Conclusions of the Review of Candidate Locations for Copernicus Ocean Colour System Vicarious Calibration Infrastructure

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EUMETSAT
Eumetsat-Allee 1, D-64295 Darmstadt, Germany
Tel: +49 6151 807-7
Fax: +49 6151 807 555
http://www.eumetsat.int

Co-authors/Contributors

Name	Organisation
Ewa Kwiatkowska	EUMETSAT
K.N. Babu – Expert Review Board	ISRO
Bojan Bojkov	EUMETSAT
David Dessailly	EUMETSAT
Richard Gilmore – Expert Review Board, EC Observer	EC
Philippe Goryl – Expert Review Board	ESA
Juan Ignacio Gossn	EUMETSAT
Fabienne Jacq – Expert Review Board, EC Observer	EC
Carol Johnson – Expert Review Board	NIST
Frédéric Mélin – Expert Review Board	JRC
Estelle Obligis	EUMETSAT
Antonio Reppucci – Expert Review Board	CMEMS
Menghua Wang – Expert Review Board	NOAA
Giuseppe Zibordi – Expert Review Board	JRC

Change Record

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v.1	25/04/2022	Initial document
v.2	11/05/2022	Document draft for the Expert Review Board meeting on 17 May 2022
v.3	08/06/2022	Document update for internal review after the Expert Review Board meeting
v.4	20/06/2022	Document update for review by the Expert Review Board
v.5	27/07/2022	Final document

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1 INTRODUCTION

The purpose of this report is to summarize a scientific review and to provide a recommendation for the potential location of an Ocean Colour System Vicarious Calibration (OC-SVC) infrastructure in European sea waters. This infrastructure location has been investigated in support of the European Commission's Copernicus Programme.

OC-SVC is a fundamental requirement for all Ocean Colour missions [RD-1], [RD-2]. Ocean Colour sensors need concurrent System Vicarious Calibration to meet mission requirements [RD-3], [RD-4]. The goal of OC-SVC is to achieve sensor absolute radiometric calibration lower than 0.5% uncertainty, which is the condition to retrieve water reflectance and bio-optical products within the mission requirements. The driver for these requirements is a broad range of applications from climate to water quality to fisheries, where Ocean Colour provides a unique insight into Earth's biological carbon pump, living aquatic ecosystems and marine resources. Sensor absolute radiometric calibration lower than 0.5% cannot be however achieved through standard pre-launch and in-flight calibrations [RD-3, section 5.9]. The concurrent System Vicarious Calibration relies on in situ water reflectance measurements, which require SI traceability and the lowest achievable uncertainties of the complete OC-SVC process. The uncertainty contributions include the radiometric measurement, the controlled measurement procedure, and the environmental conditions of the measurement – from the water through the atmosphere and to the sensor. The target of this review was to find the best location in European waters that would minimise these OC-SVC uncertainties.

EUMETSAT manages OC-SVC infrastructure development activities for the Copernicus Programme on behalf of the European Commission. The goal is to achieve the best OC-SVC infrastructure for the upcoming 20 years for the benefit of the Copernicus Programme, strengthening Europe's autonomy for the calibration of the relevant Sentinels. The immediate target is securing the Copernicus OC-SVC capability and expertise for Sentinel-3 OLCI and the corresponding Next Generation sensors. However, the OC-SVC infrastructure could also be used for other current and planned Copernicus Sentinels and Expansion missions such as Sentinel-2, CHIME and other European and international missions with ocean colour goals or possibilities.

The Copernicus OC-SVC development activities follow a roadmap and a review process [RD-4]. The process is overseen by the European Commission and may go forward or be put on hold depending on the Copernicus programmatic decisions and the availability of funding.

The Copernicus OC-SVC infrastructure roadmap is composed of six phases, Figure 1. The current Phase 3 Infrastructure Location is indicated in red in Figure 1. All six phases are the following:

1. Scientific, Technical, Operational Requirements (completed)
2. Preliminary Design, Project Plan and Costing (completed)
3. Infrastructure Location (current activity)
4. Engineering Design, Detailed Technical Definition, Specifications
5. Development, Testing and Demonstration in the Field
6. Operations

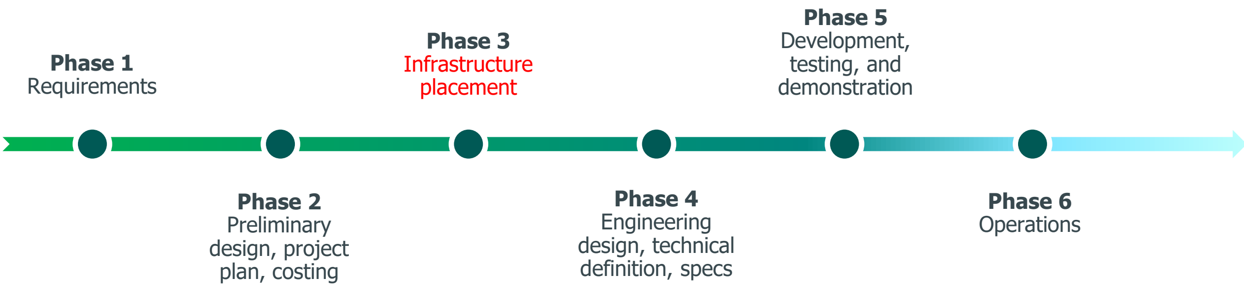

Figure 1: Copernicus OC-SVC infrastructure roadmap, the current report is the output of Phase-3.

At the end of each phase, a review process is conducted and a decision is made whether or not to start the next phase, which requires the approval of the European Commission procurement board. This decision is particularly important after Phase 4, because Phase 5 of the actual OC-SVC infrastructure development is associated with a significant and long-term commitment of the resources. Phases 5 and 6, implementing Development and Operations, particularly require a Copernicus programmatic decision to secure long-term funding.

The roadmap phases up to and including Phase-4 Engineering Design are planned as independent activities. Each of these phases is carried out as a separate Invitation to Tender open to the EU and Copernicus participating states. Input from previous phases is defined as applicable where required: for example, Phase-1 Requirements are applicable throughout all the phases.

The review process is supported by an international Expert Review Board that compiled this report together with EUMETSAT. Members of the Expert Review Board are: K.N. Babu (ISRO), Richard Gilmore (EC), Philippe Goryl (ESA), Fabienne Jacq (EC), Carol Johnson (NIST), Frederic Melin (JRC), Antonio Reppucci (CMEMS), Menghua Wang (NOAA), and Giuseppe Zibordi (JRC).

The location of the Copernicus OC-SVC infrastructure must meet the requirements defined in Phase-1 of the roadmap [AD-1]. The requirements specify the marine and atmospheric characteristics of the site that are needed to minimise the uncertainty budget of the OC-SVC process, the logistics of the site, and the capacity of the site to generate a large number of high-quality matchups with satellite data. Five regions across European waters were identified and investigated as candidate sites to host the OC-SVC infrastructure, Figure 2:

- BOUSSOLE: 43.366N, 7.9E
- Crete: MSEA-N: 35.74N, 25.07E; MSEA-S: 34N, 25E; Antikythera: 36.2N, 23.55E
- El Hierro: 27.5876N, 18.1573W
- Lampedusa: LMP1: 35.5N, 12.8E; LMP2: 35.75N, 12.35E; LMP3: 35.85N, 12.73E; LMP4: 35.78N, 13.07E
- Madeira: OPT: 32.62N, 17.27W; SOW: 32.25N, 17W.

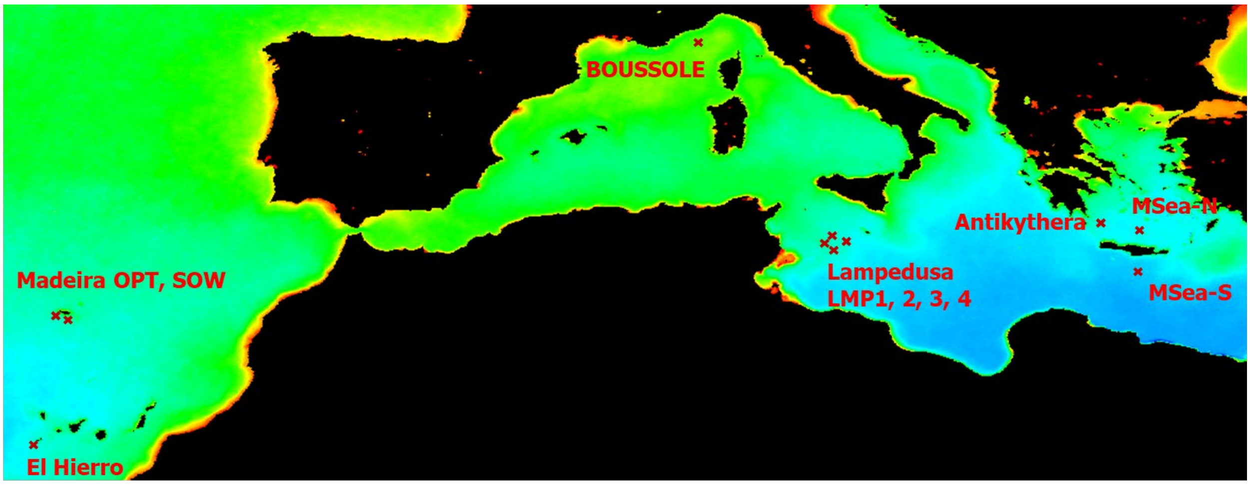

Figure 2: Copernicus OC-SVC infrastructure candidate locations.

Marine and atmospheric climatological characteristics as well as logistical and safety considerations of the five locations were investigated by five parallel studies conducted by regional institutes:

- BOUSSOLE – LOV-IMEV/ACRI-ST
- Crete – HCMR/Crete University
- El Hierro – IEO/AEMET
- Lampedusa – CNR/ENEA
- Madeira – IPMA

Reports and presentations from the five studies were assessed by the Expert Review Board and EUMETSAT and are available online [RD-5]. Additional information requested by the Board concerning the capacity of each site to generate OC-SVC matchups, further environmental and logistical inputs, and costing considerations for new sites not investigated in Phase-2, were also collected by EUMETSAT and further examined.

The goal of this review has been to identify the site or sites that meet the Copernicus OC-SVC Requirements defined in Phase-1 of the roadmap and to issue a recommendation to the Copernicus Programme. This report summarizes the conclusions of the Expert Review Board.

1.1 Scope

This report documents the conclusions of the scientific review process of the candidate locations for Copernicus OC-SVC infrastructure. The report records the high-level summary of the review. It also issues recommendations to the Copernicus Programme.

The review has been conducted by the Expert Review Board and EUMETSAT based on investigations, data and reports provided by the regional institutes associated with the candidate OC-SVC locations and additional information requested by the Board.

This report uses as a basis the detailed investigations of the candidate locations, data and reports from the five parallel studies, which are available online for reference [RD-5] and are not repeated here. For each of the candidate locations, the investigations include detailed marine and atmospheric climatological characterizations, logistical and safety considerations, capacities to generate OC-SVC matchups, as well as costing considerations and further environmental and logistics information for the new sites which were not covered in Phase-2.

Expert Review Board considerations and this report are based on the established foundations of the OC-SVC concept and the preceding phases of the Copernicus OC-SVC roadmap, particularly the Copernicus OC-SVC Phase-1 Requirements [AD-1]. This report describes only high-level considerations of the infrastructure location and readers are directed to the study documentation for details [RD-5].

This review solely addresses the selection of the Copernicus OC-SVC infrastructure location (Phase-3 of the roadmap). Types of the infrastructure were considered and reviewed during the Preliminary Design (Phase-2). The recommendations on the location (Phase-3) and the design of the infrastructure (Phase-2) are separate. These recommendations are also independent of the teams who championed them. The next phase of the roadmap (Phase-4 Engineering Design) is planned as an Invitation to Tender, open to all bidders qualified under the EU Copernicus Programme.

1.2 Applicable Documents

	Document Title	**Reference**
AD-1	Requirements for Copernicus Ocean Colour Vicarious Calibration Infrastructure	*https://www.eumetsat.int/OC-SVC-requirements*

1.3 Reference Documents

	Document Title	Reference
RD-1	McClain, C. R. and G. Meister (eds.), "Mission Requirements for Future Ocean-Colour Sensors"	Reports of the International Ocean-Colour Coordinating Group (IOCCG), No. 13, Dartmouth, Canada, https://ioccg.org/what-we-do/scientific-working-groups/report13
RD-2	White Paper of International Network for Sensor Inter-comparison and Uncertainty assessment for Ocean Colour Radiometry (INSITU-OCR)	CEOS Ocean Colour Radiometer – Virtual Constellation, https://ioccg.org/wp-content/uploads/2016/02/INSITU-OCR-white-paper.pdf
RD-3	Donlon C., "Sentinel-3 Mission Requirements Traceability Document (MRTD)"	EOP-SM/2184/CD-cd, https://download.esa.int/docs/EarthObservation/GMES_Sentinel-3_MRTD_Iss-1_Rev-0-issued-signed.pdf
RD-4	Copernicus Ocean Colour System Vicarious Calibration Infrastructure	https://www.eumetsat.int/OC-SVC
RD-5	Infrastructure Location	https://www.eumetsat.int/OC-SVC-locations
RD-6	Zibordi, G., F. Mélin, K.J. Voss, B.C. Johnson, B. Franz, E. Kwiatkowska, J-P. Huot, M. Wang, and D. Antoine. "System vicarious calibration for ocean colour climate change applications: Requirements for in situ data"	Remote Sensing of Environment, 159: 361-369, 2015, https://doi.org/10.1016/j.rse.2014.12.015
RD-7	Zibordi, G., and F. Mélin. "An evaluation of marine regions relevant for ocean color system vicarious calibration"	Remote Sensing of Environment, 190: 122-136, 2017, https://doi.org/10.1016/j.rse.2016.11.020
RD-8	Ocean Colour system vicarious calibration tool	https://www.eumetsat.int/ocean-colour-system-vicarious-calibration-tool
RD-9	Preliminary design, project plan & costing for Copernicus OC-SVC infrastructure	https://www.eumetsat.int/OC-SVC-plans
RD-10	Potential for multi-mission matchups at candidate sites for Copernicus OC-SVC infrastructure location	https://www.eumetsat.int/OC-SVC-locations
RD-11	Standardized Extraction Data Base workflow to perform OC-SVC matchups and retrieve statistics	https://gitlab.eumetsat.int/OC/External/edb
RD-12	Ocean colour services	https://www.eumetsat.int/ocean-colour-services
RD-13	Sentinel-3 OLCI L2 Ocean Colour Collection-3 Report	https://www.eumetsat.int/media/47794
RD-14	Cloud cover comparison for the OC-SVC candidate sites	https://www.eumetsat.int/OC-SVC-locations
RD-15	Sentinel-2 MSI coverage of the OC-SVC candidate sites	https://www.eumetsat.int/OC-SVC-locations

RD-16	Morel A. and B. Gentili, "The dissolved yellow substance and the shades of blue in the Mediterranean Sea"	Biogeosciences, 6, 2625–2636, 2009, https://doi.org/10.5194/bg-6-2625-2009
RD-17	Wave climate for 12 locations	https://www.eumetsat.int/OC-SVC-locations
RD-18	El Hierro volcano impact	https://www.eumetsat.int/OC-SVC-locations
RD-19	Costing comparison for the new OC-SVC candidate sites	Available only to the Expert Review Board

1.4 Terminology

Acronyms and Abbreviations

Acronym/Abbr.	Explanation
AIS	Automatic Identification System
AOP	Apparent Optical Properties of water
AOT	Aerosol Optical Thickness
CDOM	Coloured Dissolved Organic Matter
CF	Cloud Fraction
EC	European Commission
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA5	Reanalysis v5 Atmospheric products from ECMWF
ESA	European Space Agency
CHIME	Copernicus Hyperspectral Imaging Mission for the Environment
CMEMS	Copernicus Marine Environment Monitoring Service
CNR/ENEA	Italian National Research Council/National Agency for New Technologies, Energy, and Sustainable Economic Development
CV	Coefficient of Variation
DJF	December, January, February
GRASP	Generalized Retrieval of Aerosol and Surface Properties
HCMR	Hellenic Centre for Marine Research
HRES	High Resolution Forecast from ECMWF
IEO/AEMET	Spanish Institute of Oceanography/State Meteorological Agency
IOP	Inherent Optical Properties of water
IPMA	Instituto Português do Mar e da Atmosfera
ISRO	Indian Space Research Organisation
JRC	Joint Research Centre of the European Commission
L2	Level-2
LOV/IMEV/ACRI-ST	Laboratoire d'Océanographie de Villefranche/Institut de la Mer de Villefranche/ACRI-ST
JJA	June, July, August
MAM	March, April, May
MERRA-2	Modern-Era Retrospective analysis for Research and Applications, Version 2, of aerosols and meteorogical information, from NASA
MM5	Fifth Generation Mesoscale Model from Penn State University and the National Center for Atmospheric Research in the USA
MOBY	Marine Optical BuoY
MODIS	Moderate Resolution Imaging Spectroradiometer
MSI	MultiSpectral Instrument
NASA	National Aeronautics and Space Administration in the USA
NIST	National Institute of Standards and Technology in the USA
NOAA	National Oceanic and Atmospheric Administration in the USA
NPP	National Polar-orbiting Partnership
NIR	Near infra-red
OC-CCI	Ocean Colour Climate Change Initiative of the European Space Agency
OC-SVC	Ocean Colour System Vicarious Calibration
OLCI	Ocean and Land Colour Instrument
OPT	Optional site for the Madeira location
OZA	Observation Zenith Angle
POLDER	Polarization and directionality of Earth reflectances
ROM	Rough Order of Magnitude
S3	Sentinel-3
SEVIRI	Spinning Enhanced Visible and InfraRed Imager

SON	September, October, November
SOW	Statement of Work
SI	International System of Units
SZA	Solar Zenith Angle
VIIRS	Visible Infrared Imaging Radiometer Suite
WSSF	Winter, Spring, Summer, Fall

Definitions

Definition/Term	Explanation
τ	AOT in the green wavelength, typically at 550 nm (but also at 500 nm), unless otherwise stated
α	Aerosol Ångström exponent computed between the blue and the near infra-red wavelengths, unless otherwise stated
ρ_w(x nm)	water reflectance at band x nm [dimensionless]
Chl	chlorophyll-a concentration [mg/m^3]
Rrs	water remote sensing reflectance [1/sr]
CV	CV = Standard Deviation / Mean x 100%

2 LOCATION REQUIREMENTS AND SELECTION CRITERIA

The location of Copernicus OC-SVC infrastructure in European sea waters must be based on solid scientific evidence that is justifiable to data users, data services and the global ocean colour community, and must ensure value for money for the European Commission's Copernicus Programme.

The location must ensure the European capability and expertise for a state-of-the-art, autonomous and dependable OC-SVC source. The location must fulfil the OC-SVC requirements spanning the decades of the Copernicus Programme, including its upcoming Next Generation and Expansion missions. The Copernicus OC-SVC infrastructure should drive the highest quality operational OC observations and data services from the Copernicus Programme and international missions. The location shall satisfy the climate-science requirements of the OC missions, and uphold the quality of data suitable for global and regional monitoring, forecasting and alerting on water quality, aquatic ecosystems, bio-geochemistry and the implementation of marine and environmental policies.

To fulfil these goals, the location must demonstrate the optimal marine, atmospheric, environmental and logistical conditions as well as the capacity to generate a large number of OC-SVC matchups, as defined in the Phase-1 Requirements of the roadmap [AD-1].

The Requirements are driven by the uncertainty budget of the complete OC-SVC process, from the in situ radiometric measurements to the computation of mission-specific vicarious calibration gains, which is defined by strictly following metrological principles and SI traceability [RD-6]. Environmental, marine and atmospheric conditions of an in situ radiometric measurement at a given location can largely contribute to the total uncertainty budget [RD-7]. Specific weather and logistical conditions may promote or inhibit the suitability of a site. The variability of the site conditions, either seasonal, diurnal or long-term, may contribute to further uncertainties. Furthermore, the uncertainties associated with the site location are closely intertwined with all other components of the total uncertainty budget, including the field infrastructure (deployment platform, radiometers, the range of water reflectance signal, measurement procedures, environmental effects), data processing, and operations and maintenance processes.

The guiding strategy of the candidate OC-SVC location review process has been established as:

- define mandatory selection criteria and focus on them, and
- issue a recommendation on the site location, prioritising the highest ranking locations in order to have a backup in case the implementation needs to be moved from one top site to the other.

The following mandatory criteria have been selected for the Copernicus OC-SVC infrastructure location:

- number of potential high quality matchups with satellite missions
- cloud cover
- chlorophyll and water reflectance
- aerosol optical thickness and aerosol type
- physical safety, traffic, hurricanes
- seismic or volcanic activity

- logistics and existing supporting infrastructures
- communication links
- waves/winds, currents
- bathymetry

Additionally, the cost of establishing and operating a location has been considered as a critical aspect for the Copernicus OC-SVC infrastructure. The costs may vary across the sites. Nevertheless, it was agreed that if the costing of the individual locations is within a similar rough order of magnitude range, the costing details would not be used as a mandatory criterion. In this case, the emphasis should remain on the robustness of the scientific selection process.

2.1 Potential of a location for OC-SVC high quality matchups with satellite missions

The major mandatory selection criterion was defined to be the site's capacity to produce high quality matchups with satellite missions. In particular:

- a large set of matchups is required,
- matchups are to be well spread throughout the four seasons of the year to limit any possible seasonal biases in the OC-SVC gains.

Consequently, a comprehensive analysis was required of multi-year and multi-mission matchup potential for all candidate Copernicus OC-SVC sites and NOAA's MOBY, as a reference existing global OC-SVC source. The matchup strategy included Copernicus and international missions.

The matchups must be high quality and based on the matchup protocol defined for the OC-SVC gain derivation [RD-8]. The OC-SVC standard screening matchup protocol is specifically dedicated to the OC-SVC and is significantly stricter than validation protocols.

It is however highlighted that the statistics of the site potential to generate high quality matchups should be used with caution for two main reasons:

- The matchup statistics are based on the existing agencies' operational Level-2 products. The Level-2 processing may evolve in the future. Therefore, the matchup potential and future matchup projections should be evaluated in combination with the actual site characteristics, which are available from the independent climatological marine and atmospheric mandatory criteria defined in section 2.2,
- The matchup extractions assume the standard community OC-SVC screening protocol, matching the one used for S3 OLCI OC-SVC gain derivation [RD-8]. The numbers of actual matchups will change if other or stricter screening criteria are applied. The number of matchups could also change when the actual OC-SVC infrastructure is operational and the screening is implemented on the real OC-SVC in situ measurements.

2.2 Marine and atmospheric criteria

To ensure the state-of-the-art and autonomous Copernicus OC-SVC capability, the location of the OC-SVC infrastructure must be based on solid scientific evidence with respect to marine and atmospheric criteria. This requires optimal marine and atmospheric conditions at the site, to enable the lowest uncertainty budget of the complete OC-SVC process.

The indication of the optimal marine and atmospheric conditions is indirectly included in sites' capacity to generate OC-SVC matchups with satellite missions. Nevertheless, the statistics on the numbers of matchups have limitations, as defined in section 2.1. The matchup statistics are based on the standard Level-2 ocean colour products and are therefore strongly dependent on the skill of the existing processing chains. Because the Copernicus OC-SVC infrastructure is envisioned to serve for the coming 20+ years of the Copernicus Programme, including the Next Generation and Expansion missions, the marine and atmospheric characteristics at the site must remain the most optimal for future processing evolutions and future sensors. The conditions at the site must therefore fulfil strict climatological requirements to ensure that marine and atmospheric parameters will secure the infrastructure's state-of-the-art operations into the future and will minimize the OC-SVC uncertainty budget.

The marine and atmospheric conditions impact the uncertainty budget of the OC-SVC process in many ways:

- the complexity of the radiative transfer modelling, required for ocean colour water reflectance retrievals, increases with more complex in-water conditions and in non-purely maritime atmospheres;
- seasonal, diurnal or long-term variabilities of the site conditions contribute to the uncertainties if they are not minimal;
- the site conditions impact the other elements of the OC-SVC total uncertainty budget, for example they are transferred to
    - field infrastructure uncertainties (e.g. the in-water radiometers must be developed, calibrated and characterised to the prevailing marine conditions and the range of signal at the site, and must adopt dedicated measurement procedures),
    - data processing uncertainties (e.g. correction uncertainties increase with more complex site conditions), and
    - operations and maintenance uncertainties (e.g. optics cleaning, recalibrations);
- some atmospheric and marine state conditions may even inhibit the suitability and safety of a site (e.g. clouds, dust, waves, currents, hurricanes).

Please refer to the Requirements document from Phase-1 of the roadmap for details and uncertainty estimates.

The mandatory selection criteria for marine and atmospheric conditions at a site are defined in Table 1.

Parameter	Selection criteria
cloud cover	- low, per season/month/day, high persistence of cloud free conditions - statistic: number of days per year where fractional cloud cover is ≤ 0.1
chlorophyll-a concentration	- stable daily/monthly/seasonally and spatially homogeneous - statistic: Chl < 0.2 mg/m^3
radiometric variability	- low seasonal, diurnal and long-term variability in water spectra - statistic: optical range distributions: single peak, seasonal histograms
aerosol optical thickness	- stable and spatially uniform - statistic: τ(550 nm) < 0.15

aerosol type	- only quantified and limited episodes of dust, biomass burning, pollution aerosols
	- statistics:
	  - number of days per year of unfavourable aerosol outbreaks
	    • dust: $\tau \geq 0.15$ and $\alpha \leq 0.5$

	• biomass-burning and urban/industrial particles: $\tau \geq 0.1$ and $\alpha \geq 1.5$ • small urban-type aerosols: $\alpha > 1$
currents	- no major currents in the vicinity - low to minimise buoy tilt
waves, winds	- low wave height, no wave anomalies, low frequency of swells - low surface wind to minimise hydrosol advection, per season/month/day

Table 1: Mandatory selection criteria for marine and atmospheric conditions at a site

In addition to the mandatory criteria, other marine and atmospheric conditions have been investigated. They included water bio-optical properties of absorption and backscattering (i.e. Inherent Optical Properties) by Coloured Dissolved Organic Matter (CDOM) and particulates, sea surface temperature and salinity, atmospheric gases like ozone, water vapour and NO_2, atmospheric pressure, solar illumination, as well as prevailing marine and atmospheric circulation patterns. The complete corresponding material is available in [RD-5].

2.3 Logistical and safety criteria

The location of Copernicus OC-SVC infrastructure must be suitable with respect to the logistics of site operations, from day-to-day activities to long-term maintenance. The site must be in a safe location with respect to the safety of humans and the natural environment, away from maritime traffic, hurricane paths, and seismic, volcanic or fire sources. Access to qualified personnel at the site and existing supporting infrastructures, like atmospheric and marine observatories, can be beneficial.

Logistical and safety criteria must therefore ensure that the Copernicus OC-SVC investment is secure and dependable, along with providing the state-of-the-art and autonomous OC-SVC capability. If a site location is ill-chosen, it may endanger the valuable infrastructure itself or may hinder its operations, which are required to be fully functional on a daily basis. The uncertainty budget of the OC-SVC process may also be impacted by logistical issues and reduce the infrastructure's value for money for the Copernicus Programme.

The mandatory selection criteria for logistical and safety considerations of the site are defined in Table 2.

Parameter	Selection criteria
logistics and existing supporting infrastructures	- distance from land maximised within the site logistical constraints - distance within easy ship journey, accessible quickly in case of emergency - nearby port, divers, workshops to support field maintenance operations - nearby facility to support storage, maintenance and calibration operations - existing supporting infrastructures are an advantage, e.g. atmospheric and marine observatories - availability of local qualified personnel is an advantage
communication links	- high volume data communication links between the in-water infrastructure and land, and the land, the 'Ground Segment' and the data dissemination point

bathymetry	- depth > 800 m, low sea floor slope
traffic	- minimal impact from maritime traffic - statistics: nearby shipping routes, and fishing and recreational traffic density
physical safety	- hurricanes / medicanes, statistics: frequency, intensity and trends - site protection in the field: placement on nautical charts, beacons, etc.
seismic or volcanic activity	- none in the vicinity of the site or no impact on the site

Table 2: Mandatory selection criteria for logistical and safety considerations of the site

In addition to the mandatory criteria, other logistical and safety considerations of the site have been investigated. They included surrounding land and urban and industrial areas in terms of topography, vegetation and anthropogenic activities, airline routes and airline traffic density for contrail pollution and fire occurrences on nearby land. The complete corresponding material is available in [RD-5].

2.4 Location cost considerations

A critical aspect for the Copernicus OC-SVC infrastructure was defined to be the cost of establishing and operating the infrastructure at a given site. The location must ensure the best value for money for the Copernicus Programme.

Rough Order of Magnitude (ROM) costing spreadsheets were provided as a part of Phase-2 of the roadmap, Preliminary Design, for Phases 4, 5, and 6, i.e. Engineering Design, Development and Operations, respectively. These spreadsheets were for two designs of Copernicus OC-SVC infrastructure [RD-9]:

- ROSACE – a combined infrastructure at BOUSSOLE (F, Ligurian Sea) and Crete MSEA-N (Gr, Sea of Crete) locations;
- EURYBIA – a single infrastructure at Lampedusa LMP1 location (I, Central Mediterranean).

This Phase-3 Location study investigated additional OC-SVC candidate sites, where the costing was not previously available.

To ensure the best value for money for the Copernicus Programme, the costing of the new OC-SVC candidate sites was evaluated to ensure that they were not prohibitive and within the ROM of those locations already investigated.

The Expert Review Board prioritised additional costing information for the following new locations:

- Antikythera,
- MSEA-S,
- LMP2,
- LMP3,
- LMP4, and
- El Hierro.

The ROM costing for the new locations is available as a relative difference value from the existing costing from the Phase-2 Preliminary Design.

3 POTENTIAL OF CANDIDATE OC-SVC LOCATIONS FOR HIGH QUALITY MATCHUPS

The major mandatory criterion for the Copernicus OC-SVC infrastructure location was defined to be the potential of the site to generate a large number of high quality matchups with satellite missions. The matchups must also be evenly spread throughout the year to limit any possible seasonal biases in the OC-SVC gains.

Following the Expert Review Board recommendation, the analyses of the matchup potential used multi-year and multi-mission datasets and the standard matchup screening protocol for OC-SVC gain derivation. Both Copernicus and international ocean colour missions were investigated: Sentinel-3 OLCI, Aqua MODIS, Suomi-NPP VIIRS and, partly, Sentinel-2 MSI. The main statistics are average numbers of potential matchups per year, season and month over all proposed candidate locations and MOBY as a reference.

The matchup analyses are provided in [RD-10]. Standardised python scripts to replicate the satellite extractions, the screening procedures, and statistics computations were also available to the Expert Review Board [RD-11].

For OLCI, the Level-2 operational product time series from Collection-3 processing was investigated, OL_L2M.003.01 [RD-12], [RD-13], at the full spatial resolution (FR) of 300 m. For MODIS-Aqua and VIIRS Suomi-NPP, standard NASA Level-2 operational products were used, extracted in July 2021:

- OLCI-A [OL_L2M.003.01]: April-2016 to July-2021 - EUMETSAT
- OLCI-B [OL_L2M.003.01]: April-2018 to July-2021 - EUMETSAT
- MODIS Aqua [standard]: January-2005 to Dec-2009 - NASA
- VIIRS Suomi-NPP [standard]: January-2013 to Dec-2020 - NASA

The standard community matchup protocol for OC-SVC gain derivation was used to generate high quality extractions over the candidate locations. The protocol is available in [RD-10] and in [RD-8] for OLCI.

The OC-SVC screening criteria applied for OLCI are repeated below:

- Window size = 5 × 5;
- SZA < 70^0 and OZA < 56^0 (OLCI viewing geometry is limited to 56^0 and always meets the OZA threshold);
- Flags = CLOUD, CLOUD_AMBIGUOUS, CLOUD_MARGIN, INVALID, COSMETIC, SATURATED, SUSPECT, HISOLZEN, MEGLINT, HIGHGLINT, SNOW_ICE, WHITECAPS, ANNOT_ABSO_D, ANNOT_MIXR1, ANNOT_TAU06;
- Number of valid pixels = 25 (100%) [valid: non-flagged, low zeniths];
- CV[ρ_w(412, 443, 490, 510, 560 nm)] < 15%;
- $\tau < 0.15$;
- Chl < 0.2 mg/m^3;

where

- τ = Aerosol optical thickness at 865 nm,
- Chl = OLCI chlorophyll-a algorithm is a combination of the Colour Index (CI) and the OC4ME approach [RD-13].

The same criteria were applied for MODIS Aqua and VIIRS Suomi-NPP, using the wavelengths closest to the OLCI bands and the corresponding flag definitions. For MODIS:

- Window size = 5 × 5;
- SZA < 70^0 and OZA < 60^0;
- Flags = ATMFAIL, LAND, HIGLINT, HILT, HISATZEN, STRAYLIGHT, CLDICE, COCCOLITH, HISOLZEN, LOWLW, CHLFAIL, NAVWARN, MAXAERITER, CHLWARN, ATMWARN, SEAICE, NAVFAIL, ABSAER, MODGLINT;
- Number of valid pixels = 25 (100%) [valid: non-flagged, low zeniths];
- CV[ρ_W(412, 443, 488, 531, 547 nm)] < 15%;
- τ < 0.15;
- Chl < 0.2 mg/m^3;

where

- τ = Aerosol optical thickness at 869 nm,
- Chl = MODIS OCI chlorophyll-a algorithm.

Sensitivity analyses have also been conducted, by varying some of the above thresholds or flag selections, to evaluate the robustness of the matchup statistics for the candidate OC-SVC sites.

3.1 Summary of results of the high quality matchup potential with global ocean colour missions

Detailed analyses of the candidate locations to generate high quality matchups with an OC-SVC infrastructure are provided in [RD-10]. As highlighted in section 2.1, the actual matchup numbers are expected to change. The change may be driven by evolution of the Level-2 product algorithms or application of other or stricter screening criteria. Additionally, the screening will be implemented on the OC-SVC in situ measurements. Based on the current OLCI OC-SVC gain experience [RD-8], the actual matchup numbers may be lower. Therefore, the current results should be considered with caution.

Figure 3 displays distributions of average numbers of potential matchups for the four satellite missions across the twelve months of a year.

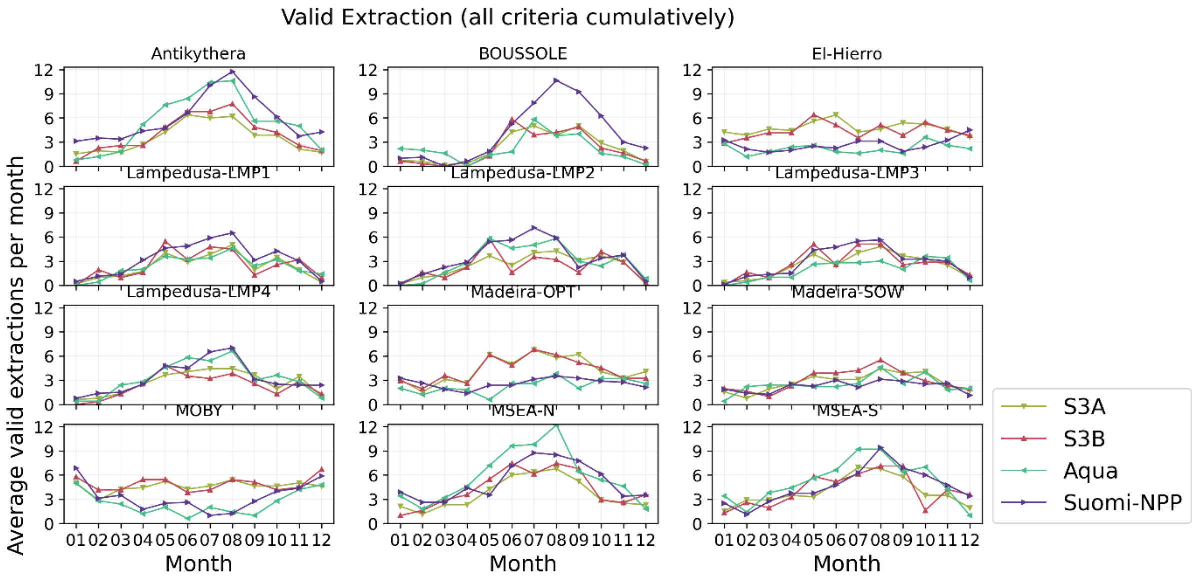

Figure 3: Distributions of average numbers of potential matchups for the four satellite missions across the twelve months of a year.

Tables 3-6 give the average numbers of potential matchups for the four satellite missions for the four seasons and the full year.

	Average number of potential matchups for OLCI-A											
Seasons/ Sites	Antikythera	BOUSSOLE	El-Hierro	LMP1	LMP2	LMP3	LMP4	Madeira-OPT	Madeira-SOW	MOBY	MSEA-N	MSEA-S
DJF	5.2	1.9	11.8	1.5	1.3	1.9	2.3	8.7	4.1	12.6	5.6	6.4
MAM	8.7	2.1	14.7	6.9	7.3	7.1	7.5	12	7.9	13.9	8.9	9.7
JJA	18.6	13.1	15.3	11.8	10.8	11.4	12.9	17.6	10.6	14.3	19.1	18.7
SON	9.9	9.9	15.3	7.3	9.6	9.4	9.1	13.5	10.2	14.3	10.6	12.8
Yearly	**42.3**	**27**	**57**	**27.6**	**29.1**	**29.9**	**31.8**	**51.8**	**32.9**	**55.1**	**44.3**	**47.5**

Table 3: Average number of potential matchups for OLCI-A for the four seasons. The colours indicate the matchup number ranking, from the highest in green to the lowest in red.

	Average number of potential matchups for OLCI-B											
Seasons/ Sites	Antikythera	BOUSSOLE	El-Hierro	LMP1	LMP2	LMP3	LMP4	Madeira-OPT	Madeira-SOW	MOBY	MSEA-N	MSEA-S
DJF	4.8	1.6	10.2	2.9	1.9	2.9	1.6	8.1	5.5	16.6	6.1	7.4
MAM	10.0	1.3	14.7	8.0	8.9	8.6	8.6	12.3	7.1	15.0	12.0	11.0
JJA	21.3	13.9	13.8	12.5	8.3	12.8	10.5	17.8	13.6	13.4	21.0	18.4
SON	11.6	8.7	13.8	7.0	8.6	8.3	6.7	13.0	9.1	13.8	12.3	12.9

Yearly	**47.8**	**25.6**	**52.5**	**30.4**	**27.8**	**32.6**	**27.5**	**51.2**	**35.3**	**58.8**	**51.4**	**49.8**

Table 4: Average number of potential matchups for OLCI-B for the four seasons. The colours indicate the matchup number ranking, from the highest in green to the lowest in red.

	Average number of potential matchups for Aqua MODIS											
Seasons/ Sites	**Antikythera**	**BOUSSOLE**	**El-Hierro**	**LMP1**	**LMP2**	**LMP3**	**LMP4**	**Madeira-OPT**	**Madeira-SOW**	**MOBY**	**MSEA-N**	**MSEA-S**
DJF	4.0	4.4	6.2	1.8	1.0	1.0	1.6	5.8	4.6	12.6	7.0	5.8
MAM	14.6	3.0	6.8	7.4	10.2	4.6	9.8	4.4	7.0	5.6	15.0	13.8
JJA	29.4	11.4	5.4	11.2	15.4	8.6	17.8	9.0	9.4	4.0	31.6	25.0
SON	16.2	6.8	7.8	7.4	9.2	9.0	9.4	8.4	8.4	8.0	16.4	17.6
Yearly	**64.2**	**25.6**	**26.2**	**27.8**	**35.8**	**23.2**	**38.6**	**27.6**	**29.4**	**30.2**	**70.0**	**62.2**

Table 5: Average number of potential matchups for Aqua MODIS for the four seasons. The colours indicate the matchup number ranking, from the highest in green to the lowest in red.

	Average number of potential matchups for Suomi-NPP VIIRS											
Seasons/ Sites	**Antikythera**	**BOUSSOLE**	**El-Hierro**	**LMP1**	**LMP2**	**LMP3**	**LMP4**	**Madeira-OPT**	**Madeira-SOW**	**MOBY**	**MSEA-N**	**MSEA-S**
DJF	10.9	4.4	9.9	2.1	2.1	2.3	4.5	8.0	4.4	15.9	10.0	7.0
MAM	12.5	2.5	6.3	9.1	10.5	7.3	8.8	5.6	6.0	7.8	10.5	10.3
JJA	28.4	23.8	8.5	17.3	18.6	15.9	18.0	9.0	8.3	4.9	24.4	20.4
SON	18.5	18.5	7.5	10.4	9.4	9.5	8.0	8.9	8.0	11.1	17.3	17.6
Yearly	**70.3**	**49.1**	**32.1**	**38.9**	**40.6**	**34.9**	**39.3**	**31.5**	**26.6**	**39.6**	**62.1**	**55.3**

Table 6: Average number of potential matchups for Suomi-NPP VIIRS for the four seasons. The colours indicate the matchup number ranking, from the highest in green to the lowest in red.

The results indicate the largest numbers of potential matchups and the balanced annual distributions at:

- El Hierro and MOBY for OLCI-A and OLCI-B, with Madeira-OPT following closely after;
- the Crete sites for MODIS and VIIRS, although with a slightly poorer annual uniformity in the winter season.

The results are consistent between OLCI-A and OLCI-B, while inconsistent between OLCI, MODIS and VIIRS. For all the sites, both OLCI-A and -B yield a larger fraction of valid extractions (i.e. valid extractions divided by total overpasses) compared to VIIRS and MODIS. The inconsistency is the largest in the open ocean sites at El Hierro, MOBY and Madeira-OPT, where OLCI records the largest number of potential matchups and balanced annual distributions, but MODIS and VIIRS show low matchup numbers. The VIIRS results are particularly divergent. From MODIS and VIIRS experience, the MOBY result is consistent with the low numbers of matchups typically obtained in spring and summer seasons due to sun glint. The largest number of potential matchups for MODIS and VIIRS are at the Crete sites, which are the second to best for OLCI.

The OLCI matchup differences with MODIS and VIIRS may be explained by differences in Level-2 processing between the missions, in particular the flagging, and by a larger number of MODIS and VIIRS extractions being affected by scattered clouds and removed during the matchup screening, as well as by the bow-tie deletion effect in VIIRS, see 'Extra slides' in [RD-10]. MODIS and VIIRS may have stricter cloud screening than OLCI, which has a greater effect at particular locations. For example, for El Hierro, about 20% of OLCI extractions versus 40% of MODIS or VIIRS extractions are eliminated by cloud masking, see slide 22 in [RD-10]. Additionally, the effect of scattered clouds increases with the decrease in the spatial resolution of a sensor, thus impacting MODIS and VIIRS more than OLCI, and the open ocean locations may have more scattered clouds than the Mediterranean locations. Morning and afternoon cloud fraction climatologies have also been investigated [RD-14], as OLCI is flown in the morning orbit and MODIS-Aqua and VIIRS in the afternoon orbits. Cloud fractions are typically very similar between morning (OLCI) and afternoon (MODIS/VIIRS) over all sites. At El Hierro, there is a slight increase in the afternoon clouds compared to the morning clouds in the months of September and November, but there is also the opposite trend in July.

RD-10 documents additional analyses performed with OLCI, MODIS and VIIRS matchup datasets, as required by the Expert Review Board, see 'Extra slides'. The analyses include the results of sensitivity to flags and different screening criteria.

In particular, the aerosol Ångström exponent is not among the parameters used in the standard matchup screening protocol for OC-SVC gain derivation but was requested by the Board. The result with the additional criterion of $\alpha < 1$ is provided in Figure 4 and it shows that the Ångström condition does not meaningfully modify the site ranking compared to the standard protocol. In this case, α is obtained from the standard ocean colour by-products of the atmospheric correction and computed between the two NIR bands at 779 and 865 nm.

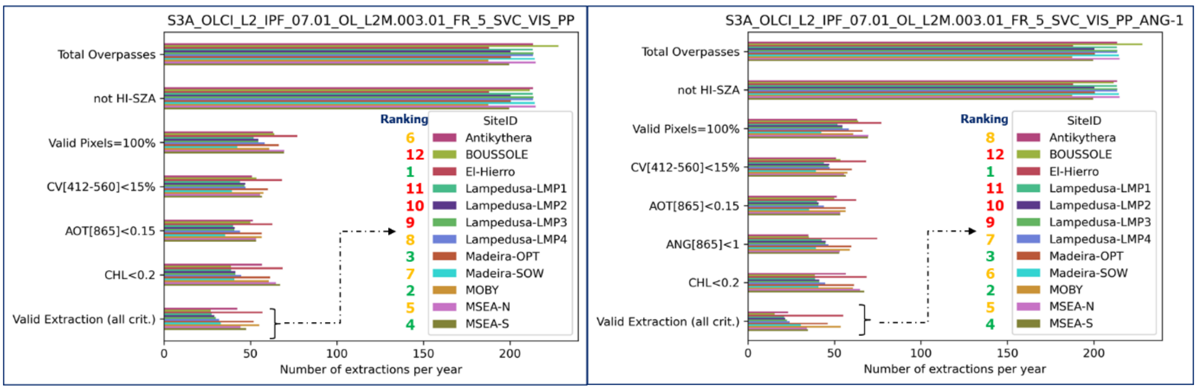

***Figure 4:** Analysis of the impact of individual matchup screening criteria on the average annual number of potential matchups for OLCI-A. The x-axis values define the mean number of extractions per year and the y-axis the specific screening criteria, cumulative with respect to the preceding criteria. All criteria, as in the standard matchup screening protocol for OC-SVC gains, are applied at the bottom of the two graphs and denoted as 'Valid*

Extraction (all crit.)'. Left plot: the standard screening protocol. Right plot: the standard screening protocol and an additional criterion of α < 1 (ANG[865]).

There was also an interest in evaluating the site matchup potential for extreme oligotrophic waters with Chl ≤ 0.1 mg/m^3. Figure 5 shows this result in comparison with the standard protocol where Chl ≤ 0.2 mg/m^3. The major difference is in the El Hierro site falling down in the ranking. This drastic change in El Hierro's score is due to the stable and narrow chlorophyll-a distributions at the site, peaking between 0.1 and 0.2 mg/m^3 throughout the year. The result is shown for OLCI-A, but El Hierro chlorophyll-a histogram distributions are similar among OLCI, MODIS and VIIRS, slides 119-122 in [RD-10]. Conversely, the seasonally stable, narrow and low chlorophyll range (≤ 0.2 mg/m^3) may also be recognised as a meaningful benefit for OC-SVC. Chlorophyll-a, however, is a satellite product here, with a degree of uncertainty that may vary by site.

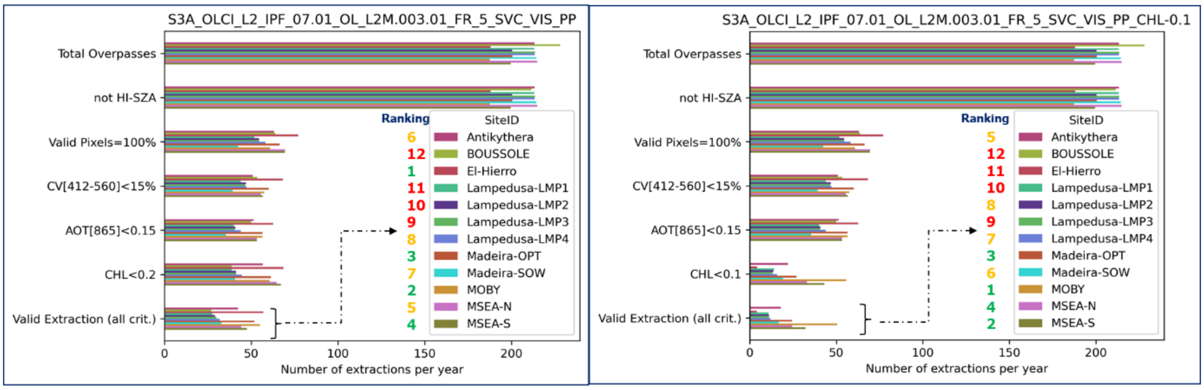

Figure 5: Analysis of the impact of individual matchup screening criteria on the average annual number of potential matchups for OLCI-A. All criteria, as in the standard matchup screening protocol for OC-SVC gains, are applied at the bottom of the two graphs and denoted as 'Valid Extraction (all crit.)'. Left plot: the standard screening protocol. Right plot: the standard screening protocol and a stricter oligotrophic chlorophyll-a threshold of Chl ≤ 0.1 mg/m^3.

Additionally, the prevalence of clouds, glint, absorbing aerosols, high chlorophyll, high AOT and other conditions at the sites has been investigated [RD-10]. Water reflectance and chlorophyll histograms at the sites have been studied before and after the OC-SVC screening, to check whether clean single-peak distributions are present. Water reflectance spectra are also shown in [RD-10] for the candidate locations.

3.2 Analysis of the matchup potential with Sentinel-2 MSI

Sentinel-2 MSI analysis of the matchup potential has been included with the main OLCI/MODIS/VIIRS investigations [RD-15]. However, MSI has been analysed separately because no operational Level-2 ocean colour products exist for this mission. Nevertheless, the Copernicus OC-SVC infrastructure needs to support possible future and Next Generation MSI products.

As MSI is mostly a land instrument, its coverage is not global and includes all coastal waters up to 20 km from the shore and the entire Mediterranean Sea. Consequently, all OC-SVC infrastructure candidate locations are covered by the routine MSI acquisition plan, including El Hierro and Madeira, although these two sites are close to the limit of the coverage. As a proxy for the MSI matchup potential, a basic cloud analysis was performed and is documented in [RD-15]. It was verified that MSI produces similar fractions of non-cloudy scenes as OLCI at the candidate locations, with somewhat fewer non-cloudy scenes at Madeira and MOBY and, to a lesser degree, at BOUSSOLE and El Hierro. It is therefore expected that the OLCI example could be used as a proxy for the MSI potential to generate high quality OC-SVC matchups at the candidate locations.

3.3 Conclusions on the high quality matchup potential

Conclusions:

- OLCI-A and -B consistently produce the highest numbers of potential matchups at El Hierro (57/52.5) and MOBY (55.1/58.8), then secondly at Madeira-OPT (51.8/51.2), and thirdly at the Cretan sites, particularly MSEA-N (44.3/51.4) and MSEA-S (47.5/49.8). The seasonal matchup distribution is the most balanced at those sites in the above order. The El Hierro matchup potential strongly relies on the standard OC-SVC screening protocol with Chl ≤ 0.2 mg/m^3.

- MODIS and VIIRS produce the highest numbers of potential matchups with relatively balanced annual distributions at the Cretan sites, specifically MSEA-N (70/62.1), Antikythera (64.2/70.3), and MSEA-S (62.2/55.3). Nevertheless, the winter month matchups are comparatively low.

- OLCI results of the matchup potential are central to these conclusions, and El Hierro and Madeira-OPT are strong candidates. However, as OLCI results are not consistent with those for MODIS and VIIRS, alternative options may be considered. In view of the caution advised in interpreting the matchup numbers, the matchup assumptions, and the robustness of the process, the Crete sites may also be weighed as a valid selection for this criterion.

4 MARINE AND ATMOSPHERIC CRITERIA

The marine and atmospheric conditions at the site must promote the lowest uncertainty budget of the complete OC-SVC process and the associated criteria are therefore mandatory to guarantee the state-of-the-art and autonomous Copernicus OC-SVC capability. Site characterization must be based on reliable climatologies to guarantee the optimal marine and atmospheric conditions now and into the future of the Copernicus ocean colour services.

Marine and atmospheric climatological characteristics of the five locations were investigated by five parallel studies conducted by regional institutes. Detailed reports and presentations from the five studies are available online, together with additional environmental information requested by the Expert Review Board [RD-5].

The difficulty of the current review was in the heterogeneity of the marine and atmospheric results available from the five teams, in that the statistics often came from different data sources or were presented differently. As the comparisons of the results have been challenging, a dedicated effort has been made to consolidate and summarise them. Such summarised results are presented in this section. All results are traceable to the individual reports and the additional inputs collected for the Expert Review Board [RD-5]. In a few cases, however, where the exact statistics are not quoted in a report, they are approximated from report figures. Nevertheless, the primary information source for this review and its conclusions remains the reports and the presentations from the dedicated institutes [RD-5].

4.1 Marine conditions at the candidate OC-SVC sites

Tables 7, 8 and 9 summarize the mandatory marine criteria for the candidate OC-SVC sites.

Site	Chlorophyll-a	Currents	Waves/Wind
BOUSSOLE	chl ≤ 0.2: **46%**; spring bloom ~0.6-1.7 JFMA (in situ); ~0.21-0.45-0.7 FMA (CMEMS)	Current mean 0.375 m/s; 0.32 Jun – 0.44 m/s F; ≥0.65 m/s 4%; SW direction (in situ) CMEMS 0.09 m/s a lot undervalued, use in situ	Wave mean 1.01 m, 0.7 S – 1.4 m W (in situ). Wind mean 6.6 m/s, 5 S – 8.5 W, > 10/20m/s 17/2%; NE / SW direction (in situ)
MSEA-N	chl ≤ 0.2: **~94%**; spring bloom ~0.18 JFM (OC-CCI) *CMEMS-chl half lower*	Current mean 0.3 m/s (in situ–better), 0.12 m/s; << 0.35 m/s (CMEMS); S/SW direction	Wave mean 0.8 m, N/W. Wind mean ~6 m/s, >10 ~7%; NW direction ERA5 coarse 30 km resolution
Antikythera	chl ≤ 0.2: **~90%**; spring bloom ~0.19 JFM (OC-CCI) *CMEMS-chl half lower*	Current mean 0.3 m/s (in situ–better), 0.11 m/s; << 0.30 m/s (CMEMS); S/E/S/N direction	Wave mean 0.8 m, N/E, W. Wind mean ~6.5 m/s, >10 ~19%; NE/W direction
MSEA-S	chl ≤ 0.2: **~99%**; spring bloom ~0.14 JFM (OC-CCI) *CMEMS-chl half lower*	Current mean 0.4 m/s (in situ-better), 0.13 m/s; < 0.45 m/s; NW in FW, SW in SS	Wave mean 0.9 m, W. Wind mean ~5.5 m/s, >10 ~9%; NW direction
El Hierro	chl ≤ 0.2: **95.5%**; spring bloom ~0.16 JFM (CMEMS)	Current mean 0.11 m/s, ≥0.42 m/s at <1%; 0.1 FW – 0.13 m/s	Wave mean 1.8 m, 1.5 S – 2.2 m W, >3.1m 1%; N/NW (CMEMS).

		Summer, WS direction (CMEMS)	Wave period mean 12 s, 10 S - 13 W; NW (CMEMS). Wind mean ~5.2 m/s, >8/12 ~18/2%; E (MM5)
LMP-1	chl ≤ 0.2: **95%**; spring bloom ~0.2-0.3 JF (CMEMS)	Current mean 0.2 m/s; 0.15 Mar – 0.3 JF m/s; SE direction (in situ)	Wave mean 0.8 m, 0.56 S – 1.4 m W; ≤ 0.5 m 60% calm conditions; NW direction (ERA5). Wind mean ~6.7 m/s, >10 ~14%; NW direction (in situ)
LMP-2	chl ≤ 0.2: **92%**; spring bloom ~0.2-0.3 JF (CMEMS)		
LMP-3	chl ≤ 0.2: **95%**; spring bloom ~0.2-0.25 JF (CMEMS)		
LMP-4	chl ≤ 0.2: **96%**; spring bloom 0.2 JF (CMEMS)		
Madeira	chl ≤ 0.2: **86%**; spring bloom ~0.27-OPT FM, ~0.24-SOW FM (OC-CCI)	Current mean 0.12 m/s; 0.2 m/s Summer; < 0.2 m/s 87%; NW direction (CMEMS)	Wave mean 2 m, 1.5 S – 2.2 m W, NW/NS. Wave period mean 9.5 s, NW. Swell 1.8 m, swell period 9 s; NW (ECMWF). Wind mean ~2.5 m/s OPT, 5 m/s SOW; NE (HRES).

Table 7: Summarised chlorophyll-a, current, wave and wind climatological statistics for the candidate OC-SVC infrastructure locations from the five regional studies. Please use the reports from the dedicated institutes as the primary information source [RD-5].

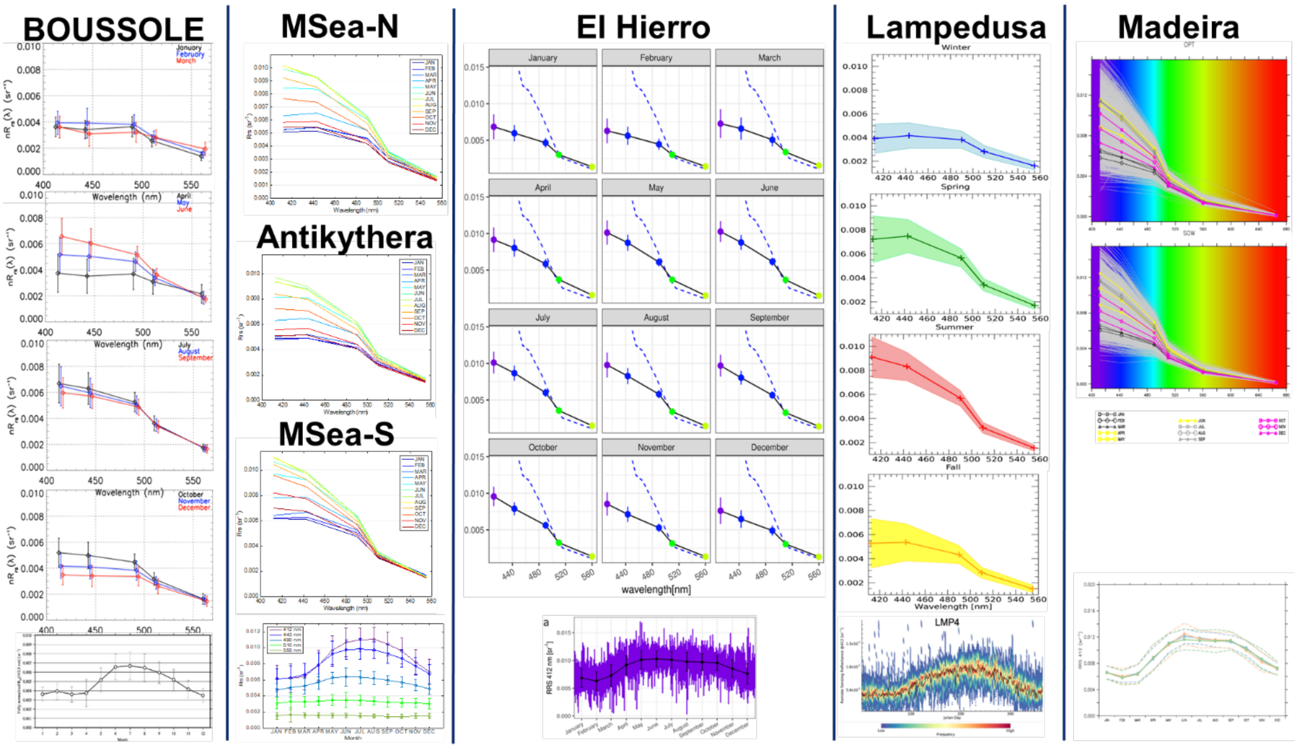

Table 8: Summarised climatological water remote sensing reflectance spectra for the candidate OC-SVC infrastructure locations from the five regional studies [RD-5].

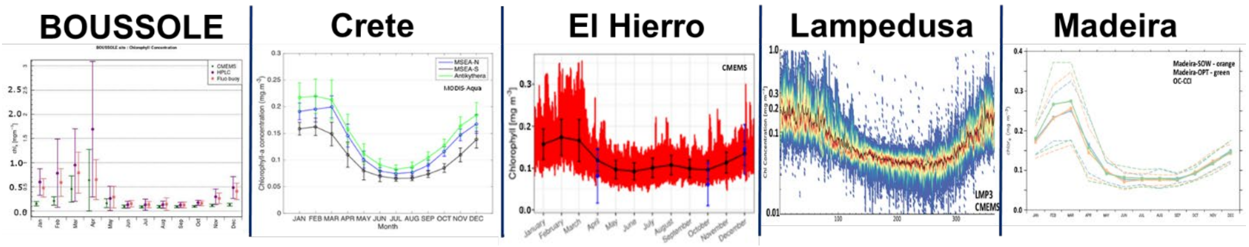

Table 9: Summarised climatological chlorophyll-a concentration annual distributions for the candidate OC-SVC infrastructure locations from the five regional studies [RD-5]. Note the different sources of the data and the different scales on the plots.

Considering the ocean colour parameters, the Atlantic sites should be fairly representative of the global oceans, while the Mediterranean sites may be affected by specific local conditions, such as excess CDOM absorption [RD-16]. Based on the chlorophyll-a and water reflectance climatologies, all sites show seasonal variability and chlorophyll concentration occurrences above the 0.2 mg/m^3 limit given in the mandatory criteria. As explained in section 2, the OC-SVC location requirements favour oligotrophic and stable water conditions, with lowest temporal variabilities, to minimize the total OC-SVC uncertainty budget.

The shape of water reflectance spectra across the seasons, Table 8, appear to categorise the sites into two groups:

- relatively oligotrophic, and
- mix of oligotrophic and mesotrophic.

The relatively oligotrophic conditions prevail at El Hierro, Madeira and the Crete sites. From the Crete sites, MSEA-S has the optically clearest waters. Madeira's oligotrophic spectra are however not fully consistent with the spring bloom chlorophyll-a peak in Table 9.
A mix of oligotrophic and mesotrophic conditions is observed at BOUSSOLE. The BOUSSOLE site is characterised by the strongest spring blooms, the highest variability of optical conditions, and the fewest chlorophyll-a concentrations below 0.2 mg/m^3.
The Lampedusa sites are in-between the two categories. Lampedusa water reflectance spectra are similar to BOUSSOLE in winter and fall but more oligotrophic in spring and summer and the chlorophyll-a is low throughout the year, even in the spring bloom, Table 9, and the lowest at LMP4.

Considering the ocean physical conditions, the significant wave height and the mean wave period, there are two site categories [RD-17]:

- low wave height: BOUSSOLE, Crete sites, and Lampedusa sites,
- high wave height, i.e. twice as high as in the Mediterranean: El-Hierro and Madeira.

All candidate sites are however subject to similar wave extremes, which are marginally largest for Madeira. Overall the wave energy is the highest at El-Hierro and Madeira, both as annual means and extremes.

In comparison, the MOBY site has medium wave heights but lower wave extremes than all candidate Copernicus sites. MOBY is also a wave rider and therefore independent of the waves. It should however be considered that, even if the wave height does not affect the in-water infrastructure, it may affect its servicing or emergency operations.

Wind conditions are the calmest at Madeira-OPT [RD-17]. The roughest winds are estimated at Antikythera and BOUSSOLE, yet the wind may not be the major safety factor [RD-17].

Currents are relatively low at all locations, however the highest at MSEA-S.

4.2 Atmospheric conditions at the candidate OC-SVC sites

Table 10 summarizes the mandatory atmospheric criteria for the candidate OC-SVC sites.

Site	Cloud cover	AOT (550)	Aerosol type
BOUSSOLE	CF ≤ 0.1: 34, 40, 50, 33% WSSF, 39%/year; **CF > 0.1: 223.3** days/year (MERRA-2)	**AOT ≤ 0.15: 41.6%**; mean > 0.15 ~0.2 MAMJJASO (MERRA-2); the same mean for data without dust (GRASP)	α mean 1.1±0.25; dust 20 days/year, mainly lasting 1-3 days; biomass/urban 32 days/year; **α>1: 50%**; α>1 & τ>0.15 AJJASO, mean α 1.1 (POLDER-GRASP) – **52 total polluted days / year**
MSEA-N	CF ≤ 0.1: ~16, 55, 78, 19% WSSF, ~42%/year; **CF > 0.1: 216** days/year (ERA5)	**AOT ≤ 0.15: 44%**; mean > 0.15 ~0.2 FMAMJJASO (MERRA2) *In situ lower*	α mean 0.85; dust 49 days/year Spring; bio/urb 1.3 day/year, max 5 days; for τ<0.15 40%mar/65% urb; **α>1: 31%**; α>1 & τ=0.18 Aug (MERRA2) (AERONET α higher) –- **50 total polluted days / year**
Antikythera	CF ≤ 0.1: ~21, 58, 82, 22% WSSF, ~46%/year; **CF > 0.1: 199** days/year (ERA5)	**AOT ≤ 0.15: 40%**; mean > 0.15 ~0.2 FMAMJJASO (MERRA-2) *In situ lower*	α mean 0.9; dust 47 days/year Spring; bio/urb 1.8 days/year; max 6 days; for τ<0.15 40%mar/65 %urb; **α>1: 38%**, α>1 & τ=0.2 JA (AERONET α higher) – **49 total polluted days / year**
MSEA-S	CF ≤ 0.1: ~26, 67, 94, 32% WSSF, ~53%/year; **CF > 0.1: 174** days/year (ERA5)	**AOT ≤ 0.15: 48%**; mean > 0.15 ~0.2 FMAMJJASO; mean 0.114 without dust (MERRA-2) *In situ lower*	α mean 0.8; dust 64 days/year; urban 0.4 day/year; for τ<0.15 40%mar/65% urban; **α>1: 25%** (AERONET α higher) – **64 total polluted days / year**
El Hierro	CF ≤ 0.1: 32, 35, 63, 24% WSSF, ~39%/year; **CF > 0.1: 224** days/year (ERA5)	**AOT ≤ 0.15: 72%**; mean 0.2 JAS; mean 0.1 without dust (MERRA-2) *MERRA-2 << AERONET*	α mean 0.54±0.24; dust 82 days/year 22% (summer); duration of dust events 1-2 days but 6-7 days possible; **α>1: 5%** but τ<<0.1 - no biomass/urban aerosols (MERRA-2) – **82 total polluted days / year (dust only)**
LMP-1	CF ≤ 0.1: ~29, 55, 72, 23% WSSF, ~48%/year; **CF>0.1: 200/190** days/year (ERA5)	**AOT ≤ 0.15: 60%**; mean > 0.15 ~0.2 MAMJJASO; mean 0.11 without dust (in situ)	α mean 0.6±0.22; dust 58 days/year, mainly lasting 1-2 days (1 day 60%); bio/urb 15 days/ year; **α>1: 30%** but

LMP-2	CF $\leq$ 0.1: ~28, 53, 70, 24% WSSF, ~45%/year; **CF > 0.1: 207** days/year (ERA5)	**AOT $\leq$ 0.15: 60%**; mean 0.2 MAMJJASO; mean 0.11 without dust (in situ)	monthly means are α<1; α>1.5 2% for $\tau \geq$0.2 (in situ) CAMS include cloudy conditions $\rightarrow$increased values – **73 total polluted days / year**
LMP-3	CF $\leq$ 0.1: ~27, 54, 71, 23% WSSF, ~46%/year; **CF > 0.1: 206** days/year (ERA5)	**AOT $\leq$ 0.15: 60%**; mean 0.2 MAMJJASO; mean 0.11 without dust (in situ)	
LMP-4	CF $\leq$ 0.1: ~27, 55, 72, 22% WSSF, ~45%/year; **CF > 0.1: 206** days/year (ERA5)	**AOT $\leq$ 0.15: 60%**; mean 0.2 MAMJJASO; mean 0.11 without dust (in situ)	
Madeira	CF $\leq$ 0.1: 13, 20, 35, 19% WSSF, 22%/year; mean CF 0.4 OPT, 0.6 SOW; **CF > 0.1: 286** days/year (SEVIRI) *OPT is clearer*	**AOT $\leq$ 0.15: 78%**-OPT **82%**-SOW (MODIS)	α mean 0.75; dust 30 MODIS passes/year (~15 days/year ?); biomass/urban 5 MODIS passes/year-SOW, 17 MODIS passes /year-OPT; **α>1.5 5%**-SOW **15%**-OPT *Stats are given in MODIS overpasses* – **~35–47 total polluted days / year**

Table 10: Summarised cloud fraction (CF), aerosol optical thickness (AOT), and aerosol type climatological statistics for the candidate OC-SVC infrastructure locations from the five regional studies. Please use the reports from the dedicated institutes as the primary information source [RD-5].

Low persistence of clouds is one of the major atmospheric criteria for the OC-SVC site, as a high cloud fraction would prevent any matchups with ocean colour satellite observations. This requirement is also indirectly covered by the investigation of the matchup potential of the candidate OC-SVC locations from section 3. Here, based on the input from the five studies [RD-5] and investigations of SEVIRI geostationary data [RD-14], Madeira sites, and Madeira-SOW in particular, have the highest prevalence of cloudy conditions. In winter, El Hierro shows the lowest cloud fraction and, in summer, the Crete sites have the lowest cloud fraction.

Aerosol conditions are another atmospheric mandatory criterion for the OC-SVC location. Low AOT, $\tau < 0.15$, and limited and quantified episodes of dust, biomass burning and pollution are required. These requirements aim to ensure the lowest possible OC-SVC uncertainty budget, particularly tied to the atmospheric correction.

In the OC-SVC processing, the dust aerosols are mostly detected and screened, as defined by the standard community matchup protocol for OC-SVC gain derivation [RD-8], [RD-10]. Therefore, the impact of dust outbreaks at a site may be investigated in combination with the site matchup potential in Section 3. The pollution, urban, or some biomass burning aerosols are often more difficult to detect.

The OC-SVC candidate locations exhibit a spectrum of aerosol conditions. All sites are impacted by dust aerosols from the Sahara. The dust outbreaks typically last from 1 to 2 or 3 days, but up to one week could sometimes be possible. Outside of the dust outbreaks, the conditions vary from a clear maritime atmosphere to an atmosphere increasingly affected by urban and biomass burning aerosols. As expected, apart from the Saharan dust events, the Atlantic sites are fairly representative of oceanic atmospheric conditions, while the Mediterranean sites are mildly affected by pollution aerosols and have an average Ångström exponent higher than that found in the Atlantic or in the open ocean in general.

Four main aerosol categories could be considered at the OC-SVC candidate locations:

- Clear maritime atmosphere but with a considerable number of dust events
  El Hierro is in this category, with the highest percentage of $\tau < 0.15$ and the smallest $\alpha > 1$ occurrences; the site has no urban or biomass aerosols, but has the highest number of dusty days, adding to 82 days per year. Madeira may also be in this category but the statistics were computed inconsistently.
- Maritime atmosphere with a moderate number of dust events and with a small level of pollution
  The Crete sites are in this category, with dust days from 47 to 64 per year, MSEA-S having the most, and with urban or biomass burning aerosols from 0.4 to 2 days per year, MSEA-S having the least.
- Maritime atmosphere with a moderate number of dust events and a slightly higher level of pollution
  The Lampedusa sites are in this category, with 58 dust days per year and 15 days of urban or biomass burning aerosols.
- Maritime atmosphere with a low number of dust events and a higher level of pollution
  BOUSSOLE is in this category, with the fewest 20 dust days per year of all candidate sites and the highest number of 32 days per year of urban or biomass burning aerosols.

4.3 Marine and atmospheric conclusions

Conclusions:

- El Hierro, Madeira and the Crete sites exhibit relatively oligotrophic conditions, minimizing the in-water uncertainty budget. The MSEA-S location has the optically clearest waters of all candidate locations, comparable to those at MOBY.

- BOUSSOLE, Crete and Lampedusa sites have the lowest significant wave height, while El-Hierro and Madeira experience waves twice as high; all locations however have similar wave extremes.

- The cloud fraction is the lowest in winter at El Hierro and, in summer, at the Crete sites.

- All candidate locations have dust outbreaks and the dust must be very accurately detected and screened out, even at low levels.

- El Hierro exhibits the clearest maritime atmosphere, to minimize the atmospheric modelling uncertainty budget, but also the largest number of dust outbreaks. Fewer dust events, but small levels of pollution, are found at the Crete sites. Madeira aerosol conditions may be similar to El Hierro or Crete but this would need further investigation. BOUSSOLE has the fewest dust events and also the highest number of urban or biomass burning aerosol occurrences.

5 LOGISTICAL AND SAFETY CRITERIA

The logistical and safety considerations are fundamental to the capability to operate the Copernicus OC-SVC site and to ensuring the minimum risk to this critical asset.

Operational data provision, safety of the infrastructure and its operators, and the strict OC-SVC uncertainty budget must be guarded through day-to-day operations, routine procedures, emergency processes, long-term maintenance and evolutions. All these activities and safeguards are inherently linked to the location of the infrastructure and must ensure value for money for the Copernicus Programme.

The logistical and safety considerations of the candidate OC-SVC locations were provided by the five parallel studies conducted by the regional institutes. The detailed reports and presentations from the five studies include these inputs and are available online, together with the additional information requested by the Expert Review Board [RD-5].

5.1 Logistical considerations

Table 11 summarizes the mandatory logistical criteria for the candidate OC-SVC sites.

Site	Logistics and existing supporting infrastructures	Communication links	Bathymetry
BOUSSOLE	60 km offshore the French Riviera, navigation time 2-3 h. Villefranche-sur-Mer / Nice: ports, ships, divers. Storage / maintenance / cal. labs. Trained staff on site. Established site with > 20 years' experience. Established oceanographic institute (LOV-IMEV). IMEV atm. observatory. AERONET site up to 2016.	Argos, Iridium, and GSM communications available at the offshore site	2440 m depth; sea floor slope 4.5% (2.5^0)
MSEA-N	44 km to Heraklion, navigation time 2.5 h. Heraklion port, ships, divers, workshops. HCMR marine centre in Heraklion, optics/bio. labs, two surface buoys (GOOS). Trained staff in Heraklion. Finokalia (Crete N coast) and PANGEA (Antikythera) atm. observatories. Active AERONET station on the Crete North shore.	GSM access is at all Crete sites but, at MSEA-S, 2G and 3G may only be possible. A combination of GSM, as primary, and satellite (Iridium), as secondary, is proposed, together with VHF/UHF/low-frequency emergency contact.	1325 m depth; sea floor slope 3.05^0
Antikythera	~48 km offshore Kythira, navigation time to Heraklion is 9 – 10 h. AERONET station up to 2021.		579 m depth *(< 800 m)*; sea floor slope 3.56^0
MSea-S	~85 km offshore South Crete, no marine support infrastructure in South Crete. Navigation time to Heraklion 24 h. Establishment of a South Crete field station, storage/maintenance/cal. labs. included in costing.		2645 m depth; sea floor slope 1.14^0

El Hierro	14 km offshore El Hierro, 19 km to La Restinga port. La Restinga port: divers, ships, suitable to establish a support/laboratory/storage centre, where a plot of land has been identified and the centre was included in costing. Trained staff is in Tenerife. El Hierro: Orchilla lighthouse / observatory. Tenerife, 213 km from La Restinga port on El Hierro, navigation time 24 h. Tenerife: IEO-COC marine centre, radiometric/calibration lab., IEO ship campaigns take place twice a year to El Hierro; and Izaña atm. obs. Several active AERONET stations in the Canarias (but not on El Hierro).	A combination of satellite (Iridium), as primary, and GSM, as secondary, is proposed. GSM 2G access is at the site but may improve in the future.	2739 m depth; sea floor slope 0.49^0
LMP-1	~15 km offshore Lampedusa. All sites within 1 to 3 h. navigation time. Lampedusa: 2 ports, ships, diving centres, blacksmiths, warehouse. Trained staff is on Lampedusa. Lampedusa: ENEA/CNR/ISMAR marine observatory, moored buoy, cal. lab. ENEA/NOAA/WMO atm. observatory. Active AERONET station on Lampedusa.	Two transmission systems for monitoring and scientific data transfer. For monitoring either Argos or Iridium are proposed. For scientific data transfer GSM is proposed as a primary system, and satellite (e.g. Iridium) as a secondary. A radio link and Starlink are also planned to be investigated. For land communications, Lampedusa atm. obs. is connected to GARR: the ultra-broadband network dedicated to Italian research and education community.	< 1% *deeper than 800 m*; sea floor slope = 0^0 for 10% area
LMP-2	~27 km offshore Lampedusa		≤ 2% *deeper than 800 m*; sea floor slope = 0^0 for 10% area
LMP-3	~37 km offshore Lampedusa		≤ 22% *deeper than 800 m*; sea floor slope = 0^0 for 5% area
LMP-4	~50 km offshore Lampedusa		≤ 27% *deeper than 800 m*; sea floor slope = 0^0 for 5% area
Madeira	OPT ~13 km offshore Madeira, SOW 43 km offshore from Madeira. Funchal port, ships, diving centres, facilities. No existing infrastructure for relevant marine observations, few radiometric or bio-optical investigations. IPMA meteorological observatory.	TBD	OPT 2865 m, SOW 3733 m; sea floor slope $\sim 13^0$OPT, $\sim 5^0$SOW

Table 11: Summarised logistical information and existing supporting infrastructures, communication links and bathymetry information for the candidate OC-SVC infrastructure locations from the five regional studies. Please use the reports from the dedicated institutes as the primary information source [RD-5].

Considering the logistics of establishing the OC-SVC site operations, all locations have access to ports, ships, services, as well as potential facilities and qualified personnel. Nevertheless, the range of existing relevant activities, infrastructures and expertise is mixed:

- Logistical readiness, thanks to established relevant infrastructures and local expertise BOUSSOLE, MSEA-N, Antikythera and the Lampedusa sites are in this category. In-water buoys are already operated at or close to these locations, therefore the bases for local operations and servicing are well established. The BOUSSOLE site is exceptionally ready, with more than 20 years of buoy radiometric measurements and associated site operations. Plans for high volume data communications with the infrastructures have been also developed. As an added benefit, supporting infrastructures, like atmospheric and marine observatories, and local qualified personnel are available at these sites.
- Necessity to establish a site and its operations but from a strong background of local expertise and existing logistical foundations
  MSEA-S and El Hierro belong to this category. The sites are remote in their location and the navigation time from the main marine centres in Heraklion and Tenerife, respectively, would take 24 hours. Nevertheless, the El Hierro site is close to El Hierro island, from where many routine and emergency operations may be established. The site is also currently supported by the existing expertise of the IEO team, two oceanographic cruises a year from Tenerife, and extensive atmospheric measurement facilities in the Canaries, including a potential for expanding the El Hierro atmospheric observatory. MSEA-S is the furthest offshore, creating operational difficulties. MSEA-S is supported by the existing expertise of the HCMR team and its readiness to operate the site at MSEA-N or Antikythera. Both MSEA-S and El Hierro teams have already planned to establish field stations closest to the site locations for storage, maintenance and laboratory calibrations. Plans for high volume data communications with the infrastructures are also developed.
- Necessity to establish a site, its operations and the complete local marine optics foundations
  Madeira is in this category. There have not been prior relevant marine infrastructures and observations at the site, and very few radiometric or bio-optical investigations. Establishing the Madeira site would require the highest investment.

The site distance to land is a critical balance:
- it must be far enough away from land to reach the clearest offshore waters and atmospheric conditions, and to avoid the remote sensing adjacency effect from the land,
- it must be close enough to land to ensure the site is easily and quickly accessible for routine operations and in emergencies.

The MSEA-S site is the most vulnerable in this respect, being far into the open sea about 85 km offshore from South Crete. Conversely, the El Hierro site is located very close to the shore at 14 km, and Madeira-OPT is about 13 km, which may be too near to fully avoid the adjacency effect. If needed, the eventual locations of these sites would have to be adapted.

Considering the bathymetry, it should be noted that Antikythera site does not meet the 800 m depth requirement. At the Lampedusa sites, only some percentage of the sea floor area meets the 800 m depth requirement.

5.2 Safety considerations

Table 12 summarizes the mandatory safety criteria for the candidate OC-SVC sites.

Site	Traffic (within 20 nautical miles)	Physical safety	Seismic or volcanic activity
BOUSSOLE	Maritime vessel density 0.005 to 2.5 h/km^2/month. 5 air routes > 1K flights/year plus smaller routes.	Existing infrastructure site with experience on ensuring site safety, all physical safety precautions are taken. None to few medicanes at the site. No fires – offshore location.	None or low.
MSEA-N	Maritime vessel density ~0.1 to 2 (20 for trawlers) h/km^2/month. ~84K flights/year to Island.	One medicane and 2 cyclones in the vicinity of the sites from 2014; additional 2 medicanes in 1989 and 2005. In the Mediterranean, medicanes are the fewest in the East, including Crete sites. Site location on digital nautical maps; “Stay Away” warning; buoy yellow paint; a yellow light beacon; a radar reflector. MSEA-N and Antikythera: ~ 1 fire/month, MSEA-S: no fires.	None or low.
Antikythera	Maritime vessel density ~0.2 to 4 h/km^2/month.		
MSEA-S	Maritime vessel density ~0.1 h/km^2/month.		
El Hierro	Maritime vessel density ~0.1 h/km^2/month. 2 air routes > 1K flights/year + smaller routes. Surface NO_2 1 ppbv.	No hurricanes or tropical storms at the site from 179-year record (cold ocean, trade winds). Site is in remote location near marine + biosphere reserves. Site location on digital nautical maps; marine beacon; St Andrews Cross; a radar reflector; security camera; AIS broadcasting; geofence; awareness in the local community. Fire ~1 event/year.	Recent eruption of La Palma volcano caused moderate AOT increase (AOT remaining < 0.15) and no variation in the physical-chemical parameters of the water column [RD-18].
LMP-1	Maritime vessel density ~0.8 h/km^2/month, > 50% fishery. ~1300 flights/ye to Lam. NO_x < 200 kg/km^2/year.	About 3 medicanes in the vicinity of the sites 1979-2016; medicane impact mostly from intense precipitation and coastal flooding, no record of severe medicane damages at Lampedusa. Site location on nautical maps; monitoring of AIS messages from commercial and leisure vessels; alerts to coastguard; virtual mark in the AIS; a location beacon (Iridium or ARGOS), a foghorn if needed. Fire ~1 / year, 0.3–0.5 events/month in Summer	Etna eruptions spread in Easterly direction away and have no impact on Lampedusa.
LMP-2	Maritime vessel density ~0.7 h/km^2/month		
LMP-3	Maritime vessel density ~0.4 h/km^2/month		
LMP-4	Maritime vessel density ~0.3 h/km^2/month		
Madeira	Maritime vessel density ~0.1 to ~8 h/km^2/month. ~2 air routes < 400 flights /year plus smaller routes.	About 5 hurricanes in the vicinity in the 179-year record. All necessary physical safety precautions would be taken. No fires.	None or low

Table 12: Summarised traffic, safety and seismic or volcanic activity information for the candidate OC-SVC infrastructure locations from the five regional studies. Please use the reports from the dedicated institutes as the primary information source [RD-5].

All candidate OC-SVC locations are in relatively safe locations with respect to marine traffic. However, not only is the exact location important but also its surroundings must be safe in case of equipment drifting or other emergencies. In this case, the Antikythera site is the closest to the busy routes from the Black Sea and Aegean to the Western Mediterranean and is the most vulnerable. On the opposite, the El Hierro and MSEA-S sites are likely to be the least affected by ship and air traffic.

Plans exist for all sites to adopt all physical safety precautions, like placing the site on nautical maps, installing light beacons, radar reflectors, AIS monitoring or broadcasts. Such specifications have not been provided by the Madeira team but would be implemented if required.

With respect to hurricanes or medicanes, none of the locations is meaningfully impacted. El Hierro is located in a specific area free of hurricanes and tropical storms, and future projections indicate that this status will prevail. The ocean in the Canary Island region is very cold for its latitude, and it is north of the area where most of the tropical storms and hurricanes originate in the Atlantic. Madeira, north of El Hierro, has been on a track of a few hurricanes but more detail would be needed for this location. In the Mediterranean Sea, medicanes are mostly formed in the western and central basins and occur less frequently in the East Mediterranean, to the benefit of the Crete locations. Medicane occurrences at BOUSSOLE and Lampedusa sites have however also been infrequent. Climate simulations for the Mediterranean show an overall decrease in the frequency of medicanes, while the relative frequency of higher-intensity medicanes increases.

While the in-water OC-SVC infrastructure may be largely independent of the hurricane or medicane waves or other inclement conditions, the impact may be more important on the associated land infrastructure and its operations. The on-land OC-SVC infrastructure may be affected by coastal flooding, loss of power, loss of the cellular network or other communications, as well as by interruption of routine or emergency servicing activities.

Considering the El Hierro candidate OC-SVC location safety and security of operations, a known meaningful event occurred 19 September to 13 December 2021, which was the eruption of a volcano on the nearby Canary Island of La Palma. The volcano's impact on AOT at the El Hierro site was shown to be moderate, with AOT remaining below the 0.15 value [RD-18] (although likely containing volcanic ash pollution). Despite the volcanic emissions, there was also no variation in the physical and chemical parameters of the water column. The La Palma volcanic eruption is of a notable concern but is also considered to be a rare event.

5.3 Logistics and safety conclusions

Conclusions:

- BOUSSOLE, MSEA-N, Antikythera and the Lampedusa sites are logistically ready, thanks to established relevant infrastructures, services and local expertise; while the MSEA-S and El Hierro sites would have to be established, yet a strong background of local expertise and planned logistical foundations exist. The Madeira location is the least logistically ready. Madeira local marine optics foundations and site operations would need to be established.

- The MSEA-S site is located the furthest offshore in open sea, which is a drawback for routine and emergency operations. The El Hierro and Madeira-OPT sites are very close to the shore; possibly too near to fully avoid adjacency effects. A re-evaluation of the distance from the coast for the above sites may be considered.

- All candidate locations meet the bathymetry requirement except for Antikythera; at the Lampedusa sites, only some percentage of the sea floor area meets the 800 m depth requirement.

- All candidate locations are in safe areas with respect to marine traffic, except for the Antikythera site. Plans also exist to adopt all physical safety precautions (Madeira plans would still have to be developed).

- All candidate locations are documented to be safe with respect to hurricanes or medicanes; notably, El Hierro is in an area free of hurricanes and tropical storms.

- With respect to safety and security of operations, the eruption of a volcano on La Palma in 2021 showed an impact on El Hierro's atmospheric measurements. The AOT rose during the event while it still averaged below the 0.15 requirement. The event is considered to be rare.

6 LOCATION COSTING CONSIDERATIONS

Another critical criterion for the Copernicus OC-SVC infrastructure location was defined to be the cost of establishing and operating the site, which must ensure the best value for money for the Copernicus Programme.

The Phase-2 Preliminary Design of the roadmap provided detailed ROM costing for two OC-SVC infrastructures: at the combined location at BOUSSOLE and MSEA-N (ROSACE), and at the LMP1 location (EURYBIA) [RD-9]. This costing gave total costs of 'Field Segment' (including the optical systems, deployment platforms, onshore facilities, services, and field operations), 'Ground Segment', and 'Complete Infrastructure'. The costing was estimated for three infrastructure development phases: Phase-4 Engineering Design, Phase-5 Development, and Phase-6 Operations.

This Phase-3 of the roadmap on the infrastructure location, investigated additional OC-SVC candidate sites, where the costing was not available. The Expert Review Board prioritised additional costing information for new locations at Antikythera, MSEA-S, LMP2, LMP3, LMP4, and El Hierro.

The additional ROM costing for the new sites was provided by the regional institutes participating in the Phase-3 Location study [RD-19]. The institutes delivered their ROM estimates of the delta costs specific to their candidate locations. In practice, the institutes provided input to the excerpts from the costing spreadsheets that were specific to the 'Field Segment' infrastructure location, while the costing inputs corresponding to the infrastructure itself and 'Ground Segment' were left unchanged. The Antikythera and MSEA-S inputs were provided relative to the ROSACE complete costs. The LMP2, LMP3, LMP4 and El Hierro inputs were provided relative to the EURYBIA complete costs.

The costing of the new candidate locations has therefore to be considered as a relative difference in value from the Phase-2 Preliminary Design costing. The costing is a ROM estimate, particularly because the site location costs are intermixed with the infrastructure itself and its operations. The El Hierro team has been at a special disadvantage because it has not participated in any of the previous Copernicus OC-SVC infrastructure phases.

6.1 Summary of the delta costing estimates

Tables 13, 14 and 15 provide the percentage delta costs estimated for the new candidate OC-SVC locations. Only delta costs are shown, as it has been agreed not to publish the costing of the infrastructure before the Phase-5 Development is awarded and depending on the EC decisions.

The delta costs allow to estimate whether the ROM costing approximated in Phase-2 would change for the new OC-SVC candidate locations and how significantly. The costs of the three infrastructure phases are however different in absolute magnitude, hence the impact of the delta costing on the total costing is explained below. Please refer to [RD-9] for the detailed description of activities in each of phases 4, 5 and 6, and note that manpower costs, which are a significant share of the total costs, are diverse in different countries and institutions, therefore [RD-19] contains different manpower scenarios for the consideration of the Expert Review Board.

- Phase 4 Engineering is a one-off activity and a one-off cost. Phase 4 is to provide a detailed design, technical specifications and the final costing. This phase costs are mostly in manpower and, to a small degree, in travel, services or hardware/software.
- Phase 5 Development is a one-off activity and a one-off cost. Phase 5 is to develop and demonstrate the physical infrastructure in the field and its operations. This activity contributes a major one-off cost expense. The costs are in procurement of hardware/software as well as in manpower and external services; other costs also are in property procurements, if needed, and in travel.
- Phase 6 Operations is a recurrent continuous activity and the costing is estimated per one year of operations. Phase 6 is to provide day-to-day operations of the infrastructure, operational data services, activities to ensure the quantified and minimal uncertainty budget, emergency response, maintenance, and evolutions. The costs are mostly in manpower and external services and, to a smaller degree, in replacement hardware/software and in travel.

Phase	Combined location Manpower management by LOV-IMEV	Antikythera + BOUSSOLE vs MSEA-N+BOUSSOLE	MSEA-S + BOUSSOLE vs MSEA-N+BOUSSOLE
Phase 4 Engineering	up to 1 year activity, detailed design, specs	+ 4.7 %	+ 4.7 %
Phase 5 Development	2 - 3 year activity, major procurement costs	+ 4 %	+ 6 %
Phase 6 Operations	continuous activity, cost per year of operation	- 1.4 %	- 0.4 %

Table 13: Delta costing in percent of the total costs for establishing and operating the OC-SVC infrastructure at Antikythera or MSEA-S locations plus BOUSSOLE, compared to the costing at MSEA-N plus BOUSSOLE locations.

Phase	Baseline costs	LMP3 vs LMP1 / LMP2	LMP4 vs LMP1 / LMP2
Phase 4 Engineering	up to 1 year activity, detailed design, specs	+ 0 %	+ 0 %
Phase 5 Development	2 - 3 year activity, major procurement costs	+ 4.9 %	+ 7.3 %
Phase 6 Operations	continuous activity, cost per year of operation	+ 0.9 %	+ 1.3 %

Table 14: Delta costing in percent of the total costs for establishing and operating the OC-SVC infrastructure at LMP3 or LMP4 locations, compared to the costing at LMP1. LMP2 costing is the same as LMP1.

Phase	Partial manpower by IEO and by CNR	El Hierro vs LMP1 / LMP2
Phase 4 Engineering	up to 1 year activity, detailed design, specs	- 14 %

Phase 5 Development	2 - 3 year activity, major procurement costs	**+ 10.5 %**
Phase 6 Operations	continuous activity, cost per year of operation	**- 1 %**

Table 15: Delta costing in percent of the total costs for establishing and operating the OC-SVC infrastructure at El Hierro location, compared to the costing at LMP1.

6.2 Conclusions for the delta costing estimates

Conclusions:

- Costing adjustments for the new Crete (Antikythera and MSEA-S) sites and the Lampedusa (LMP2, LMP3 and LMP4) sites are within the uncertainty of their ROM estimates.

- Costing adjustments for El Hierro site are more volatile, either lower due to low manpower costs, or higher as a new and remote site is being established.

- Costing adjustments for the new OC-SVC candidate locations are relatively small compared to the complete development and operation costs of the OC-SVC infrastructure estimated in Phase 2 Preliminary Design. The costing criterion was therefore recommended to be de-prioritised in favour of the robust scientific investigation.

7 CONCLUSIONS AND RECOMMENDATIONS

As defined at the beginning of this document, this review of Copernicus OC-SVC candidate locations must be based on solid scientific evidence. The recommended OC-SVC location must secure the European capability and expertise for a state-of-the-art, autonomous and dependable OC-SVC source, and ensure the best value for money for the Copernicus Programme. This is however a scientific review and the Copernicus OC-SVC roadmap may or may not progress into the development phase depending on the Copernicus programmatic decisions and the availability of funding.

The following candidate OC-SVC locations have been investigated: BOUSSOLE, the Crete sites (MSEA-N, Antikythera, and MSEA-S), El Hierro, the Lampedusa sites (LMP1, LMP2, LMP3, and LMP4), and the Madeira sites (OPT and SOW).

To fulfil the Copernicus OC-SVC goals, the candidate locations have been investigated in terms of their capacity to generate a large number of high quality matchups with satellite missions and the optimal marine, atmospheric, environmental, logistical and safety conditions [RD-5], also defined in the Requirements Phase-1 of the Copernicus OC-SVC roadmap [AD-1].

Expert Review Board considerations focused on the mandatory criteria that were selected for the infrastructure location:

- potential of a location for OC-SVC high quality matchups with satellite missions,
- cloud cover,
- chlorophyll concentration and water reflectance,
- aerosol optical thickness and aerosol type,
- currents, waves and winds,
- logistics and existing supporting infrastructures,
- communication links,
- bathymetry,
- physical safety, traffic, hurricanes,
- seismic or volcanic activity.

Differences in ROM costing estimates between the candidate locations were also evaluated but de-prioritised because no significant change in costing was identified. In addition to the selected mandatory criteria, other site characterisations included water IOPs, sea surface temperature and salinity, atmospheric gases and pressure, prevailing marine and atmospheric circulation patterns, surrounding land and urban and industrial areas, airline routes for contrail pollution, and fire occurrences at nearby land [RD-5].

From the investigations described in the preceding sections, all candidate Copernicus OC-SVC locations exhibit competencies in one or many of the mandatory criteria selected for the infrastructure location. On a few criteria, most sites are relatively equivalent, e.g. on location safety. The recommendation for the site selection is not straightforward.

Consequently, this Expert Review Board has adopted the following logic:

- firstly, to examine a subset of the mandatory criteria that are the most fundamental to the Copernicus OC-SVC investment, and
- secondly, to use the remaining mandatory criteria to narrow down the recommendation.

7.1 The most fundamental of the mandatory criteria for the OC-SVC Location

Considering the mandatory criteria for the Copernicus OC-SVC location, the following have been considered to be the most fundamental to the selection process:

1. The site's capability to produce high quality satellite matchups, in large numbers and with balanced annual distributions, is a major selection criterion, see sections 2.1 and 3. The matchup analysis must however be considered cautiously. El Hierro, Madeira-OPT and the Crete sites are the highest ranking candidate locations in this respect. As the Copernicus missions are central to this OC-SVC selection process, El Hierro is the site that produces the highest number of matchups with Copernicus Sentinel-3 OLCI observations. However, there are two additional considerations:
   - For MODIS and VIIRS, the Crete sites are the most successful and El Hierro and Madeira-OPT yield significantly reduced numbers of matchups;
   - El Hierro plunges in ranking when the standard OC-SVC screening protocol is changed from Chl ≤ 0.2 mg/m^3 to Chl ≤ 0.1 mg/m^3 due to a stable, low and very narrow chlorophyll-a distribution range at this site.

2. Stable and clear water optical conditions are fundamental to the ocean colour OC-SVC process and the minimization of its uncertainty budget, see sections 2.2 and 4.1. The Atlantic sites of El Hierro and Madeira are the most representative of the global oceans and exhibit the clearest and most stable oligotrophic conditions. In addition, the Crete sites in the Eastern Mediterranean are also located in the clearest oligotrophic waters. The Lampedusa sites come next, with less favourable water reflectance spectra in winter and fall but persisting low chlorophyll-a. The BOUSSOLE site is characterised by the strongest spring blooms, the fewest low chlorophyll-a concentrations, and the highest variability of the optical water conditions.

3. Stable, clear and maritime atmospheric conditions are further critical to the ocean colour processes and the minimization of the OC-SVC uncertainties, see sections 2.2 and 4.2. Nevertheless, all candidate locations are affected by Saharan dust outbreaks and the dust must be accurately detected and screened out, even at low levels. El Hierro exhibits the clearest oceanic atmosphere but also the largest number of dust outbreaks, Madeira is possibly similar. Fewer dust events but small levels of pollution are found at the Crete sites. Then progressively fewer dust events but increasing levels of pollution, including urban or biomass burning aerosols, are observed at the Lampedusa sites and, finally, at BOUSSOLE.

4. Logistical readiness is important to ensure the value for money and the security and dependability of the OC-SVC investment. BOUSSOLE, MSEA-N, Antikythera and the Lampedusa sites are logistically ready. The MSEA-S and El Hierro sites would have to be established but strong local expertise and logistical arrangements already exist. The Madeira location is the least logistically ready. Madeira has no relevant marine infrastructures, observations and knowhow at the site, and it would require the largest development investment.

Taking into account all mandatory OC-SVC criteria, an initial review of the Expert Board narrowed down the selection of the candidate locations to the El Hierro, Crete and Lampedusa sites. Current additional spotlight on the most fundamental criteria, as listed above, focused the deliberations on two top ranking locations: El Hierro and the Crete sites.

7.2 Discussion of the top-ranking selection for the OC-SVC Location – 1

The El Hierro site is a top selection in terms of a number of the most fundamental criteria for the OC-SVC location:

1. it achieved the maximum of potential high quality matchups for OLCI,
2. it has stable and clear oligotrophic waters,
3. it has the clearest and the most stable oceanic atmospheric conditions from all candidate locations, excluding dust outbreaks,
4. it is not logistically ready and would have to be established but the strong local expertise and logistical arrangements already exist.

The El Hierro location is the most representative of the global oceans in terms of water and atmospheric conditions, which is a significant advantage for ocean colour. El Hierro is well performing in the context of the existing OLCI ocean colour Level-2 processing chain and it fulfils the climatological marine and atmospheric requirements to secure the OC-SVC infrastructure state-of-the-art operations into the future. Despite all the benefits, however, there also are some concerns and moderate risks associated with the El Hierro location.

The detailed benefits of the El Hierro OC-SVC candidate location are as follows:

- the largest number of high quality matchups for OLCI,
- stable and clear oligotrophic water conditions representative of the global oceans,
- the clearest oceanic atmosphere of all candidate sites, apart from dust events,
- a site location close to the island with quick access for routine operations and in case of emergencies,
- existing local infrastructure: port, divers, land for purchase to set up site operations, a local community and fishermen sensitive of environmental needs, nearby marine and ecological reserves,
- experienced team in Tenerife with history of atmospheric observations, two annual oceanographic cruises to El Hierro from Tenerife, and existing plans for establishing the El Hierro OC-SVC site,
- sheltered location in the lee of the island,
- location notably free from hurricanes and tropical storms.

El Hierro considerations and moderate risks are the following:

- reduced matchup potential for MODIS and VIIRS, mostly because of the differences in the current L2 operational processing chains and the scattered clouds impact on lower resolution imagers,
- the highest occurrence of dust events, which must be accurately detected and screened out, although all candidate sites are affected by dust,
- the highest significant wave height and wave energy, together with Madeira, although wave extremes are similar across all the candidate locations,
- hazard of volcanic events in the vicinity, similar to the one that occurred on La Palma in 2021, although with a modest impact on atmospheric conditions at the El Hierro site itself,

- narrow chlorophyll-a distribution with a single peak between 0.1 and 0.2 mg/m^3 does not allow to focus on extreme oligotrophic waters Chl $\leq$ 0.1 mg/m^3; it can however also be considered as a benefit with respect to signal radiometric stability,
- no aerosol monitoring stations on El Hierro needed to determine dust events,
- costing volatility,
- the location slightly too close to the shore to fully avoid the remote sensing adjacency effect from the land.

7.3 Discussion of the top-ranking selection for the OC-SVC Location – 2

The Crete sites are the other top selection in terms of a number of the most fundamental criteria for the OC-SVC location:

1. with respect to the high quality matchup potential, they provide a compromise: the second after El Hierro (and Madeira-OPT) for OLCI, and the first for MODIS and VIIRS missions,
2. they have stable and clear oligotrophic waters, MSEA-S waters are the clearest of all candidate locations,
3. they have a maritime atmosphere with small levels of pollution and a moderate number of dust events, fewer than at El Hierro,
4. MSEA-N and Antikythera are logistically ready and MSEA-S would have to be established but the strong local expertise and logistical arrangements already exist.

The Crete locations are performing well in the context of the existing ocean colour Level-2 processing chains for the OLCI, MODIS and VIIRS missions and their climatological marine and atmospheric characteristics are the highest ranking among all Mediterranean sites, in support of the sites' potential into the future. The sites pose a good compromise for an alternative OC-SVC infrastructure location. Despite the benefits, however, there also are some concerns and moderate risks associated with each Crete location.

From all three Crete sites, Antikythera is located the closest to busy marine traffic routes and does not meet the bathymetry requirement, see section 5. The Crete site options were therefore focused on MSEA-N and MSEA-S.

The two MSEA-N and MSEA-S sites are interchangeable considering the criterion of the high quality matchup potential. On the other two most fundamental criteria of stable and clear marine and atmospheric conditions, MSEA-S has the clearest water optical conditions and the lowest level of atmospheric pollution (except for dust) from among all Crete sites. MSEA-S is also less impacted by busy airline traffic to Crete and marine operations. Although MSEA-S is not logistically ready and would have to be established as a site, the strong local expertise and logistical arrangements are already available. Consequently, the MSEA-S site is favoured, as the marine and atmospheric conditions are the most fundamental criteria and needed to secure the state-of-the-art OC-SVC infrastructure operations.

The detailed benefits of the MSEA-S OC-SVC candidate location are the following:

- the second largest number of high quality matchups for OLCI, after El Hierro and Madeira-OPT, and the first largest for MODIS and VIIRS, together with the other Crete sites,
- the clearest and most stable oligotrophic water conditions of all candidate sites,

- the smallest level of atmospheric pollution in the Mediterranean, apart from the dust events,
- the least cloudy location of all candidate sites, persistent cloudless spells,
- experienced team in Heraklion with knowledge of oceanographic buoy operations, atmospheric observations, and plans for establishing the South Crete OC-SVC site,
- low waves and winds,
- Eastern Mediterranean is the least impacted by medicanes.

MSEA-S considerations are the following:
- the open sea location, far from land, and logistically difficult for both routine operations and emergency access,
- no existing relevant infrastructures in South Crete, but plans exist to establish a site,
- the highest occurrence of dust events of all Mediterranean locations, but lower than El Hierro; the dust must be accurately detected and screened out, although all candidate sites are affected by dust,
- contamination by polluting continental aerosols in the Mediterranean due to surrounding land and atmospheric circulation patterns, however, MSEA-S is the least polluted because of its open sea location,
- water optical properties specific to the Mediterranean with some CDOM absorption decreasing the radiometry in the blue, yet the MSEA-S open sea East-Med location may be the least affected,
- slightly higher currents,
- no aerosol monitoring stations in South Crete needed to determine dust events.

7.4 High level summary of the top-ranking selection for the OC-SVC Location

In summary:

- Two top ranking sites have been selected: El Hierro and MSEA-S.

- Both sites have overwhelming advantages as well as some site-specific concerns or risks.

- El Hierro is superior in terms of being the most representative of the global oceans and logistically convenient. However, the impact of high waves, volcanic activity, land proximity, scattered clouds and other matchup conditions would have to be examined.

- MSEA-S is superior in terms of the clearest and most stable oligotrophic water conditions, low waves and persistent cloudless spells. However, the site distance far from the shore with difficult logistics, and the impact of local Mediterranean water and atmospheric conditions would have to be examined.

7.5 Recommendation for the Copernicus OC-SVC Infrastructure Location

The scientific recommendation:

- The Expert Review Board recommends to move to the next phase of the Copernicus OC-SVC infrastructure roadmap, Phase 4 Engineering Design – see Figure 6, with two candidate OC-SVC locations: El Hierro and MSEA-S.

The justification:

- Investigation of both El Hierro and MSEA-S locations in Phase 4 will reduce the risk for the Copernicus Programme in case one of the sites proves deficient.

- Having both sites investigated in further detail in Phase 4 will allow to develop
    - engineering constraints, technical definitions and specifications,
    - firm costings,
    - additional scientific OC-SVC evaluations,

  in order to present to the European Commission the most informed and confident recommendation for the following Copernicus OC-SVC phases.

- Accomplishing Phase 4 Engineering Design for both locations will allow to move the location to the backup one in case the following Phase 5 Development at the primary site becomes problematic.

Recommended way forward:

- Phase 4 Engineering Design is recommended to be conducted with two candidate OC-SVC locations: El Hierro and MSEA-S.

- Phase 4 will include engineering and technical specifications, firm costing, and additional scientific OC-SVC examinations. Phase 4 Engineering will assess the integration of the infrastructure from Phase 2 Preliminary Design at both locations of El Hierro and MSEA-S. The infrastructure design will be engineered to be suitable to move between the two El Hierro and MSEA-S locations.

- Phase 4 will be implemented as a single study and an open Copernicus Invitation to Tender.

- Phase 4 is a one-off activity and a one-off cost. The costs of this phase are mostly associated with manpower and, to a smaller degree, in travel, services or hardware/software.

- After the completion of the Phase 4 activities, the Expert Review Board, including the European Commission observers, will evaluate the outcome and recommend a single primary site to be considered for the Phase 5 Development, depending on the Copernicus programmatic decisions and the availability of funding.

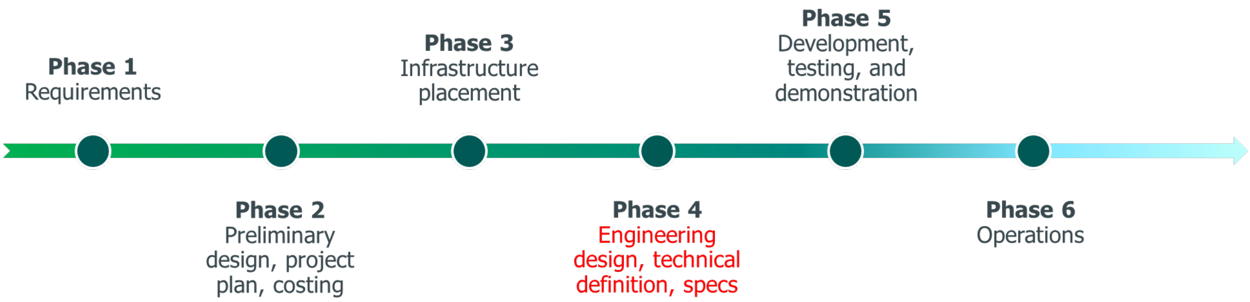

Figure 6: Copernicus OC-SVC infrastructure roadmap, the next Phase 4 concerned with this recommendation is highlighted in red.

Detailed recommendations for the Phase 4 Engineering activity:

- For both locations of El Hierro and MSEA-S, the Phase 4 Engineering Design is to include
  - an in situ aerosol observation station close to the in-water site with sufficient sensitivity to detect dust at even low concentrations,
  - specifications of the operational OC-SVC chain that will use the in situ aerosol observations as an element of quality control of the OC-SVC water reflectance measurements.

- For the El Hierro site, locations slightly further away from land are to be investigated, about 20-25 km offshore
  - the location shall still be in the lee of the island for ideal marine, atmospheric and logistical conditions but shall eliminate any possibility of the land adjacency effect,
  - the location shall be confirmed with respect to the Sentinel-2 MSI coverage,
  - at the new location the site mandatory criteria shall be re-examined, including the potential for matchups as well as the water and atmospheric climatological conditions.

- For the MSEA-S location, sites closer to the shores south of Crete are to be investigated
  - the location shall optimise the logistics of the site operations and emergency procedures versus the best marine and atmospheric conditions,
  - at the new location the site mandatory criteria shall be re-examined, including the potential for matchups as well as the water and atmospheric climatological conditions.

- For the El Hierro location, the following additional scientific OC-SVC examinations shall be carried out

    - the impact of the sea state on the infrastructure and its operations, including high waves and wave energy,
    - the potential of volcanic activities around the Canaries,
    - the impact on matchup potential of L2 processing chain, scattered clouds, spatial resolution and other instrument and environmental effects.

- For the MSEA-S location, the following additional scientific OC-SVC examinations shall be carried out
    - contamination by polluting continental aerosols from the surrounding land and the prevailing atmospheric circulation patterns,
    - the specifics of water optical properties in the Mediterranean, including CDOM absorption,
    - the impact of currents on the infrastructure.

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- HCMR/Crete University for the Crete sites,
- IEO/AEMET for the El Hierro site,
- CNR/ENEA for the Lampedusa sites,
- IPMA for the Madeira sites.

Strong support is extended for the existing ocean colour and contributing in situ measurement sites and programmes. These measurements are and will remain fundamental to the Copernicus operational activities. It is urged that the support for these sites and programmes is continued into the future.

BOUSSOLE activities are exceptionally acknowledged for their contribution to global ocean colour missions for the last 20+ years.

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