The geographical data latency is computed on the basis of the instrument swath, the maximum Sun-zenith angle (only for optical instruments) and the area of interest, reproducing the true coverage of the on-board instruments. Table 6 reports the maximum and average data latency for each measurement of the MWF use case considering the selected architecture. Values can be compared with the requirements in Table 2: in green data latency that complies with goal requirements and in red values slightly above the threshold.

Being the ground stations placed at the North Pole, average data latency is always close to zero (assuming that data can be acquired and simultaneously downloaded to a GS in visibility of the S/C), while data over some small regions observed just after the end of a contact with a GS have to wait about one orbital period to be downloaded. In order to be able to download all the data in less than 1 hour, a ground station in the Southern Hemisphere, like Troll, should be considered.

Table 6. Maximum and average data latency for MWF with the selected architecture.

MWF Measurement	Max Data Latency [h]	Ave Data Latency [h]
Ocean surface currents	**0**	**0**
Wind speed over sea surface	**1.4**	**~0**
Significant wave height	**1.4**	**~0**
Dominant wave direction	**0**	**0**
Sea surface temperature	**1.4**	**~0**
Atmospheric pressure	**1.4**	**~0**
Sea-ice cover	**1.4**	**~0**

6.3 Data Flow Analysis

Data flow analysis computes the evolution of the on-board memory to verify that no data is accumulated on board causing memory overflow. Platform properties for the data flow analysis are presented in Table 7.

Table 7. Platform inputs for data flow analysis.

Platform	Heavy	Small
Download Rate [Mbit/s]	26.5	0.19
ISL Data Rate [Mbit/s]	8.5	0.275
Memory Capacity [MB]	128	500

The maximum memory capacity is never reached for both platforms, being 1010 Mbit for heavy platforms and 182 Mbit for small platforms.

6.4 Power Budget Analysis

One of the most common parameters to be evaluated in a power budget analysis is the battery depth of discharge (DoD). Its evolution in time strongly depends on the platform power demand (stand-by power, instrumentation, on-board processor, data download, inter-satellite link) and on the platform power generation and storage system (solar arrays area characteristics, battery properties). The power generation capacity strongly depends also on the selected orbital plane (the choice of LTAN is of fundamental importance).

Power consumptions of the selected platforms for the MWF, solar panel and battery characteristics are presented in Table 8.

The maximum battery depth of discharge (DoD) of each satellite composing the MWF selected architecture has been computed and the results for each platform type are:

- Maximum DoD for small platforms: 0.198%
- Maximum DoD for heavy platforms: 9.932%

Values of DoD equal to zero mean that the battery is fully charged. The power budget analysis leads to feasible results, being the maximum DoD always below the acceptable limit of 30%.

Table 8. Platform inputs for power budget analysis.

Platform	Heavy	Small
Stand-By Consumption [W]	400	2
GS Downlink Consumption [W]	64.19	0.1
ISL Transmitting Consumption [W]	52.19	0.3
ISL Receiving Consumption [W]	12	0.4
Solar Panel Area [m2]	10	0.15
Battery Capacity [Ah]	78	10
Maximum DoD [%]	15	30

6.5 Delta-V and Fuel Budget Analysis

Based on a typical EO mission timeline, the ΔV budget analysis for ONION encompasses four main contributions, with the following apportionment:

- Nominal orbit acquisition, composed by:
  - Correction of launcher injection errors.
  - Acquisition of nominal satellite position inside the constellation.
- Orbit maintenance to control altitude
- Collision avoidance to avoid collision with space debris objects.
- End-of-Life (EOL) disposal to comply with EOL guidelines ([30], [31]).

The overall ΔV budget is computed by summing all the contributions outlined above and following the ESA guidelines for ΔV and fuel budget computation [32]. ΔV contributions are obtained on the basis of a bottom-up increasing spacecraft (S/C) mass, starting from the spacecraft dry mass at EOL and adding the fuel consumption associated to maneuver execution. No supplementary margin is added. Table 9 summarizes the assumptions taken into account for the ONION ΔV and fuel budget analysis.

Orbit acquisition is performed by firstly correcting launcher injection errors and then achieving the final, operational orbit through small refinement maneuvers. The propellant budget is computed by taking into account the launcher dispersion errors at 2σ for correcting altitude and inclination, and the frozen orbit conditions that will be used for the final target orbit. ESA Vega [33] is considered as baseline launcher.

Table 9. Inputs for delta-V and fuel budget analysis.

Reference orbit	SSO around 800 km
Launch date	1st July 2022
Mission Lifetime	S/C Heavy Platform: 4.5 years S/C Small Platform: 1.5 years
Drag parameters	Heavy Platform drag area: 10 m^2 Small Platform drag area: 0.1 m^2 Drag coefficient (C_D): 2.2
Dry Mass	S/C Heavy Platform: 600 kg S/C Small Platform: 6 kg
S/C specific impulse	S/C Heavy Platform: 220 s (Hydrazine or similar) S/C Small Platform: 85 s

The acquisition of the ONION nominal satellite positions in the constellation entails a phasing sequence after the release from the launcher and the corrections of the injection errors. A possible strategy to achieve the target in-plane separation at beginning of life is to use the launcher to inject two ONION spacecraft into the target operational orbit. Then the two satellites perform a transfer maneuver to reach two initial phasing orbits, with different semi-major axis (SMA), and hence a different period, with respect to the reference ONION orbit. The orbital period difference triggers a relative drift between the ONION S/C positions in the phasing orbits. Once the target in-plane relative position of two ONION satellites belonging to the same plane has been obtained, an in-plane maneuver can be applied to modify the SMA and achieve the nominal SMA of the reference mission orbit.

Since there are no explicit requirements regarding orbit control, the ONION orbit-control strategy has been defined aiming at guaranteeing the required mission performances in terms of revisit time and data latency. A control band width of ±1 km has been found to suit the ONION payloads needs and revisit time performance, since it guarantees that the orbit is maintained close enough to the initial reference one. This control band leads to an average in-plane maneuver size in the order of 1 m/s for both the platform types considered, being the ballistic coefficient the same. Depending on the propulsion system embarked, this value of maneuver size might need to be split in a series of smaller ones.

ΔV for collision avoidance for ONION is computed following ESA guidelines [32], according to which 6 maneuvers per year are envisaged. This collision avoidance approach is put forward for orbit altitudes between 700 km and 1000 km, due to a debris density peak in this altitude band.

A decay analysis has been performed considering the strategy of lowering the perigee altitude in order to guarantee a safe uncontrolled decay within 25 years. For this strategy, the target is to find the highest perigee altitude that still allows an uncontrolled re-entry within 25 years. Given the relatively high orbit altitude of the ONION satellites, a perigee lowering maneuver is expected to be needed to enable S/C re-entry in less than 25 years. Fig. 14 shows the evolution of orbital perigee and apogee after the EOL disposal maneuver.

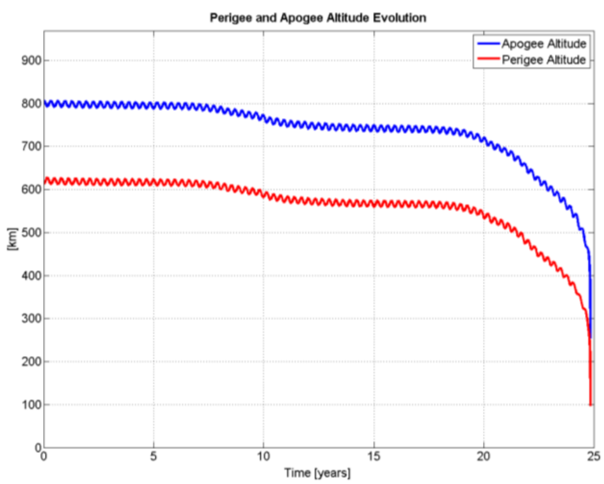


Fig. 14. Perigee and apogee altitude evolution for ONION EOL disposal.

Total ΔV and fuel budget for small and heavy platforms is reported in Table 10.

Table 10. ONION ΔV and fuel budget for the MWF use case.

Platform	Heavy	Small
Nominal Orbit Acquisition ΔV [m/s]	18.2	18.2
Orbit Phasing ΔV [m/s]	3.1	3.1
In-Plane Control ΔV [m/s]	8.3	3.1
Collision Avoidance ΔV [m/s]	2.8	0.93
EOL Disposal ΔV [m/s]	47.4	47.4
Total ΔV [m/s]	79.8	72.7
Total Fuel Mass [kg]	22.61	0.52
Initial Mass [kg]	622.61	6.52
Final Mass [kg]	600	6

7. Architecture Versatility

This section shows the versatility and the feasibility of the chosen architecture to be adapted to other three use cases of major interest for the ONION project, each of them with a different area of interest and a different set of relevant measurements. Versatility can be introduced in the design process by modeling it as one of the "ilities" [27] considered in the architectural selection framework described in section 2. Versatility is defined as the ability to achieve multiple functions with similar form and operations, so, in this context, it evaluates the ability of a given constellation geometry to perform well, regardless of the embarked instruments on board, but considering platform distribution and orbital configuration. For this reason, among all possible architectures for the "Marine Weather Forecast" use case, the most versatile ones are expected to be the best candidates to be employed in other use cases with different measurements and requirements. However, it is implied that optimal architectures for other use cases should be selected ad-hoc, by repeating the mission and system architecture design presented in this paper from the beginning, considering the corresponding requirements.

Keeping the architecture selected for the "Marine Weather Forecast" use case (described in Section 6), it is highly probable that the requirements of the other use cases will not be fully satisfied, for example in case of measurements that cannot be acquired by the set of instruments considered to fulfill the MWF needs (SAR-X, optical imager and GNSS-R). This analysis evaluates the degree of reusability of the selected architecture to comply with requirements coming from other use cases. The three use cases considered are:

- Arctic sea-ice monitoring
- Maritime fishery pressure and aquaculture
- Agriculture: hydric stress

7.1 Arctic Sea-Ice Monitoring

The service aims at providing near-real time sea-ice data (sea-ice extent, type and thickness) to ensure navigation safety in polar shipping routes. It also aims at improving the precision of sea-ice thickness measurements and at providing EO information on arctic sea-ice concerning climate change. The measurements included in this use cases are: Sea-ice extent, Iceberg tracking, Sea-ice thickness, Sea-ice type, Sea-ice drift, Wind speed over sea surface, Significant wave height, Dominant wave direction, Sea surface temperature. The last four measurements are present also in the MWF use case.

The area of interest of this use case is the same as the MWF, which is the Arctic region over 60º of latitude north.
Requirements for this use case are quite strict from the revisit time point of view, being less than 3 hours for all measurements. Attractive data latency would be of 1 hour.
Results of the detailed revisit time and data latency analysis for the "Arctic Sea-Ice Monitoring" use case considering the MWF architecture are presented in Table 11, where maximum and average values are reported and values complying with requirements are marked in green, while values higher than the required ones are in red.

Results are similar to the MWF use case because the area of interest is the same and some measurements, too. These measurements feature the same revisit time and data latency as the MWF use case. Some requirements are not fully satisfied, with the highest value represented by the sea surface temperature, which is only measured by the Optical Imager. On the other hand, considering the mean values, revisit times are always compliant with the 3 hours requirement.
For what concerns data flow and power budget, the results are the same as the MWF use case because the area of interest is the same.

Table 11. Revisit time and data latency for Arctic Sea-Ice Monitoring with MWF architecture.

Measurement	Revisit Time Max/Ave [h]	Data Latency Max/Ave [h]
Sea-ice extent	**7.0/0.5**	**1.4/0**
Iceberg tracking	**7.0/2.1**	**0/0**
Sea-ice thickness	**2.5/0.7**	**1.4/~0**
Sea-ice type	**7.0/2.1**	**0/0**
Sea-ice drift	**7.0/2.1**	**0/0**
Wind speed over sea surface	**2.5/0.7**	**1.4/~0**
Significant wave height	**2.5/0.7**	**1.4/~0**
Dominant wave direction	**7.0/2.1**	**0/0**
Sea surface temperature	**11.1/0.5**	**1.4/0**

7.2 Maritime Fishery Pressure and Aquaculture

The second additional selected use case is focused on fishery, a sector of developing interest for EO data exploitation, especially concerning monitoring illegal fishery and resource stock management. It has been decided to focus the use case on two major fishing areas: the Western Indian Ocean (around Madagascar) and the Arctic Sea (same area of interest as the MWF and "Arctic Sea-Ice Monitoring" use cases, i.e., 60º North latitude).

The measurements included in this use case are: Sea surface temperature, Ocean chlorophyll concentration, Ocean imagery and water leaving radiance, Color dissolved organic matter (CDOM), Vessel and fish farming cages position tracking.

The last measurement cannot be recorded by any of the instruments on-board the selected ONION constellation; in fact, an Automatic Identification System (AIS) would be required. Consequently, it will not be possible to perform measurements of this last parameter. The other four measurements can only be recorded by the optical imager, which means that only the heavy platforms will be working in this use case analysis, while the small ones will not be acquiring any data.

Requirements for this use case are 72 hours for revisit time and 1 hour data latency for all the measurements.

Results of the detailed revisit time and data latency analysis for the "Maritime Fishery Pressure and Aquaculture" use case considering the MWF architecture are presented in Table 12, where maximum and average values are reported and values complying with requirements are marked in green, while values higher than the required ones are in red. Maximum revisit time is always below 18 hours, while maximum data latency is in the order of one orbital period.

Table 12. Revisit time and data latency for Maritime Fishery Pressure and Aquaculture with MWF architecture.

Measurement	Revisit Time Max/Ave [h]	Data Latency Max/Ave [h]
Sea surface temperature	**17.7/1.3**	**1.4/0.2**
Ocean chlorophyll concentration	**17.7/1.3**	**1.4/0.2**
Ocean imagery and water leaving radiance	**17.7/1.3**	**1.4/0.2**
Color dissolved organic matter	**17.7/1.3**	**1.4/0.2**

Data flow and power budget analysis for the heavy platform show feasible values, being the maximum memory reached around 700 Mbit and the maximum DoD around 10%.

7.3 Agriculture: Hydric Stress

The last additional use case concerns the issue of scarcity of water and drought in the planet. The use case focuses on measuring water scarcity factors and indicators and uses that information to better understand how much water crops need and how they respond to stress. To perform this kind of investigation, several parameters have to be monitored. These data are obtained by satellite observations on a wide area of interest that covers all the emerged lands.

Measurements considered in the current use case are: Detection of water stress in crops, Soil moisture at the surface, Estimation of evapotranspiration in crops, Crop growth & condition.

Also in this use case most of the measurements can be acquired by means of an optical imager, with the contribution of the GNSS-R instrument for what concerns the soil moisture. SAR-X instrument is not required. As in the "Maritime Fishery Pressure and Aquaculture" use case presented in section 7.2, a measurement cannot be estimated by means of the instruments of the selected ONION space segment configuration (MWF-driven): the "Crop growth and condition" measure needs a LIDAR altimeter. This instrument is not embarked on the selected ONION space segment configuration and, therefore, applying this configuration to the agriculture use case will not bring any results concerning that specific measurement.

Requirements for this use case are less stringent than the other use cases considered: 24 hours for revisit time and 24 hour data latency for all the measurements.

Results of the detailed revisit time and data latency analysis for the "Agriculture: Hydric Stress" use case considering the MWF architecture are presented in Table 13. All the values are in green because they fulfill the requirements.

Table 13. Revisit time and data latency for Agriculture: Hydric Stress with MWF architecture.

Measurement	Revisit Time Max/Ave [h]	Data Latency Max/Ave [h]
Detection of water stress in crops	**17.7/2.0**	**1.5/0.5**
Soil moisture at the surface	**15.2/1.0**	**1.5/0.5**
Estimation of evapotranspiration in crops	**17.7/2.0**	**1.5/0.5**

Given the extended area of interest, values of platform's maximum mass memory and DoD are higher than the other use cases. Memory can reach 1200 Mbit for heavy platforms and 850 Mbit for small platforms, while maximum expected DoD for heavy platforms is about 10%. Depth of discharge for small platforms located in orbital planes with long eclipse periods (LTAN at 00:00 and 12:00) reaches the maximum acceptable value of 30%. Given the loose requirements on revisit time and data latency, a more optimal constellation distribution for the Agriculture: Hydric Stress use case would encompass all the satellites placed on the same orbital plane with a favorable LTAN.

8. Conclusions

This paper presents the mission and system architecture design of the Horizon 2020 ONION project, a European Union research activity, focusing on the user needs for Marine Weather Forecast. The proposed methodology applies tradespace exploration paradigm and is presented as a generic framework that enabled the optimization of constellation designs for all the use cases in ONION. The architecting framework divides the evaluation of performance in two stages, coarse and fine, to allow both the analysis of global design trends and the optimization of designs based upon high fidelity metrics. This paper has focused on the analyses carried out for a small subset of the design space which is identified during the application of the architecting methodology.

The best ranked architectures for the MWF use case have been analyzed in detail evaluating several key parameters as revisit time and data latency of each measurement, on board memory evolution and power budget of each satellite of the constellation. For the selected architecture, a thorough mission analysis has been performed encompassing coverage, revisit time, data latency, mass memory evolution, power budget, delta-V and fuel budget analyses.

Some general considerations can be derived from the overall results. The data flow and on-board data handling are not critical points in any of the selected architectures, due to the fact that the area of interest is not very large (polar region). Due to ISL range limitations on small platforms and to the reduced available time to perform ISL (only when a platform is already in contact with a ground station), the connectivity of the constellation is poor most of the times and ISL does not significantly improve the maximum data latency. However, the average data latency benefits from the constellation connectivity. Data latency appears as a stringent requirement and a possible solution to be investigated in the future to reach real-time performance could be the use of data relay satellites, like the EDRS (European Data Relay Satellite) in GEO or a constellation of communication satellites in lower orbits (LEO).

Maximum revisit time for the less demanding measures is in general achieved; however, when the requirement goes below few hours, few architectures are able to fulfill it. To improve revisit time, the number instruments delivering data for that measurement, should be increased, both on the same orbital plane and on more orbital planes. The most critical aspect is the power budget due to many orbital planes to consider, the different illumination conditions from plane to plane and the limitation of a unique design for the power subsystem capable to provide enough power to the spacecraft.

Even if the architecture has been selected to be compliant with the specific Marine Weather Forecast use case, it is still compliant with some of the requirements of other use cases, including Arctic Sea-Ice monitoring, Maritime Fishery Pressure and Aquaculture, and Agriculture: Hydric Stress, due to the thorough selection of instruments on-board the satellites.

This paper presents the design, evaluation and selection process for an Operational Network of Earth Observation Satellite Nodes developed in the frame of a research and development programme (Horizon 2020), involving different entities among universities and private companies. Each entity has developed a computational module of the entire process, which has been validated either using commercial available software tools for the coarse analysis, or in-house tools for the architecture selection and detailed analysis, like Deimos mission analysis tools developed during more than one decade of EO mission studies. Runtime performances have been evaluated during the ONION project: the generation of 5586 unique solutions (section 4) starting from decision variables in Table 1 takes about 6 hours, while the refined analysis for architecture selection reported in section 5 requires about 5 hours for each architecture.

To achieve a fully-automated process and facilitate an easy integration, a generic software framework can be designed to support standardized end-to-end simulation capabilities, in order to be able to plug in models and analysis modules using a well defined integration process.

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