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Project : **UK EO Marine & Climate Mission Development Programme (EO4MCM)**

Title : **Indicative requirements: where EO constellations might benefit the UK**

Abstract : This document is a compilation of contributions from UK government departments and other interested parties on the requirements for satellite constellations that may be developed under the UK EO Marine & Climate Mission Development Programme. The contributions were gathered between January and April 20023 and are offered for consideration by potential developers of EO satellite constellations.

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STFC CONTRACT REPORT

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AMENDMENT RECORD

This document shall be amended by releasing a new edition of the document in its entirety. The Amendment Record Sheet below records the history and issue status of this document.

AMENDMENT RECORD SHEET

ISSUE	DATE	REASON FOR CHANGE
A	24-04-23	Draft for internal review
B	25-05-23	Added requirements on ocean colour and greenhouse gasses.
C	26-05-23	Added Section 4.
1	31-05-23	First formal issue.

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1. INTRODUCTION

1.1 Purpose and Scope

This document is a compilation of contributions from UK government departments and other interested parties on the requirements for satellite constellations that may be developed under the UK EO Marine & Climate Mission Development Programme. The contributions were gathered between January and April 20023 and are offered for consideration by potential developers of EO satellite constellations.

1.2 Structure of the Document

After this introduction, the document is divided into the following major sections:

2. PROJECT OVERVIEW

   This section outlines the DSIT EO investment programme announced on 23 November 2023 and the aims of the EO4MCM programme; it summarises the scope of this report.

3. CONSULTATIONS

   This section consolidates the inputs of the organisations consulted on the potential requirements for constellations of small EO satellites.

4. NEXT STEPS

   This section recommends next steps for potential providers of EO constellations that seek to address the indicative requirements in this document.

2. PROJECT OVERVIEW

2.1 DSIT Earth Observation (EO) Investment

The programme, of which this project is a part, was announced on 23 November 2022.

"*Earth observation (EO) is a vital science and a growing industry. Now is the right time to time to invest in projects which benefit our planet and grow our economy. EO supports the UK to become a science superpower and prioritises our space and Net Zero ambitions - more than half of key climate data comes from space.*

In the National Space Strategy, HMG committed to remain at the forefront of earth observation technology and knowhow. The investments that form the EO Investment Package (EOIP) deliver an essential funding boost to recognise the importance of this work and will benefit academia and industry and build our national capability. The funding is spread across 17 projects delivered through government partner organisations.

This significant investment package aims to benefit EO scientists and firms across the sector, from developing new sensor technologies to using EO data for improved understanding of climate change. And we are funding further skills training to ensure that we have a pipeline of talent for the future.

The EOIP aims to:

- *support the UK EO sector and mitigate the economic impact of non-association to Copernicus*
- *drive the UK's ambition to be a science and technology superpower and to remain at the forefront of Earth Observation technology and know-how*
- *create a foundation for a national strategy which builds on the world-leading excellence in UK EO for decades to come*.

The UK EO Marine & Climate Mission Development (EO4MCM) Programme is one of the 17 projects funded by DSIT (see https://www.gov.uk/government/publications/earth-observation-investment/projects-in-receipt-of-funding#science-and-technology-facilities-council-stfc---1473-million), which work through delivery partners including:

- **ESA (via UKSA)**; £122.6M for FutureEO, TRUTHS, Aeolus-2, Digital Twin Earth, and InCubed-2.
- **UKSA**; £15M for EO Technology Programme.
- **NERC**; £19.3M for UK EO Climate Information Service (UKEO-CIS), EO Data Hub, and SENSE Centre for Doctoral Training Programmes for EO.
- **STFC**; £14.73M for EO4MCM, Small Satellite Calibration Facility, UK/Australia EO AgroClimate Programme, and Surface Temperature Radiometer Network.

- **Met Office**; £11.73M for Transatlantic Data Science Academy, Twinning capability for the Natural Environment (TWINE), UK Marine & Climate Advisory Service (MCAS).

- **Innovate UK**; £4.21M for Innovation in EO.

2.2 EO4MCM Programme

As stated in the 23 November 2022 announcement:

"*The EO4MCM programme will deliver early preparation to gather UK requirements, research and industry strengths, and space technologies to build and operate a UK-led Earth Observing system to support the fight against climate change and achieving Net Zero. By working with government, academia, industry and international partners, the project will capture and translate new climate and environmental challenges of the UK and its surrounding waters into a set of mission technologies and concepts, that will help the UK prepare for future challenges.*"

The aim of the programme is to support the development of EO instrumentation for constellations of micro to small satellites that will complement the capabilities of the Sentinel spacecraft and provide the UK with a leading capability in marine and climate applications.

Our intention is to issue up to 5 grants of around £500K each to prototype an instrument with a further grant to design a spacecraft bus for instrument constellations. The timescale for the programme is short; we are aiming to issue an RFP in April with the selected projects starting by September. The end date for the project is 31 March 2025, giving a project duration of 18 months. We expect the instruments selected to already be in an advanced stage of design.

2.3 Scope of this Report

This report presents consolidated user requirements to assist in the RFP process.

The following groups were contacted for their inputs and comments:

- Government departments and agencies, including UKSA, Defra (Cefas and Natural England) and MoD.

- The Met Office

- Scientists, including NCEO and the UKEO-CIS project

- Industry via the UK Space EO Committee (EOC) and Space4Climate

- International agencies, including ESA and Eumetsat

The inputs received to date, in various formats, are synthesised in this document. They are provided as a "bucket list" guide to the current requirements of the organisations concerned.

3. CONSOLIDATED USER REQUIREMENTS

3.1 General Requirements

ESA's general points on CubeSats and climate data

- To be relevant or complementary to ESA/Copernicus, data shall be free and open data access, respecting the FAIR principles, and not bound by any commercial limitations.

- Instruments shall be characterised and calibrated on ground, and FIDUCEO requirements respected. Thus the instruments "shall" be calibrated and validated – vital for climate science.

- To be relevant – product data shall respect strict latency requirements. Instruments for weather shall satisfy this to be relevant to any data assimilation scheme. Thus, there is no point in putting up a constellation of CubeSats to improve time/space sampling unless the data are recoverable within a very specific delivery timeline. For example, today a 6U CubeSat with a 5 m GSD multispectral optical instrument would completely fill 1 Terabit of onboard memory/storage within a couple of orbits. But high-end X-Band transmitters for nano- or microsatellites currently require hours of downlink time to get the data to the ground. This means that the instruments are off when the memory is full – resulting in delays of days before the data arrive at the ground processing facility. So, removal of storage limitations, onboard image processing, exploring the possibility of optical links, and/or inter-satellite communication are fundamental to the future of CubeSat constellations

- For info, at ESA level,

  - InCubed co-funds most of our EO CubeSats with a commercial-objective, and not necessarily very scientific (e.g. limited calibration) – details are in incubed.esa.int (e.g. for MANTIS, Hyperfield, Ororatech, …)

  - Phi-sat(s) are technology demonstrators

  - We have studies on VHR (Very High Resolution) complementing Copernicus Sent.2, but not all concepts are in CubeSat format.

  - Scouts: 2 in implementation (HydroGNSS not a CubeSat + CubeMAP with RAL) + 2 very likely to be chosen for implementation in Nov-2023

  - GSTP Fly missions, some with EO concepts

- A public presentation from ESA in 2021 for UK CEOI gives an overview of Small sat missions/instruments for future EO in the ESA landscape with part 2 here.

Other high level points

- A high spatial resolution is achievable but there is a trade-off with the amount of data that can be handled so there is likely to be more targeting with higher spatial resolution to keep the data volume to an acceptable level.

- The algorithms and data processing model needs to be considered so that the operational needs of users for timely processed data are met. Consider a close collaboration between the instrument developer and final data processor developer from the early phases of the programme.

3.2 Marine use cases

For maritime surveillance (fisheries protection etc)

- Passive SAR in constellation with S1 for bistatic vessel characterisation (and if you can achieve the performance, surface current retrieval)

- RF signal detection over VHF to X band (for mobile telephone to surface radar detection/location)

- Optical/NIR panchromatic video capability for activity monitoring in port areas

For marine science/sea level and sea state observations

- You could consider a constellation of 12 small altimeters. Volume and power constraints would probably mean that we cannot use the fully-fledged SAR interferometric altimeter like the one ESA will have on CRISTAL, so trade-offs in terms of the technology that can be fit on the system would have to be explored. But the availability of sea surface height and sea state data from such a constellation would allow a quantum leap in our monitoring of ocean surface dynamic and sea state. Suboptimal spatio-temporal sampling is the current main limitation of altimetry. Both variables (sea level and sea state), when downloaded in NRT, would have very high operational value exactly by virtue of the unprecedented sampling; the constellation would also be highly synergistic with the current and future topography constellation and we would use the many crossovers for calibrating the CubeSats against the accurate Sentinel -3 and -6, so that the non-time-critical data would greatly enhance the monitoring and understanding of ocean dynamics and sea state at scales not currently resolved.

Salinity sensor

- A salinity sensor capable of a resolution of 100m i.e. to determine the dynamics of major rivers (Thames, Humber) at target frequency of daily - the hydrological cycle is increasing in importance due to droughts and floods at increasing frequency and severity. Basic salinity data at high resolution is also essential base data for oceanic circulation (ice melt) and precipitation. Further inshore, understanding ground water movements (and their expression offshore) is important for small island states. Finally, fresh water seeps may provide sources in arid parts of the world e.g. Gulf. (see also attached pdf).

Environmental Situational Awareness

- The constellation aspect is also essential for processes that have evolution times or advection times shorter than overpasses by Sentinels. A recent example is from NE coast of the UK where crabs were washing ashore (see Teesside crab deaths investigation - Defra in the media (blog.gov.uk)). Whilst a major algal incident was a significant possibility, the lack of data from the region at sufficient resolution (10's of metres at sub daily timescales) of chlorophyll, suspended sediment concentration and temperature resulted in an algal incident being identified as "possible" but no firm causative link could be made. In the end a disease outbreak was assessed as the most likely source. (see Independent Expert Assessment of unusual crustacean mortality in the north-east of England in 2021 and 2022 (publishing.service.gov.uk)). Furthermore, a large number of activities in the marine environment are relativity short lived (say a few hours for dredging, disposals, cable laying, construction), Sentinels are intrinsically biased against capturing the instantaneous maximum impacts. Thus, "environmental situational awareness" is one of major goals. This also plays in the Net Zero agenda, as sending research ships is expensive in both terms of UK Pounds but also carbon.

Storm surge monitoring and impacts on sargassum seaweed, mangroves and coral reefs

- Sargassum seaweeds are a significant issue for beaches in the Caribbean. Monitoring the spread of sargassum would be useful; the same data might also be useful for sea grass bed and coral monitoring in shallow waters.

- Storm surge modelling is fundamentally about assessing changes in shallow bathymetry, which is a crucial input to such models. Seagrass, coral reef and mangrove mapping all impact on resilience to storm surges.

Marine litter

- Cefas are using drones to achieve 1 cm resolution to look at marine litter (can also be used to look at plastic pollution). Small satellites would give 1 m resolution, a bigger spacecraft could get down to 10 cm. 1m resolution would be useful to detect floating litter (the more bands the better to separate plastic and algae etc.). There is global interest in this application, e.g. from Ghana, Belize and Caribbean islands.

Offshore windfarms and sediment movements

- Impacts of windfarms, including likely sediment movements/scouring. Assessments of sediment movement in the marine environment is also critical in terms of sediment input as runoff in coastal areas. This ties in with the requirement to monitor impacts of decommissioning of oil and gas infrastructure.

SAR applications

- SAR is also an option; specialised small SARs are now possible for specific uses. Different SAR frequencies would be useful in some applications, e.g. to detect illegal fishing vessels in marine protected areas in waters off Belize or around the Ascension Islands, for instance. Illegal fishing is a financially significant loss to small states.

Natural England "wish list"

- Increased repeat coverage to combat key issue for NE is that to get hi-res inter-tidal coverage -chance is only 3% as a result of cloud cover and satellite orbits/ narrow swath. Functionally usable Intertidal and infralittoral data relates to tidal cycles.
- Satellite path - a wider range of orientation (than currently available) to increase coverage could be helpful for gathering evidence?
- Supporting attributes (help us understand the condition of our features and their ecosystem delivery)
    - Text below is taken from a report Science Search (defra.gov.uk) that NE contributed too in 2019 identifying evidence and knowledge gaps for monitoring of MPAs. Basically it boils down to better resolution info, real time and processed outputs covering:
        - Satellite ocean colour imagery enables the measurement of productivity (Chlorophyll a) (Vargas et al., 2009),
        - Suspended Particulate Matter (turbidity) (Loisel et al., 2014),
        - Nutrient enrichment (coloured dissolved organic matter (CDOM)), and Dissolved Oxygen.
        - Microwave radiometry and infrared imagery can map sea surface temperature (Prigent et al., 2013; Kilpatrick et al., 2015).
        - Satellite borne optical sensors can also measure derived parameters such as Secchi Disk Depth, Total Organic Carbon, Dissolved Organic Carbon, Total Suspended Matter, Sea Surface Salinity, Total Phosphorus, Ortho-Phosphate, Chemical Oxygen Demand, Biochemical Oxygen Demand, Electrical Conductivity, and Ammonia Nitrogen.
        - record wave height and direction (Stopa and Mouche, 2017) and monitor sea ice (Geldsetzer et al., 2015).
- Physical parameters – very relevant to climate change modelling. Wave height (sea state), speed and direction of travel. Tidal ranges, accurate sea level rise. Identification of tidal fronts/ upwellings
- Species
    - Marine mammals – 20cm-50cm monitor megafauna (Fretwell et al., 2014). Large marine mammal and mammal groups (aggregations of warm -blooded marine mammals) temperature.
    - Intertidal habitats.
- **Anthropogenic pressures**. Pressures (2cm-50cm resolution) High resolution visible and infrared imagery can be used to indicate illegal fishing activity (Elvidge et al., 2015) and
    - <10 m vessels – inshore fishing fleet. Repeat datasets to build up an understanding of inshore fishing fleet distribution, and analysis of wake direction and distance to infer speed of travel as a proxy for activity (actually fishing or transiting – or powerboating etc

  - Non-powered craft – surfing, jetskis, paddleboards Kayaks etc
  - Intertidal recreational use?
  - Intertidal damage? (can EO backscatter identify bait-digging, anchor scaring etc?)
  - Plastics pollution detection
  - Surface Oil Synthetic Aperture Radar (SAR) imagery can be used to detect oil spills (Xu et al., 2014)),
- Sea surface bathymetric as a proxy for seafloor
- **Seafloor bathymetry** – deeper waters and higher resolution. Bathymetry can be measured using sonar or, in shallow water, LiDAR, satellite imagery or hyperspectral aerial imagery (Gao, 2009; Klemas, 2011).
- **Seafloor backscatter** – is this possible? Coupled with better bathymetry this would be a game changer for habitat mapping in the infralittoral zone <=25m (where most of our MPA features are).
- Near shore bathymetry and backscatter for habitat mapping. Satellite-derived bathymetric (SDB) remote sensing research utilizes ocean optics to estimate near-shore bathymetry elevation values using satellite imagery (e.g. Satellite-Derived Bathymetry (SDB) - Earth Observation & Environmental Services | EOMAP).

3.3 Climate use cases

Arctic

- Arctic capabilities require all-weather microwave instrumentation (e.g. ultracompact radiometers), and since high latitude climate observations rely on year round (seasonal-interannual) observations, we are no longer talking about CubeSats (or nanosats) - rather satellites of the order of 8U or 16U. These are by definition microsatellites. So there needs to be clarity on the power/volume/mass restrictions for any of this info to be relevant.
- microwave instrumentation remains largely out of reach for current CubeSats of < 3-4U. Radio occultation or Sounders are the principal options – but RO is already implemented (e.g. SPIRE/Clydespace) – and ESA is already pushing the Arctic Weather Sat, with scale up in the EPS-STERNA constellation for polar sounding.
- *So for the Arctic it may be better to focus on passive optical instrumentation.*
- Highly elliptical 12h Molniya or 24hr Tundra orbits were originally used for Soviet military communications satellites, and are currently exploited by the Arktika satellite series led by Russia. Molniya orbits would therefore be good for improving persistent polar imaging (using multichannel optical instruments) – but this would place very special requirements on the smallsat launcher - and would require special spacecraft protection, since passing through the Van Allen belt. The latter constraint means that a feasibility study would be of use before any other more elaborate concept is drawn up. The fixed inclination angle of such an orbit (63.4 degrees) is required to mitigate the need for propulsion for active orbit station keeping.

Surface temperature

- The UK EOCIS has an activity to create better EO-based climate information for surface temperature across all surface types for the UK at high enough spatial resolution for enhancing climate resilience and decision making. Applications include urban heating, effects of green space in cities, inland and coastal water temperature for ecosystem impacts, and landscape temperature affecting agriculture and health of ecosystems including peatlands.
- Requirement: sub-daily-repeat (day and night), semi-autonomously targeted surface temperature measurement at <50 m (nadir) resolution for UK.
- What features of instrument?
    - At minimum, a "split window" infrared radiometer (11, 12 μm) which enables adjustment of top of atmosphere brightness temperature to the surface, given emissivity assumptions. Consider also 8.7 μm to enable use of temperature-emissivity separation algorithms.
    - Additionally at minimum, a set of visible reflectance channels to aid cloud detection and targeting (towards cloud-free areas). Example minimum set: green, red, 1.6 μm near-infrared.
    - Infrared uncertainty to be <0.2 K with respect to pixel-to-pixel relative noise. Infrared uncertainty with respect to bias to be <0.75 K using on-board calibration. Calibration to be sufficiently stable to enable in-flight estimation of bias adjustments achieving <0.2 K bias, e.g. calibration stability to <0.1 K throughout an orbit, to <0.1 K across every image acquisition, and <0.1 K in mean bias variation between successive orbits. These requirements target a surface temperature uncertainty in total in a single-pixel surface temperature of order 1 K, accounting for error-amplification within the retrieval process.
- What platform?
    - Need multiple sensors on constellation of multiple platforms in Low Earth Orbit (LEO), giving the opportunity for acquisition across the British Isles every 3 hours.
    - A key concept is that the platform (or instrument) should be pointable with an optimised strategy to exploit available swath width: e.g., semi-automatic pointing either side of nadir to (1) maximise the coverage of UK-land-and-coasts at zenith angles up to 35 degrees, (2) maximise the clear-sky coverage by on-board detection of clouds and tasking accordingly, and (3) maximise clear-sky acquisition of taskable prioritised targets such as urban heat island areas or water bodies of particular amenity.
- Heritage?
    - Consider Landsat, TRISHNA, Copernicus LSTM, ECOSTRESS, and the HEEPS/Optical and Satellite Vu technologies are presumably relevant too.
- Design for improvements in the following regards:
    - Higher spatial resolution than Landsat, moving towards large-building scale and able to resolve many more UK-scale water bodies etc.

  - Pointability to maximise useful acquisitions, distinct from other missions, and also to sample the radiative flux from multiple angles. (Note: the variety of satellite zenith angles thus obtained for a given urban area is ultimately a useful additional set of information for understanding urban radiative emissions.)
  - Constellation is able to collect information on the full diurnal cycle of temperatures under clear skies, crucial for issues like health impact of heat waves (health impacts vary with time of day, e.g., the persistence of heat built up during the day into the evening is important).

- Limitations?

  Surface temperature uncertainty will inevitably be relatively high in trade-off against resolution and detector technology, but can be improvement in complementarity with well-calibrated missions like SLSTRs in flight by cross calibration.

- Validation, in situ data?

  Would probably rather validate and in-flight adjust calibration of such a sensor against clear-sky sea surface temperature acquisitions from well-calibrated sensors such as SLSTR. These in turn are calibrated against in situ.

Coastal, Transitional and Inland Water Colour

- What data?

  Requirement: daily water colour measurement at <50 m (nadir) resolution for UK coastal, transitional and inland waters.

- What requirement for the data?

  The UK EOCIS is creating better EO-based climate information for water quality in coastal and inland waters in the UK at higher spatial resolution (100m initially) for enhancing climate resilience and decision making. Applications include ensuring inland and coastal water quality, including managing pollution or runoff events, preventing economic and health effects of harmful algal blooms, and understanding the underwater light climate through dissolved and suspended matter distributions.

- What features of instrument?

  Wavebands in the visible in key parts of the spectrum e.g., blue (412, 443 and 490) green (510, and 560 nm) and red (620, 665 nm) with near infrared wavebands as reference bands (709 nm) and for atmospheric correction (740, 783, 842, 865 nm). Ideally, shortwave infrared wavebands are included to improve atmospheric correction and water detection. Typically, wavebands include the configuration of current constellations used for aquatic applications on high resolution (Sentinel-2 MSI) and moderate resolution ocean colour sensors (Sentinel-3 OLCI).

Signal to noise needs to be > 500 at reference radiance typical of water. Pointing capability to view away from the sun to avoid sunglint. Ideally, on-board calibration monitoring to assess sensor degradation.

- What platform?

  Need sensors on constellations of multiple platforms in LEO, giving the opportunity for acquisition across the British Isles at least daily and ideally every 3 hours during daylight to avoid cloud cover and detect tidal influence. Ideally, instruments would be co-located with an SST instrument.

  A key concept is that the platform (or instrument) should be pointable with an optimised strategy to exploit available swath width: e.g., semi-automatic pointing either side of nadir to (1) maximise the coverage of UK-land-and-coasts at zenith angles up to 35 degrees, (2) maximise the clear-sky coverage by on-board detection of clouds and tasking accordingly.

- Heritage?

  Sentinel 2 MSI, Landsat 9, Sentinel 3 OLCI.

- How is this an improvement?
  - Higher frequency observations (Sentinel 2 typically every 2-3 days over the UK before cloud masking) concept would be daily to multiple daily
  - Narrower visible wavebands than Sentinel 2 MSI or Landsat 9, with bands optimised for water colour observation and increased S/N.
  - Additional wavebands to target key aquatic components, compared to current high-resolution instruments: towards shorter wavelengths at the edge of the UV (400 nm) for dissolved organic matter detection, additional wavebands in the near-infrared for quality control (capturing the absorption signature of pure water), and in the visible around key pigment absorption and fluorescence features of cyanobacteria (620, 650 nm) and red algae (580 nm).
  - Pointability to maximise useful acquisitions, distinct from other missions.

- Limitations?

  Sensor calibration may be limited on a small sensor; narrow swath; linking with TRUTHS would be beneficial.

- Validation, in situ data?

  In situ radiometry at locations around the UK and in inland waters (system vicarious calibration, including atmospheric correction performance), together with TRUTHS (sensor cross-calibration at top of atmosphere).

- How does the instrument maintain UK leadership in this area?

  The UK led on lake water EO projects such as GloboLakes and is science co-lead on the ESA Lakes Climate Change Initiative and Ocean Colour projects.

EUMETSAT input

For marine Surface Temperature we can point you to a couple of published documents in the public domain, originating from the GHRSST and CEOS SST-VC communities respectively:

https://www.frontiersin.org/articles/10.3389/fmars.2019.00420/full

https://ceos.org/document_management/Virtual_Constellations/SST/Current_Future_SST_Missions_Towards_2050.pdf

These documents address priorities and gaps in the constellation from the user perspective.

Greenhouse gas monitoring

- methane observations are a critical application and are needed to verify estimates provided to the IPCC.
- Together, carbon dioxide (CO_2) and methane make up around 90% of global anthropogenic greenhouse gas (GHG) emissions. In the UK, better monitoring of emissions of both CO_2 and methane is essential to support legally binding carbon emissions reductions efforts such as the “Net zero” 2050 Target Amendment to the Climate Change Act, as well as voluntary pledges from the private and public sectors. A dedicated satellite instrument or constellation providing the required temporal and spatial resolution in combination with sufficient GHG measurement sensitivity, accuracy, precision, and measurement traceability would be invaluable in helping achieve UK EO goals and would be a strong candidate for a national mission.
- Direct and useful observations of CO_2 will likely not be feasible from a cube to small-sat sized platform. NO_2 measurements are used widely as a robust proxy for combustion CO_2, considering atmospheric chemistry, and so it is this species that is proposed as an observation target for a cube / small sat sized platform: around 80% of UK GHG emissions are associated with combustion, with transportation contributing the greatest proportion (2021 UK GHG Emissions Figures). NO_2 is also directly harmful to human health as a pollutant and as a precursor for tropospheric ozone and aerosols. Using NO_2 as observation target eases instrument design significantly, with operation in the UV and visible as opposed to the infrared spectrum for CO_2 resulting in high levels of observed solar flux helping establish good instrument SNR with relatively compact optical designs.
- An NO_2 instrument with a ground resolution of around 100 – 500 metres would provide the resolution needed to improve source attribution and to help refine bottom-up inventories. A retrieval accuracy of 2×10^{-15} molecules/cm^3 has previously been suggested by ESA for the HAPI instrument, and this is suggested here as a starting point. Constellation deployment to reduce revisit times to around a day would be valuable for monitoring of short-term trends. Sub-daily revisits would allow diurnal cycles to be identified.
- Methane is a powerful but short-lived greenhouse gas (lifetime of ~12 years), with both natural and human-driven emissions. Reducing emissions of methane is therefore an effective and rapid mitigation strategy for rising surface temperature.

Leaks from point sources, especially from the oil and gas industry, represent a significant proportion of anthropogenic emissions, and a major cost to the economy and global environment. Higher spatial resolution methane sensing from space enables better detection and repair of these methane leaks.

- Methane is a more challenging observation target than NO_2, with observations in the short wave infrared preferred for sensitivity to near-surface methane emissions. Observations of non-point source emissions are also more challenging, especially from a small satellite platform, and a trade-off must be made between spatial resolution and methane detection limit. A small satellite methane instrument with high spatial resolution of around 50 metres and a leak detection threshold of around 400 kg/hr would see a significant proportion of EU point source emissions (90% or more) and help drive significant emissions reductions efforts from the natural gas sector. More diffuse emissions such as from agriculture could potentially be identified through spatial averaging as required. A short revisit time would allow intermittent sources to be captured – a constellation of around 10 satellites should provide an approximately weekly revisit with global coverage, however this does not account for cloud cover.

Met Office requirements

The Met Office will be able to use marine and climate data to improve their weather forecast and climate models through verification, data assimilation and post-processing, and better detect climate change through improved climate monitoring. This will help:

- Government, the public and businesses benefit from more accurate weather and marine forecasts nationally and internationally.

- Government departments, local authorities and businesses plan better for the mitigation and adaptation to the effects of climate change in the UK, and internationally.

What Marine and/or Climate data are required?	What is the requirement for these data?	What in situ measurements are required to validate the data? What existing EO missions would these data complement?	Additional Comments
Increased sample sea-surface height, significant wave height and wind speed (altimeter equivalent) At least equivalent to altimetry 1Hz data	More regular passes over European Northwest Shelf Seas region to improve sampling of temporal variability in storm surge	Offshore water level gauges Sentinel-3, Sentinel-6, AltiKa, Jason-3	Existing altimetry sample the region with 1-2 tracks daily; a significantly higher number of passes are needed to properly capture a short lived storm Ability to sample the coastal zone (1-10km from shore) would be highly valuable
Total surface current velocities	Fills a major observation gap – spatial variability of currents offshore is rarely observed.	Current meters, drifting buoys	
Inland waters (lakes, major rivers) surface height and temperature	Improved monitoring of inland waters impacts on flooding and local weather	River gauges SST missions (see below) often provide lake surface temperatures, but these are usually not optimised for lakes	
Ocean colour	Improved coverage of ocean colour data through more regular sampling (increased likelihood of measurements during breaks in cloud cover)	In situ moorings Sentinel-3, Aqua	Should enable derived parameters, e.g. Chlorophyll concentration and estimate of Secchi depth

What Marine and/or Climate data are required?	What is the requirement for these data?	What in situ measurements are required to validate the data? What existing EO missions would these data complement?	Additional Comments
Sea-surface wave spectra	Either – fills a sampling gap by providing more passes - or – provides new capability by sampling wave spectral energy in the 25m – 1km wavelength range	Sentinel-1, CFOSAT	Existing Synthetic Aperture Radar only really capable down to 150m wavelengths
Sea-surface temperature	Accurate sea-surface temperature data to complement existing sources, including highly accurate temperatures to use as validation data, information on the diurnal cycle and temperatures near the coast.	Argo floats, CTD surveys, ocean gliders, drifting buoys Sentinel-3, MetOp, MSG, JPSS, NOAA-20, GCOM-W, etc.	Existing satellites provide global coverage at discrete times of the day from polar orbiting satellites and multiple times per day at low to mid latitudes from geostationary platforms. New data would need to compliment these sources through, for example, providing more looks at the ocean per day at high latitudes or at improved resolution.
Sea-surface salinity	Satellite sea-surface salinity data are not currently assimilated at the Met Office but there is a desire to do so in future. New observations would complement other data sources and help to constrain the modelled salinities.	Argo floats, CTD surveys, ocean gliders SMOS	

What Marine and/or Climate data are required?	What is the requirement for these data?	What in situ measurements are required to validate the data? What existing EO missions would these data complement?	Additional Comments
Sea-Ice concentration and thickness	Sea-ice concentration data could be used to validate existing satellite sources and provide resilience to loss of existing satellites; thickness data are not currently assimilated at the Met Office but there is a desire to do so in future. New observations would complement other data sources and help to constrain the modelled sea ice.	GCOM-W, DMSP, Cryosat-2, SMOS	
Observations targeted to fill measurement gaps in understanding key systems related to climate tipping points.	e.g. for answering key scientific questions relating to the Amazon rainforest, the N Atlantic sub-polar gyre and the Antarctic circumpolar currents and specifically the deep-water currents relevant to ice-shelf melting.		Very open and needs further scoping.

What Marine and/or Climate data are required?	What is the requirement for these data?	What in situ measurements are required to validate the data? What existing EO missions would these data complement?	Additional Comments
Observations of the urban environment	Higher "resolution" (i.e., greater ability to discriminate different features) over urban areas already being observed by "conventional" satellites would be of interest. If the more detailed "novel" satellite observations could be used to disaggregated the existing observation for things like land-use or flooding in urban environments they could be used to generate decadal-scale timeseries of urban land-use which could be relevant in understanding trends in urban climate impacts, effectiveness of resilience or adaptation actions etc.	High resolution urban networks Sentinels (and other current or past satellites)	Could be relevant in the context of the first activity planned for the IPCC 7th Assessment Report cycle - a special report on climate change and the urban environment.

What Marine and/or Climate data are required?	**What is the requirement for these data?**	**What in situ measurements are required to validate the data?** **What existing EO missions would these data complement?**	**Additional Comments**
High temporal resolution observations from constellations of small satellite relevant to:	Near surface soil moisture changes Flooding, river flow, ice melt Monitoring local scale CO2 (and other atmospheric gases) fluxes in near real time – identification of sources/sinks, potential for alignment with surface flux measurements Ecological changes – monitoring change, early warning indicators, disaster risk reduction. Crop productivity changes Forest health – pest/pathogen attack, fire spread Species movements – locust monitoring (other pests), large herds, migrations.	Sentinels	

Note on Met Office operations

- Operational forecast models are updated up to 4 times daily, therefore a repeat cycle that was similar would be helpful. Ideally, data would be available within 3-hours of measurement to fit with data assimilation windows for a 4 times daily update.

- Repeat cycles and coverage should take into account how these augment existing EO constellations (e.g. Sentinel missions).

- Our present model resolutions and process representation scales are of order 1-100km and 10 minutes – 3 hours. This is likely to remain the case for our major operational systems for another 10 years. Observations on significantly higher scales (e.g. metres and seconds) would need to be post-processed to be compatible with the models.

- Ideally, accuracy should try to attain similar standards to existing systems and Global Climate Observing System requirements. As important is that accuracy is measured and stated, as Met Office will use this information within data assimilation methods (observations error estimate).

- Quality flags are a necessity for application of the data.

- Our preferred formats for data ingestion are BUFR and netCDF.

3.4 Other Needs

Other needs identified by ESA

- Limb imaging spectrometers for atmospheric composition of Upper Troposphere and Lower Stratosphere

- Microsat-based Gravity field or magnetometry missions

- Optical/NIR MS with channels optimized for coastal benthic habitat status characterization (in particular the yellow band)

- HR TIR but using LSTM as calibrated reference source – resulting constellation increases capability to characterize diurnal variation in coastal SST and also map changes in river outflow, industrial discharge etc

- HR TIR sensors for diurnal vegetation stress, NRT fire detection and urban heat islands as application areas, but there are already related developments ongoing e.g. Orora Tech, Satellite Vu for HR MIR

4. NEXT STEPS

This document provides a selection of UK requirements for higher resolution and/or more frequent data, which constellations of small EO satellites might be able to provide. The examples given are not exhaustive and additional requirements may be added in future issues of the document.

Providers and potential providers of EO constellations are invited to consider the indicative requirements in this report, and similar requirements that they are aware of, in the light of the technology that is available to them. For more detailed information on particular requirements, providers are invited to contact the organisation that has provided the indicative requirement.

The associated Announcement of Opportunity (AO) provides a route for providers to propose preliminary designs for EO constellations that could provide data required to meet particular user requirements, backed by a business case and an outline plan for the further development and operation of the constellation.