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Design and Optimization of a Polar Satellite Mission to Complement the Copernicus System

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ABSTRACT The space industry is currently witnessing two concurrent trends: the increased modularity and miniaturization of technologies and the deployment of constellations of distributed satellite systems. As a consequence of the first trend, the relevance of small satellites in line with the “cheaper and faster” philosophy is increasing. The second one opens up completely new horizons by enabling the design of architectures aimed at improving the performance, reliability, and efficiency of current and future space missions. The EU H2020 ONION project (“Operational Network of Individual Observation Nodes”) has leveraged on the concept of Fractionated and Federated Satellite Systems (FFSS) to develop and design innovative mission architectures resulting in a competitive advantage for European Earth Observation (EO) systems. Starting from the analysis of emerging needs in the European EO market, the solutions to meet these needs are identified and characterized by exploring FFSS. In analogy with terrestrial networks, these systems envision the distribution of satellite functionalities amongst multiple cooperating spacecrafts (nodes of a network), possibly independent, and flying on different orbits. FFSS are considered by many as the future of space-based infrastructures, as they offer a pragmatic, progressive, and scalable approach to improve existing and future space missions. This work summarizes the main results of the ONION project and the high-level design of the Marine Weather Forecast mission for polar regions.

INDEX TERMS Satellite, Mission, Constellation, Federation, Sensors, Fractionation, SAR, GNSS-R, VIS/NIR/SWIR/LWIR, imagers, Polar, Weather, Ice, Marine, Currents.

I. INTRODUCTION

Federated Satellite Systems (FSS) [1] are one of the newest distributed architecture paradigm proposals, featuring opportunistic resource exchange among fully independent missions. It bridges a gap in the taxonomy of Distributed Satellite Systems (DSS) regarding component uniformity and independency. On the operational status side, a number of constellations have been deployed and have been operational for decades, e.g. the A-Train constellation [2]. On the side of fractionated system architectures, DARPA's F6 [3] program remains the most recent comprehensive research effort. The F6 Program (Free Flying Future, Fast, Flexible, Fractionated Free-flying Spacecraft United by Information Exchange) was a US Defense Advanced Research project that started in 2007 aiming to demonstrate the feasibility of Fractionated Spacecraft by 2015. The project was discontinued in 2012. It targeted a broad range of missions, not necessarily related with Earth Observation. Besides this effort, specific EO applications for fractionated systems have been studied [4], but no fully fractionated EO system has been launched to date. The same thing can be said about federations, although the Disaster Monitoring

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Constellation can be consider a precursor of it, in which each satellite belongs to a different partner and resources are shared as needed [5]. However, there are a number of deployed missions that can be considered precursors of DSS [6,7,8] and more achievements and operational systems are expected over the next decade.

This work summarizes the main results of the EU H2020 ONION project aiming to review the emerging Fractionated, Federated and Distributed Satellite System concepts, to identify potential benefits to be obtained in light of the observation needs in different Earth Observation domains, and to propose to the EU an overall strategy and technical guidelines to develop and implement such concepts in the time frame 2021-2027.

This manuscript is organized as follows. First, a brief overview of fractionated and federated observation system concepts is presented. The potential benefits that can be obtained in light of the observation needs in different Earth Observation domains are then identified. After a comprehensive analysis, the Marine Weather Forecast in polar regions use-case ranked as the top priority, followed by the Artic Sea Ice Monitoring, Maritime Fishery Pressure and Aquaculture, and the Agriculture Hydric Stress.

Then, a Systems Architecture Study is performed for the Marine Weather Forecast use-case, including the architectural analysis, the tradespace exploration, the performance analysis and simulation, and the selection of the winning candidate architecture. Finally, a more detailed design of the final architecture is conducted, and its applicability to the other top priority use-cases is assessed concluding that the resulting mission concept can be a truly Polar Copernicus mission. The key required technology challenges to be faced in time frame 2021-2027 are identified. The last section summarizes the main conclusions of this work.

II. REVISION OF FRACTIONATED AND FEDERATED OBSERVATION SYSTEM CONCEPTS

In the frame of ONION, a survey of the state of the art in Distributed Satellite Systems (DSS) was conducted, including a comprehensive review of Fractionated and Federated technologies. A detailed classification of the different distributed architectures, the expected trade-offs, the key enabling technologies, and the translation of user needs and technology maturity into functional requirements were performed. The requirements were structured in 4 thematic areas: the requirements on payloads, the operational requirements, the space-to-space interface requirements, and the space-to-ground interface requirements. These complementary approaches enable mission concepts that otherwise would be impractical, or even impossible, with traditional approaches, while enhancing reliability, affordability, sustainability, scalability, and flexibility. Table I [1] summarizes the different DSS architecture types, their main goals, and properties. Note that several DSS could also be classified as formation-flying missions.

TABLE I
TYPES OF DSS ARCHITECTURES [1]

Type	Mission goals	Cooperation	Homogeneity	Autonomy
Constellations	Mission goal shared (e.g. Iridium, GPS)	Cooperation required to support mission goals	In general homogeneous components, some differences possible (e.g. GPS generations)	Autonomous
Trains	Mostly independent, but could be shared	Cooperation from optional to required	Heterogeneous components	Autonomous
Clusters	Mission goal shared	Cooperation required to support mission goals	Homogeneous components	From autonomous to completely co-dependent
Swarms	Mission goals shared	Cooperation required to support mission goals	From homogeneous to heterogeneous components	From autonomous to completely co-dependent
Fractionated Satellites	Mission goals shared	From optional (service areas) to required (distributed critical spacecraft functions)	Heterogeneous components	From autonomous to completely co-dependent
Federated Satellites	Independent mission goals	Ad-hoc, optional	Heterogeneous components	Autonomous

III. IDENTIFICATION OF POTENTIAL BENEFITS AS A FUNCTION OF THE OBSERVATION NEEDS IN DIFFERENT EARTH OBSERVATION DOMAINS

The needs of different users, stakeholders, and beneficiaries of Earth Observation (EO) services were reviewed and analyzed, identifying the key elements of the value chain of the European EO infrastructure and building a comprehensive knowledgebase of those elements, represented as a relational database (Fig. 1).

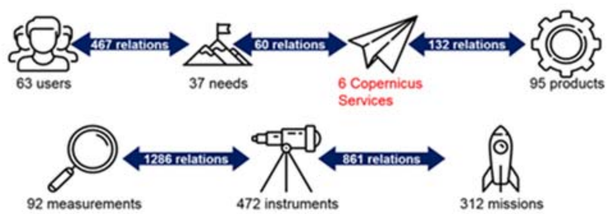

FIGURE 1. Graphical relationship of the data in the database.

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TABLE II
SCORING OF THE TOP 10 USE-CASES NOT SATISFIED BY THE EXISTING EU COPERNICUS INFRASTRUCTURE

Use-case name	Number of users	Related need score	Related Service score					Final Score normalized
			FPBI* coverage	FPBI accuracy	FPBI frequency	FPBI access	Service score	
Marine Weather Forecast	14	0.8823	<10%	60-70%	50-60%	50-60%	1	1
Sea ice monitoring	15	0.8749	<10%	60-70%	50-60%	50-60%	1	0.9916
Fishing pressure, stock assessment	12	0.6829	<10%	60-70%	50-60%	50-60%	1	0.774
Land for Infrastructure Status Assessment	17	1	30-40%	10-20%	10-20%	50-60%	0.67	0.7556
Agriculture (hydric stress)	24	0.9972	30-40%	10-20%	10-20%	50-60%	1	0.7535
Land for Basic Maps	18	0.9055	30-40%	10-20%	10-20%	50-60%	0.67	0.6842
Sea Ice melting emissions	15	0.7135	<10%	60-70%	50-60%	50-60%	1	0.6739
Atmosphere for Weather Forecast	14	0.8823	<10%	30-40%	50-60%	30-40%	0.67	0.6667
Climate for Ozone Layer & UV	14	0.7058	<10%	40-50%	30-40%	50-60%	0.83	0.6666
Natural habitat monitoring, protected species monitoring	18	0.6903	<10%	40-50%	40-50%	50-60%	0.83	0.652

(*)FPBI – Fraction of Products that Would Benefit from Improvement

The creation of this database and the quantitative scoring methodology developed to analyze and select the most promising use-cases not satisfied by the existing EU Copernicus infrastructure was described in detail in [9]. The top 10 uses cases identified are listed in Table II, which also indicates the total number of identified users, the overall ranking and the fraction of products that would benefit from and improvement in terms of coverage, accuracy, frequency (i.e. revisit time), and access (data availability). Finally, the ONION project User Advisory Board recommended to address the four use-cases indicated with a mark of 1 in the service score. As it will be shown after the detailed analysis, the "Marine Weather Forecast" mission can almost satisfy the other three use-cases leading to a single ONION "polar" mission, the "ONION Marine Weather Forecast" (OMWF) to complement the Copernicus system. The ONION "Agriculture Hydric Stress" (OAHS) mission was also analyzed in view of the synergies with the OMWF one. Tables II-VI summarize the main characteristics of the above proposed services, which are graphically described in https://www.youtube.com/watch?v=LF7alaLTSyc.

TABLE III
MAIN CHARACTERISTICS OF THE PROPOSED SERVICE "MARINE WEATHER FORECAST"

End-users	Oil/Gas/Mining industry & Fishing and aquaculture industry etc.
Summary of Needs	**Monitoring** sea conditions for offshore operations in polar regions. Operational tool type **early warning system**.
Location	Arctic and subarctic regions (over latitude 60°N, target value: over 50°N)
Services activated	Deliver in Near Real Time (**NRT**), **and routinely,** weather forecasts (nowcasting and 3-day forecasts), maps and service alerts via web applications and compatible with modelling software. • *Marine weather forecasting* • *Ocean current forecasting* • *Route optimization* • *Search and rescue operations*
Service characteristics	Spatial resolution: < 1 km Temporal resolution (model): 1 h Latency time: near real time (<1h) Revisit time (observation) : < 24 h Service duration: continuously and on demand for specific offshore operations.

IV. SYSTEMS ARCHITECTURE STUDY AND IDENTIFICATION OF KEY REQUIRED TECHNOLOGY CHALLENGES TO BE FACED IN TIME FRAME 2021-2027

The Systems Architecture Study has been performed in different steps. First, an analysis of the architectural elements has been performed, followed by an exploration of the tradespace (i.e. different configurations, namely orbital planes, number and type of spacecrafts, payloads etc.). Then, a performance analysis and simulation have enabled the evaluation of architecture candidates. Finally, the best candidate has been selected and an accurate design performed. The procedure is explained graphically in Fig. 2. This systematic approach aims at addressing the following open questions:

TABLE IV
MAIN CHARACTERISTICS OF THE PROPOSED SERVICE "ARTIC SEA ICE MONITORING: EXTENT, TYPE AND THICKNESS"

End-users	Sea Ice as a barrier for ship traffic, fisheries and offshore operations
Location	Arctic regions (over latitude 60°N)
Services activated	**Sea-ice monitoring:** extent, type and thickness Deliver **in NRT, and routinely**, maps and service alerts via web applications. **Route optimization**
Service characteristics	**Sea-ice thickness** Spatial resolution: < 10 m (horizontal), 1 cm (vertical) Temporal resolution: 1 h Revisit time: < 3 h Coverage: Arctic Latency time: near real time (<1h) Usage conditions: 1 cm accuracy Service duration: continuously and routinely service and on demand for specific operations **Sea-ice type & extent** Spatial resolution: 10 m horizontal Temporal resolution: 1 h Revisit time: <3 h Coverage: Arctic Latency time: near real time (<1h) Usage conditions: 5 % accuracy Service duration: continuously and routinely service and on demand for specific operations

TABLE V
MAIN CHARACTERISTICS OF THE PROPOSED SERVICE
"MARITIME FISHERY PRESSURE"

End-users	Fishing and aquaculture industry
Summary of Needs	Knowledge of oceanographic conditions and fishing pressure in support of monitoring fish stocks environment. Improve understanding of fish stock resilience and vulnerability to natural and anthropogenic factors (e.g. climatic versus over-fishing effects). Surveillance and control of marine resources for enhanced fisheries protection and detection of illegal, unreported, and unregulated fishing and supporting activity (e.g. refueling or catch transfer).
Location	Major fishing areas: priority 51- Western Indian Ocean (6-Madagascar) & 18 Arctic Sea
Service activated	Satellites can assist the fishing industry in many ways for **fish stocks monitoring**. The types of assistance that satellites can offer include the following: An **online tool** providing continuously observations, combining satellite and *in-situ* data, to assist fishermen to plan their **fishing operations**. Fast communications to vessels for transmitting satellite observations and derived-products. Accurate information of the "state" and "evolution" of fish stocks on all of world's major fishing areas by coupling the fishery pressure and oceanic conditions. Widen **area surveillance** and control of marine resources in Member State Exclusive Economic Zones for enhanced fisheries protection and detection of illegal, unreported, and unregulated fishing and supporting activity.
Service characteristics	Spatial resolution: 1 km Temporal resolution (given by models): 24 h Latency time: near real time (< 1h) Revisit time: 72 h (cloud free) Service duration: on demand.

1. How can FFSS be optimally architected? That is, how should the instruments be distributed? Is there an optimal instrument technology to address all measurements? Which kind of spacecraft platforms is more likely to satisfy certain user needs while allowing for cost-effective and technologically feasible solutions? Are small-satellite technologies feasible alternatives to design such architectures? How many spacecrafts are needed? And what should their orbital parameters be?
2. How can user needs be satisfied? That is: low-latency (near-real-time), short revisit times (ideally 1 h), and high spatial resolution (10 m to 1 km, depending on the application).
3. How can FFSS be designed so that they satisfy high-level system qualities? That is, how to force or promote certain *ilities* in final designs? And what is the impact of small satellite technologies on system *ilities*?

A. ARCHITECTURAL ANALYSIS

The architectural elements analysis included an analysis of the different payloads required to obtain the measurements needed to fulfill the user requirements, and a survey of the commercial platforms where these payloads can be boarded. Basic payload parameters include mass, power, swath, and

TABLE VI
MAIN CHARACTERISTICS OF THE PROPOSED SERVICE
"HYDRIC STRESS MONITORING FOR AGRICULTURE"

End-users	Agriculture professionals / insurance companies / Decision makers
Need summary	**Detection and Monitoring** of water stress on crops to better manage irrigation.
Type of operations	Water management and drought monitoring for agriculture
Location	Europe and Water scarcity prone areas (regions such as China, India, and Sub-Saharan Africa)
Services activated	**Routine delivery** of information, indicators and geospatial products assessing the crop conditions. **Alert service** showing the area affected by the drought according to a predefined threshold. **Portal / Global information system** providing a range of services aimed at the better monitoring of droughts
Service characteristics	Spatial resolution: < 1 km Revisit time: daily Latency time: intra-day Geographical coverage : Local to global Service duration: continuously

spatial resolution, which were mostly derived from the OSCAR [10] and CEOS [11] databases.
However, the estimated power consumption, required aperture (either optical or microwave), mass, and the achievable swath were recomputed according to the required spatial resolution, swath, and satellite altitude. Basic parameters of commercial platforms were taken into account, including the payload mass and power, as well as the pointing control knowledge and accuracy. Platforms are classified as large (200 kg payload, 600 kg dry mass), such as the SSTL 600 or the Astrosat 100, mid class (50 kg payload, 166 dry mass), such as the TETx from OHB, the SSTL 150, or the SN-50, and small class (2 kg payload, 6 kg dry mass), such as a 6 U CubeSat. After this analysis, a matching between payloads (or combination of payloads) and platforms was conducted. The list of sensors satisfying the requirements is summarized in Table VII, where the light, mid and dark gray colors indicate that the payload can be embarked on a small, medium or large platform [12]. The selection process is illustrated in Fig. 3. A number of possible combinations of payloads and platforms are feasible. Table VIII summarizes the main instrument types, the type of platform (small, medium or large), and the properties of a reference instrument in terms of mass, power, data rate, and swath. At this stage, the tradespace exploration can be performed by selecting the optimum configuration of platforms/instruments, orbital planes, and number of spacecrafts per orbital plane.

B. TRADESPACE EXPLORATION

The tradespace exploration includes the 3 first steps of the classic paradigm: Formulation, Enumeration, and the Evaluation of the different architectures implies some assumptions on the revisit time model (i.e. instrument apertures, ground control points etc.), and on the latency model

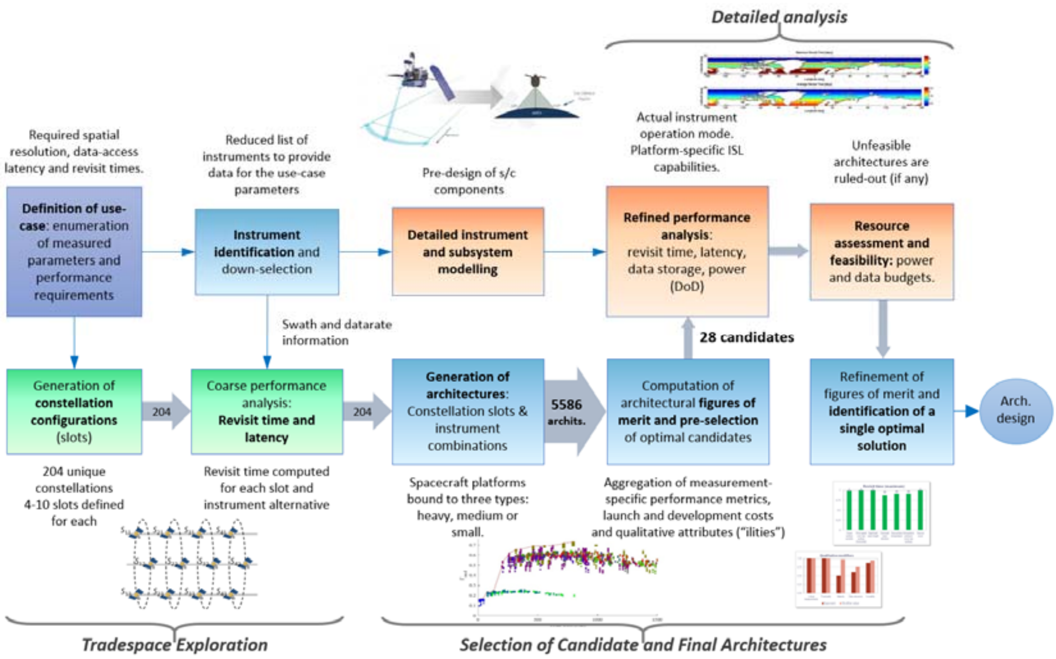

FIGURE 2. Graphical explanation of the Systems Architecture Study to select the optimum configuration.

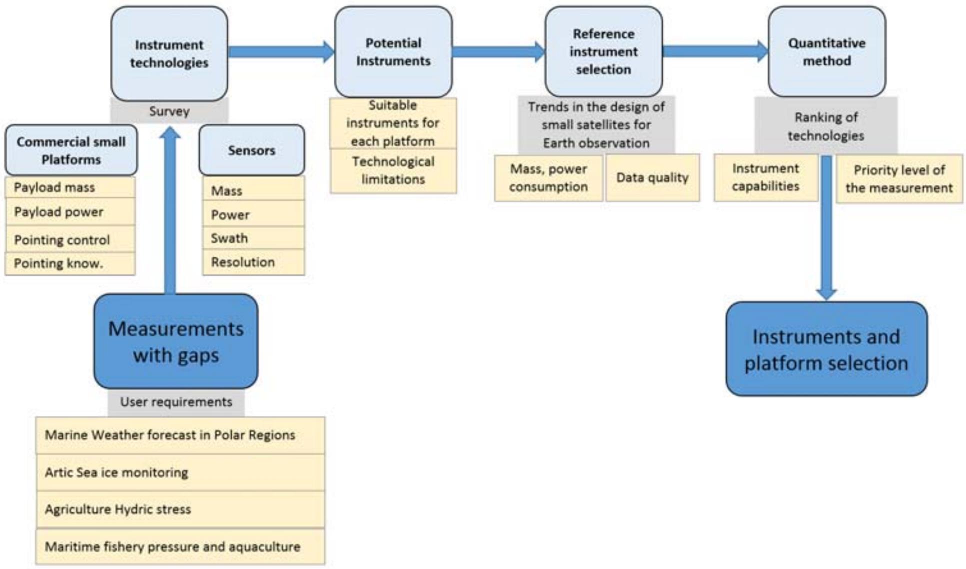

FIGURE 3. Instrument and platform selection process to meet the user observation requirements.

(i.e. inter-satellite link behavior, location of the ground stations etc.) The down selection, analysis, and visualization steps are performed later as part of the architecture candidate selection.

For the OMWF use-case the number of nodes was selected among the following eleven possibilities {4,6,8,10,12,16,20,24,32,40,48}, orbital height among the following three values {510,657,807} km, number of orbital planes among the following five values {2,3,4,6,8}, and the Walker constellation either Delta, or Star type. For the OAHS use-case the number of nodes and orbital heights are the same as for the OMWF case, but the number of orbital planes was selected among the following three values {1,2,3}, because of less stringent requirements on revisit time. Since the design methodology is the same, only OMWF results are presented.

For the above possible configurations, uneven distributions (e.g. 8 nodes in 3 planes) are ruled out. Additionally each architecture presents several slot configurations (i.e. positions of the spacecrafts in the orbit) that increase the tradespace.

An ad-hoc simulation-based revisit time assessment tool ("ONIONETA") and a simulation-based latency estimator tool ("OCOMNET") were used to evaluate the different architectures. These tools are geometry based and include the SGP4 orbital propagator [13].

The optimization procedure is quite sophisticated. The interested reader is referred to [14], where it is described in detail. An aggregated figure of merit is defined which encompasses: system-level performance metrics; use-case requirements; development and launch costs; and architectural quality attributes, which assess and weight several of the so-called "*ilities*" of an architecture and allow selecting designs that exhibit the desired qualities.

TABLE VII
LIST OF REQUIRED SENSORS TO SATISFY THE OBSERVATIONAL REQUIREMENTS OF THE DIFFERENT USE-CASES.

Technologies		Passive Optical		Active Optical			Passive Microwave					Active Microwave	
Use cases	IR Spectrometer	Multispectral imager VIS/MWIR/TIR	Hyperspectral imager (VIS/NIR)	Lidar	Microwave Radiometer (K, Ka, W-bands)	Microwave Radiometer (X, K, Ka, W-bands)	Microwave Radiometer (L-band)	Microwave Sounder (W, Y-bands)	GNSS-R	AIS	Scatterometer	Altimeter	Altimeter (SAR)	SAR
Marine Weather Forecast-polar regions	x	x		x	x	x			x		x	x	x	
Sea ice monitoring	x	x	x	x	x	x	x		x			x	x	x
Fishing pressure, stock assessment	x	x	x							x				x
Land for infrastructure status assessment		x	x											x
Agriculture (hydric stress)		x	x				x		x		x			x
Land for basic maps		x	x				x		x					x
Sea ice melting emissions	x	x	x	x	x	x	x		x			x	x	x
Atmosphere for weather forecast		x		x	x	x		x			x			
Climate for ozone layer & UV			x											
Natural habitat monitoring, protected species monitoring		x					x		x					x

TABLE VIII
MAIN INSTRUMENT TYPES, REFERENCE INSTRUMENT, PARAMETERS, AND REQUIRED PLATFORM: LARGE: 600 KG DRY MASS, 200 KG PAYLOAD; MEDIUM: 166 KG DRY MASS, 50 KG PAYLOAD, AND SMALL: 6 KG DRY MASS, 2 KG PAYLOAD 6U CUBESAT). SWATHS AT 3 DIFFERENT HEIGHTS: 510, 657, AND 807 KM.

Instrument and platform type	Reference instrument	Mass (kg)	Power (W)	Data rate (kbps)	Swath (km)	Mature (y/n)
Optical VIS/NIR/TIR Imager (Medium)	AVHRR/3 (MetopC)	31	27	515	1636, 2186, 2812	y
Hyperspectral VIS/NIR Optical Imager (Small)	CHRIS (PROBA-1)	14	8	1000	10, 12, 18	n
TIR sounder (Small)	EON-IR (CIRAS)	14	40	320	937, 1220, 1518	n
L-band MWR (Medium)	MIRAS (SMOS)	355	511	89	661, 856, 1058	y
MWR W, Y (Small)	TEMPEST-D	3	8	20	1066, 1392, 1739	n
MWR K, Ka, W (Medium)	SSM/I	48.5	45	5	925, 1159, 1367	y
MWR X, K, Ka, W (Large)	TMI (TRMM)	65	50	8.8	1065, 1325, 1576	y
GNSS-R (Small)	DDMI (CYGNSS)	2	12	200	730, 946, 1170	n
Radar Altimeter, Ka (Large)	Altika (SARAL)	40	85	43	6.5, 8.2, 10.1	y
SAR Altimeter (Large)	SRAL (Sentinel-3)	70	149	12000	12.53, 16.13, 19.6	y
SAR-X (Large)	Severjanin-M	150	1000	10000	289, 358, 425	y

MWR: Microwave Radiometer, GNSS-R: Global Navigation Satellite Systems Reflectometry, SAR: Synthetic Aperture Radar

C. PERFORMANCE ANALYSIS, SIMULATION, AND SELECTION OF WINNING CANDIDATE ARCHITECTURE

After having down-selected a set of candidates from all possible architectures, a detailed analysis is needed to find the optimum architecture. Orbits are assumed to be Sun Synchronous (SSO). Visibility intervals with the ground station network are computed, Inter-Satellite Link (ISL) constraints are applied to calculate when a platform can communicate with another one via ISL and Sub-Satellite

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Point (SSP) data latency is calculated taking into account contacts with the ground stations and the ISLs. Then, revisit time and data latency are computed as a function of instrument properties (i.e. swath) and the areas of interest for each measurement separately, taking into account only the instruments generating that particular measurement. Finally, the used capacity of the mass memory and the evolution of the batteries Depth of Discharge (DoD) are computed taking into account instrument's activity intervals, ground station contact intervals, and ISL intervals. The whole process is described in Fig. 4, and the final results are summarized in Table IX. Providing simulation parameters is out of the scope of this manuscript, as it aims at describing the methodology and results. The interested reader is referred to [15].

To perform the simulations of the OMWF, two ground stations are assumed: one in Svalbard (latitude 78.1°, longitude 15.5°), and a second one in Inuvk (latitude 68.4°, longitude -133.7°). Data flow and on-board data handling are not critical points, but the poor constellation connectivity reduces the opportunities for ISL due to small platform's range limitations, thus the maximum data latency is about one orbital period (around 90 min), and in this configuration the ISLs do not help to improve maximum data latency. The maximum revisit time requirement for the less demanding measurements is in general fulfilled, but when the requirement goes below a few hours, just few architectures are able to fulfill it. However, the most critical aspect turns out to be the power budget, because the illumination conditions are different from orbital plane to orbital plane (different LTAN, i.e. Local Time of the Ascending Node), and a unique design for the power subsystem is not able to provide enough power to all the spacecrafts.

Finally, the winning architecture for the OMWF use-case consists of a constellation of 16 nodes distributed in 8 orbital planes at about 800 km altitude. Nodes are 8 large platforms including an X-band SAR and a multispectral optical imager, and 8 small platforms including a GNSS-R payload. As illustrated in Fig. 5 and listed in Table X, where M indicates the satellite orbital mean anomaly.

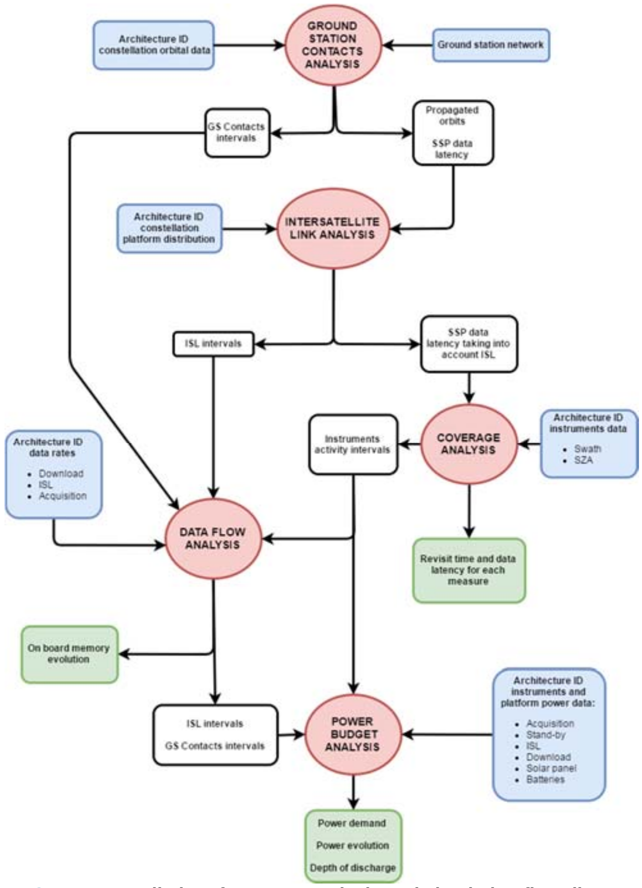

FIGURE 4. **Detailed performance analysis and simulation flow diagram for each configuration (defined by its identification number –ID-).**

a) b)

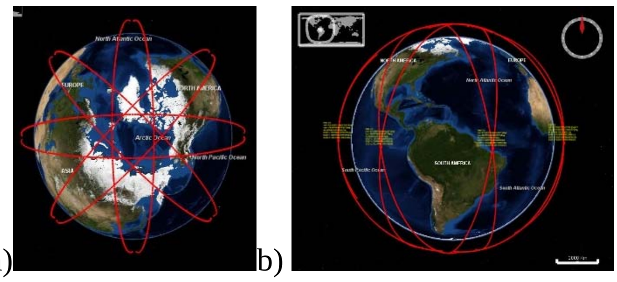

FIGURE 5. a) Polar and b) Equatorial views of the winning architecture.

TABLE IX
DOWN SELECTED CONFIGURATIONS: PAYLOADS, PLATFORM, MASS, POWER AND MAXIMUM DATA RATE.

Name	1	2	3	4	5	6	7	8	9	10	11	12
GNSS-R	y	n	y	y	y	n	n	n	n	y	y	n
Optical Imager (med. res.) VIS/NIR/TIR	n	n	y	n	n	y	y	n	y	y	y	n
Radar altimeter (Ka-band)	n	n	n	y	n	y	n	n	n	y	n	n
MWR W-, Y-bands (small)	n	y	n	y	n	n	n	n	n	n	n	n
MWR K-, Ka-, W-bands (medium)	n	n	n	n	y	n	n	n	n	n	n	y
MWR X-, K-, Ka-, W-bands (large)	n	n	n	n	n	n	n	n	n	y	y	n
MWR K-, Ka- (for WV, nadir-looking)	n	n	n	n	n	n	y	n	n	n	n	y
Ku-, C- band SAR altimeter	n	n	n	n	n	n	y	n	n	n	y	n
X-band SAR	n	n	n	n	n	n	n	y	y	n	n	y
Mass [kg]	2	3	33	45	51	71	128	150	181	138	168	218
Power [W]	12	8	33	105	45	112	210	1000	1027	138	168	1058
Total Max Data Rate [kbps]	232	24	764	291	238	567	10662	1101	1633	810	10900	1135
Platform size	S	S	M	M	L	L	L	L	L	L	L	L

TABLE X
WINNING ONION ARCHITECTURE FOR THE MARITIME MARINE WEATHER FORECAST USE-CASE.

Sat	LTAN [h]	M [°]	Type	Instruments
1	3	0	Large	SAR-X+Optical
2	3	180	Large	SAR-X+Optical
3	6	0	Small	GNSS-R
4	6	180	Small	GNSS-R
5	9	0	Large	SAR-X+Optical
6	9	180	Large	SAR-X+Optical
7	12	0	Small	GNSS-R
8	12	180	Small	GNSS-R
9	15	0	Large	SAR-X+Optical
10	15	180	Large	SAR-X+Optical
11	18	0	Small	GNSS-R
12	18	180	Small	GNSS-R
13	21	0	Large	SAR-X+Optical
14	21	180	Large	SAR-X+Optical
15	0	0	Small	GNSS-R
16	0	180	Small	GNSS-R

The final performance in terms of revisit time, latency, mass memory usage and DoD are presented in Tables XI to XIII.

TABLE XI
REVISIT TIME PERFORMANCE FOR THE DIFFERENT VARIABLES OF THE OMWF USE-CASE AND THE OPTIMAL SELECTED ARCHITECTURE

Revisit Time [h]	Ocean Currents	Wind speed	Wave height	Wave direction	Sea surface temperature	Atmospheric pressure	Sea ice coverage
Requirement	<24	<24	<3	<3	<24	<24	<3
Maximum	7	2.5	2.5	7	11	11	2.5
Average	2.1	0.7	0.7	2.1	0.5	0.5	0.4

TABLE XII
LATENCY PERFORMANCE FOR THE DIFFERENT VARIABLES OF THE OMWF USE-CASE AND THE OPTIMAL SELECTED ARCHITECTURE

Data Latency [h]	Ocean Currents	Wind speed	Wave height	Wave direction	Sea surface temperature	Atmospheric pressure	Sea ice coverage
Requirement	<1	<1	<1	<1	<1	<1	<1
Maximum	0	1.4	1.4	0	1.4	1.4	1.4
Average	0	~0	~0	0	~0	~0	~0

TABLE XIII
MASS MEMORY AND POWER PERFORMANCE FOR THE DIFFERENT VARIABLES OF THE OMWF USE-CASE AND THE OPTIMAL SELECTED ARCHITECTURE

	Mass Memory [MByte]	Depth of Discharge [%]
Requirement	<256	<20
Maximum	126	10
Average	65	5

D. FINAL ARCHITECTURE DESIGN

The detailed OMWF mission analysis of the winning architecture has included the communications architecture, taking into account different RF and Optical ISLs per platform type and the trade-off between different network protocol architectures [16]. Refined data flow and power budget analysis have been performed (not presented). Moreover, a detailed assessment of the Delta-V and fuel budget analysis is included for: a nominal orbit acquisition composed by correction of launcher injection errors, and acquisition of nominal satellite position inside the constellation, orbit maintenance to control the orbit altitude, collision avoidance to avoid collision with space debris objects, and End-of-Life (EOL) Disposal to comply with EOL guidelines (Tables XIV and XV). This is important as nowadays most small (nano-) satellites, namely CubeSats, do not have orbit control capabilities, and this feature will drive important design considerations for the small platform nodes.

TABLE XIV
REFERENCE PARAMETERS USED IN THE DETAILED DESIGN

Reference orbit	14+7/27 (around 800 km)
Launch date	1st July, 2022
Mission lifetime	S/C Heavy Platform: 4.5 years S/C Small Platform: 1.5 years
The S/C configuration is modelled with a constant effective drag area.	The value depends on the platform type: - S/C Heavy Platform: 10 m^2 - S/C Small Platform: 0.1 m^2 - Drag coefficient (CD): 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

TABLE XV
ΔV AND MASS BUDGETS FOR THE LARGE AND SMALL NODES

Platform	Large	Small
Nominal Orbit Acquisition ΔV [m/s]	18.2	18.2
Orbit phasing ΔV [m/s]	3.1	3.1
In-plane orbit 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 Budget 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

5. CONCLUSIONS AND FUTURE RESEARCH LINES

This manuscript has described the process from the definition of the use-case to the selection of an optimal satellite system architecture fulfilling the requirements. The analysis has been based on the recommendations of the ONION project User Advisory Board focusing on the Marine Weather Forecast (OMWF) use-case.
The following steps have been addressed:

- Selection of the payloads adapted to the OMWF use-case, to be used in the simulations.
- Tradespace exploration process, during which a design space has been generated and different architectures evaluated based on a coarse performance model.
- Pre-selection of a reduced set of candidate architectures from the whole design space.
- Different simulations are performed on these candidate architectures to define the best one. Those simulations include downlink and inter-satellite link simulations, as well as mission and system simulations.

Based on these results, the final architecture has been selected, and it has been analyzed in detail, including orbit control requirements, which is important for the small satellites.

As it has been seen, most of the payloads in the OMWF use-case can also address some of the needs of other use-cases, and in particular for Artic sea ice monitoring and Maritime Fishery Pressure and Aquaculture use-cases it can be interesting to examine to which extent the ONION infrastructure could be used for these other applications as well.

For the Arctic sea ice monitoring use-case the area of interest corresponds to the same one as for the OMWF. Strict revisit time requirements are only fulfilled for some of the measurements, maximum data latency is on the order of an orbital period, and constraints on the maximum on-board memory and DoD are fulfilled.

For the Maritime Fishery Pressure and Aquaculture, the area of interest includes the sea over latitude 60° N and the Western Indian Ocean. However, vessels cannot be tracked because of lack of an appropriate instrument in the OMWF (only medium-resolution optical instruments are available). Revisit time requirements, maximum on-board memory and DoD are fully satisfied, and the maximum latency are on the order of an orbital period as for the OMWF.

Table XVI summarizes the requirements that are met, those that are partially met, and those that are not feasible for this combined "Polar Marine Weather Forecast" mission, formed by the combination of the Marine Weather Forecast, Sea Ice Monitoring, and Marine Fisheries use-cases.

The extension to other use-cases, such as the OAHS one would require an L-band microwave radiometer payload that is not present in the OMWF one and, with today's technology, would require a large array (either real or synthetic).

Future DSS developments will greatly benefit from payload fractionation, but this requires the development of high speed inter-satellite links for data exchange and clock synchronization to create such large synthetic and real aperture arrays for high resolution imaging at low microwave frequencies. Also, the development of new unfocused InSAR instruments with coarse resolution for ocean applications possibly with on board processing will reduce the data downlink requirements. Finally, the development of more compact GNSS-R [17] and multispectral/hyperspectral imagers with spatial resolution below 1 km in the TIR and ~10 m in the VIS/NIR [18] will foster their use in small satellites (e.g. CubeSats). Moreover, the inclusion of network communications is still a research line hat shall be addressed in the near future in order to deploy efficient heterogeneous FSSs.

TABLE XVI
REQUIREMENTS MET, PARTIALLY MET, AND NOT FEASIBLE FOR THE POLAR USE-CASES

	Requirements met	Requirements partially met	Requirements not feasible
Marine Weather Forecast	Horizontal wind speed over sea Significant wave height Dominant wave direction Sea surface temperature Atmospheric pressure at sea level	Ocean surface currents Percentage of sea ice cover	Percentage of sea ice cover
Sea Ice Monitoring	Horizontal wind speed over surface Significant wave height Dominant wave direction Sea surface temperature Atmospheric pressure at sea level	Sea Ice drift Sea Ice extent Iceberg tracking Sea ice thickness Sea ice classification	
Marine Fisheries	Ocean Colour radiometry Ocean surface Chlorophyll Sea surface temperature Atmospheric pressure at sea level Coloured Dissolved (Organic) Matter		Vessels and fish farming cages, position tracking.

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Earth and Space sciences to find novel solutions for managing natural resources and addressing environmental challenges.

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