## Cover sheet for response to an Ofcom consultation

### BASIC DETAILS

Consultation title: Strategic review of satellite and space science use of spectrum

To (Ofcom contact): James Richardson

Name of respondent: Professor John Remedios

Representing (self or organisation/s): National Centre for Earth Observation and the Natural Environment Research Council

Address (if not received by email):

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Name Professor John Remedios

Signed (if hard copy)

# NERC-NCEO Response to Ofcom strategic review of Space Science use of spectrum

## August 2015

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# 1 Introduction to the Response from NERC and NCEO

**This response to the Ofcom review is produced by the National Centre for Earth Observation (NCEO) on behalf of Natural Environment Research Council (NERC).** We concentrate only on the Earth Observation (EO) aspects of Space Science which is the aspect that we are expert in and which is extremely relevant to our business.

**Satellite data in the form of Earth Observation (EO) are vital to the world-leading environmental science that is undertaken in the UK.** Approximately 35% of NERC science uses EO as part of its activity, resulting in hundreds of published papers every year in leading journals. Furthermore, the EO datasets, and the research knowledge of the NERC-funded community, are subsequently embedded in benefits to UK of public and private services such as weather forecasting, evidence for policy decisions at national and global level (e.g. UK legislation, international treaties), societal benefits arising as a result of informed choices in sectors such as health, agriculture and infrastructure, and business benefits involving use of EO data such as in the insurance industry or carbon markets.

**Estimated monetary values of the benefit areas are on the order of billions to tens of billions for public services[1], increasing to hundreds of billions (or even trillions; c.f. the Stern review[2]) for international treaty consequences[3].**

**Within the spectrum exploited by EO science and beneficiaries, there are essential satellite services operating in the region below 100 GHz** as well as higher microwave, terahertz, sub-mm and onwards into the infra-red and optical/near ultra-violet. Frequency usage is mainly driven by the laws of Physics (as explained later), i.e., by atmospheric absorption, surface emissions of signals, and surface reflectivity (albedo)/scattering; technology plays a role but more in terms of mission implementation drivers such as power and cost. All of the satellite services, whatever the observation frequency, use downlink channels in the region below 100 GHz so that the value chain for the entire EO sector in space science is dependent on this region.

In this response, we provide information principally on the use of electromagnetic spectrum below 100 GHz whilst pointing briefly also to frequencies up to Terahertz.

Below we include more detailed information on our organisation so that the expert nature of the response is clear.

*The Natural Environment Research Council (NERC)* is the UK's leading public funder of environmental science. it invests £330 million each year in cutting-edge research, postgraduate training and innovation in universities and research centres. NERC scientists study the physical, chemical and biological processes on which our planet and life itself depends – from pole to pole, from the deep

[1] The Montreal Protocol and the Green Economy, United Nations Environment Programme 2012, http://www.unep.org/ozonaction/Portals/105/documents/publications/green-economy-report.pdf

[2] Stern Review on the Economics of Climate Change, http://webarchive.nationalarchives.gov.uk/+/http:/www.hm-treasury.gov.uk/sternreview_index.htm

[3] United Nations Framework Convention on Climate Change and related treaties, http://unfccc.int/2860.php

Earth and oceans to the atmosphere and space. NERC partners with business, government, the public and the wider research community to shape the environmental research and innovation agenda. NERC science provides knowledge, skills and technology that deliver sustainable economic growth and public wellbeing.

NERC science leads the world in excellence and efficiency:

- UK environmental scientists produce more top-ranked publications per pound invested than any comparable nation.
- NERC scientists deliver 5000 refereed publications each year that are cited 40 per cent more often than the UK average.

NERC supports:

- 3000 scientists and 1000 PhD students.
- 1000 research projects and 60 UK or international programmes.
- 55 universities and 20 research institutes.
- UK research capability including 4 ships, 7 aircraft, 6 polar stations,
- 6 data centres and 32 community facilities.
- Knowledge exchange and innovation activities with businesses, government departments and agencies, and local authorities.

NERC includes a number of high profile research centres such as the British Antarctic Survey, British Geological Survey, the National Oceanography Centre, and the Centre for Ecology and Hydrology.

These facts and further information on NERC can be found on the web-site www.nerc.ac.uk and in NERC's strategy "The business of the environment".

*The National Centre for Earth Observation (NCEO)* is one of NERC's Research Centres and specialises in satellite and other remote sensing data. NCEO has more than 80 expert scientists distributed across leading UK universities and research organisations and hosts key satellite data processing and archival facilities for the research community. NCEO provides the UK with core expertise in Earth Observation science, data sets and merging techniques, and model evaluation to underpin Earth System research and the UK's international contribution to environmental science. NCEO scientists work strategically with space agencies, play significant roles in mission planning, and generate internationally-recognised data products from 20 different satellite instruments. NCEO scientists publish more than 100 research articles every year and contribute to major environmental science reports.

*NERC and NCEO have a range of stakeholders and partners* across government and business. NERC works closely on research science exploitation with the Met Office and the Satellite Applications Catapult. It provides advice to government ranging from BIS organisations such as the UK space Agency to Defra and DECC. Defra is just instituting an EO Centre of Excellence with support from NCEO. Indeed EO is being examined as a valuable tool across government. NERC works with both upstream industry building satellite instruments for EO, particularly next generation satellite instruments to address key scientific questions, and downstream industry working on EO applications building on scientific techniques and data. NERC trains significant numbers of scientists who subsequently join these organisations and provide much-needed capability. We have liaised with the UK Space Agency and Met Office in developing our response.

# 2 Response to Ofcom questions

## 2.1 Question 1

*Question 1: Do you have any comments on our approach to this review?*

We very much welcome the review as part of the improving opportunities for constructive inputs and dialogue between the Space science sector and Ofcom. We are particularly keen that Ofcom recognises the value of the EO sector in making use of the spectrum through its research activities which have impact in productive services, policy, societal benefit, and growing industry. W**e believe that there will need to be further exchange of information and evidence, post review, to ensure that the value of the sector is well represented.**

There is use of EO both in government and in industry (upstream or "satellite operators and instrument manufacturers"; and downstream or "services"). We are not convinced that the title of Space science will have encouraged these organisations to participate and provide submissions. Some follow-up work could be necessary to capture the main government imperatives and market drivers. We can only inform about those aspects of which we are particularly cognisant.

## 2.2 Question 3

*Question 3: Do you have any comments on our broad overview of the space science sector? In particular, do you have comments on the completeness of the list of applications, their definitions and their use of the relevant radiocommunications service(s)?*

Broadly the overview covers most of the categories but **there is considerable complexity in the mapping** between missions, instruments, services and end users (to use the space industry terminology) which is not captured.

The first complexity is the fact that each service may use multiple instruments, each with different owners, platform providers etc. Land cover mapping uses principally optical satellites and synthetic aperture radar (SAR) instruments to achieve holistic products. Weather forecasting relies on data from instruments across the electromagnetic spectrum merged (assimilated) into a numerical weather prediction model.

A second complexity from a scientific standpoint is that scientists can be involved all the way through the value chain from instrument leader (Principal Investigator) to data provision to usage of the data and development of applications (the innovation and impact agenda). For the science community and hence for science bodies, many of the boxes in the value chain involve a partnership with entities in that box, e.g., with equipment manufacturers to integrate scientific technology into the instrument, with satellite operators such as ESA to jointly deliver products from the instruments, and with service providers to share scientific knowledge and discoveries. **For EO science and**

**operational missions, the NERC community would sit more naturally in a box marked "Research knowledge, data and innovation"**.

**A notable omission is the usage by EO research and applications of Global Navigation Satellite systems (RNSS-type) signals for remote sensing**. The main usage is the large increase in satellite and ground-based *receivers* which use GNSS signals to obtain information on tropospheric water vapour (principally for weather forecasting) and ionospheric electron density (for space weather). A new developing application is GNSS reflectometry which allows for the derivation of ocean roughness and ocean winds. Hence there is a Space science value chain for navigation signals; such a chain would include the increasing research base using navigation signals for high accuracy work in geology, geodesy, oceanography, remote instrumentation, citizen networks etc.

**The section on passive remote sensing should include atmospheric information including temperature profiles, humidity profiles, cloud liquid water content etc.**

**The section on active remote sensing does not emphasize the strong contributions of synthetic aperture radar to terrestrial surface sensing** (land cover, agriculture, earthquakes, subsidence) and to **ice determination** (sea ice change, ice sheet mass balance). Active remote sensing is the only technique for obtaining vertical profiles of cloud properties and precipitation.

**A further application not well covered in the definitions is satellite-AIS**. The Automatic Identification System (AIS), originally designed to prevent ships from colliding, operates in the VHF. SAT-AIS technology provides essential information for worldwide monitoring of any maritime vessel equipped with an AIS device and is now an essential component of worldwide maritime security.

## 2.3 Question 14

*Question 14: Do you have any comments on our representation of the value chain for the space science sector? How do you think industry revenues are broken down between players at different positions in the chain?*

Environmental science plays a crucial role throughout the EESS value chain. Instruments, missions and applications start in the scientific domain and progress to provide operational and commercial systems and services. This can be clearly illustrated with the progressive development of EESS in Europe. Scientific endeavours from ERS-1, through ERS-2 to ENVISAT have now resulted in 6 series of operational Copernicus Sentinel missions aimed at supporting and providing evidence for environmental and security policy across Europe. Net economic and societal cost-benefit ratios for the Copernicus value chain have been estimated to be at least 3.7 and probably closer to 10[4,5].

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[4] Cost-Benefit Analysis for GMES, European Commission: Directorate-General for Enterprise & Industry Booz and Company, London, 19 September 2011

[5] Reported at "Copernicus- Sentinels Serving Society and the Environment", Conference organised by Greek Presidency of the Council of the European Union, the European Space Agency, and the European Commission, May 2014.

Experience has shown that it is important to **recognise and allow for the interplay between scientific, public sector and commercial interests** which is a key feature of EESS at all points in the value chain from development of new technologies, to scientific understanding to development of operational and commercial systems and services. Many of the missions currently in the scientific domain, may expect to be forerunners of operational and commercial missions of the future. **Therefore the value of a research science mission cannot be judged solely on the science results of the day important though they are.** In the Research Excellence Framework (REF) assessments of impact, twenty years has been allowed for the impact of science to take place. The Ofcom review does recognise the long timescales involved in satellite planning and delivery. This is absolutely key and is important for the space science sector as for the communication and navigation sector.

Previous system analyses have identified that a particularly important distinction in EO value chains is to delineate **intermediate users,** receiving EO-related products or EO knowledge and data, from **"end users"** who receive deliverables from the intermediate users. At least for government investments in EO, it is the end users who are the ultimate beneficiaries and who provide the ultimate rewards to the value chain. Examples include the public health benefits arising from scientific findings on ozone depletion, air pollution or knowledge of hazards; other examples include the end users of weather forecasting applications such as the insurance industry or agriculture.

## 2.4 Question 15

*Question 15: What is the extent of your organisations' role(s) in the value chain? Which space science applications (as summarised in Table 2 in section 3) does your organisation:*

- *use;*
- *provide; or*
- *help to deliver?*

*Please list all applications that apply and your role in each in your response.*

In the EO value chain, **the NERC community, NCEO and more generally the academic EO community act across the entire chain** as mission designers, data generators, data providers (to the research community and for innovation and demonstration projects), users of data and increasingly co-developers of services and applications. These activities fall into both the Passive Earth sensing and Active Earth sensing (EESS) as well as community experts working on GNSS for remote sensing (i.e., using navigation signals).

**Many of our science research activities fall into the "Service, content and applications providers" box** of the Ofcom value chain although more properly **this might be termed "Research knowledge, data and innovation"** in our case. However, many of our scientists also use EO products directly or through products derived from EO such as weather forecasts and analyses, land cover maps, climatologies of environmental parameters etc. Therefore **we are also "users"**.

**The mission design aspect and science leadership for missions** is probably better described as part of the domain of satellite operators. It is in working with agencies such as ESA, NASA, Eumetsat and the UK Space Agency that missions are realised (but see comment below).

**The UK research and academic community also has a well-documented capability to deliver critical technology items** for satellite instruments, calibrate satellite instruments and lead the build of instruments (STFC and Universities). Therefore some activities fall within the equipment manufacturer domain. Surrey Satellite Technologies Ltd is the biggest UK spin-out in this area from academia.

The UK environmental science community is increasingly strong in active techniques and data generation in the part of the spectrum below 100 GHz. Operational techniques in the UK are however strongest in the passive arena (and are well covered by the agencies such as the Met Office and ECMWF).

**Table 1: Example NERC and EO community use, provide and "help to deliver" activities for EO missions.**

| | Use | Provide (< 100 GHz) | Help to deliver (< 1 GHz) (examples) |
|---|---|---|---|
| Passive Earth Sensing | All passive EO sensing products for climate, meteorology, oceanography, surface energy balance studies. Weather forecasting and analyses produced from EO data are also used extensively | | microwave sea and land surface temperature; GNSS reflectometry; ice cloud properties |
| Active Earth sensing | All active EO sensing products for deforestation, REDD+, for climate including Arctic and Antarctic change, for imaging studies for the land surface, for earthquake research , surface deformation studies and geophysics | forest biomass estimates; land cover change for UK; sea ice mapping; ice sheet mass balance estimates; earthquake faulting and strain rates | Ice sheet elevation; sea ice thickness; cloud properties; rainfall estimates; ocean altimetry |

## 2.5 Question 16

*Question 16: For each of the space science applications you use, provide or help deliver (as identified in Question 15), and taking into account your role in the value chain, where applicable please provide:*

- *the specific spectrum frequencies used, distinguishing between the frequencies used for the science application, the frequencies use for downlinking data and, for TT&C;*

- *whether the application is limited to use of specific frequencies and why (e.g. due to fundamental characteristics of the phenomena being measured and/or availability of technology designed for that frequency);*

- *whether the applications use continuous or intermittent measurements;*

- *the typical resolution and associated measurement bandwidths, including an indication of any implication for spectrum requirements;*

- *the geography this use extends over (e.g. land or sea, and regional or global);*

- *the location of the gateway station(s) for TT&C and downlinking data;*

- *the estimated number of users.*

**This question requires quite some detail as there are a large number of EO missions, each with unique functions and others which co-contribute alongside other EO sensors. Some of the principles are also generic. Our approach to this question is first to cover the top level generic answers, summarise the frequencies used by EO sensors as a function of conventional definitions of band (C band, L band etc, describe simply the theory behind choice of frequencies by class of instrument, and then describe the applications of each class of instruments (plus a section on communications).**

**The EO research and operational satellites are typically global in geography**, unless limited by downlink bandwidth such as SAR systems and some Sentinel satellites. Commercial EO satellites are more limited and generally are tasked, i.e., by customer demand.

**The satellites for EO are in polar, low Earth orbit** or geostationary orbits. The former are intermittent in observation of a given place, driven by the orbit (typically 90 minutes) and the swath width of the sensors. However, there are a large number of sensors and so there would be a daily changing pattern of observation of any one country such as the UK. Geostationary sensors observe continuously through at least the sunlit part of the day and often both day and night. However there are no sensors operating at less than 100 GHz in geostationary orbit at the current time (but this could change in the future).

**The location of gateway stations** is better described by others such as the UK Space Agency. NERC supports the Dundee receiving station. NCEO and Universities have access to a number of small Eumetcast receivers; there are probably a few hundred in the UK belonging to a range of organisations.

**A measure of the numbers of users for these satellites is difficult** as true users connect directly to the many NERC scientists and to the NERC facilities and include UK and international users. Most of the satellites are international in operation and so UK specific numbers are not necessarily available. In addition, the numbers of true users is probably dominated by the users of intermediate products which rely on EO data. However to give a measure, UK scientists have over 500 projects registered with ESA to obtain EO data; the Dundee EO facility has 370,000 registered users. The Met Office forecast for example will be used by a large fraction of the UK population.

**The utilisation of frequencies for EO sensors, i.e., EESS (active) and EESS (passive), is fundamentally driven by the interaction of the targets with electromagnetic radiation and therefore the frequency choices for each sensor are specific, focussed on the target application and often multi-frequency.** The frequency choices have to account for signal losses (for example, in the atmosphere for surface sensors), signal sensitivity, and signal penetration (for example, in vegetation and in soil). Later in this section, we comment on the reasons why sensors are designed to operate in specific bands.

**We provide an example overview of the current utilisation of the electromagnetic spectrum by civilian EO sensors first in Figures 1 and 2**; note that we are not privy to information on EO assets used for military purposes and appropriate information on UK use of such assets (whether nationally owned or available through alliances) need to be sourced elsewhere. These figures are example overviews because there are a large number of sensors for EESS utilised in the UK either with direct involvement of UK government or through specific organisation-to-organisation arrangements with a range of international research and commercial satellite missions. Our figures and tables are not comprehensive but are a best effort to illustrate the spectrum and missions of interest to large parts of the EO community in the UK.

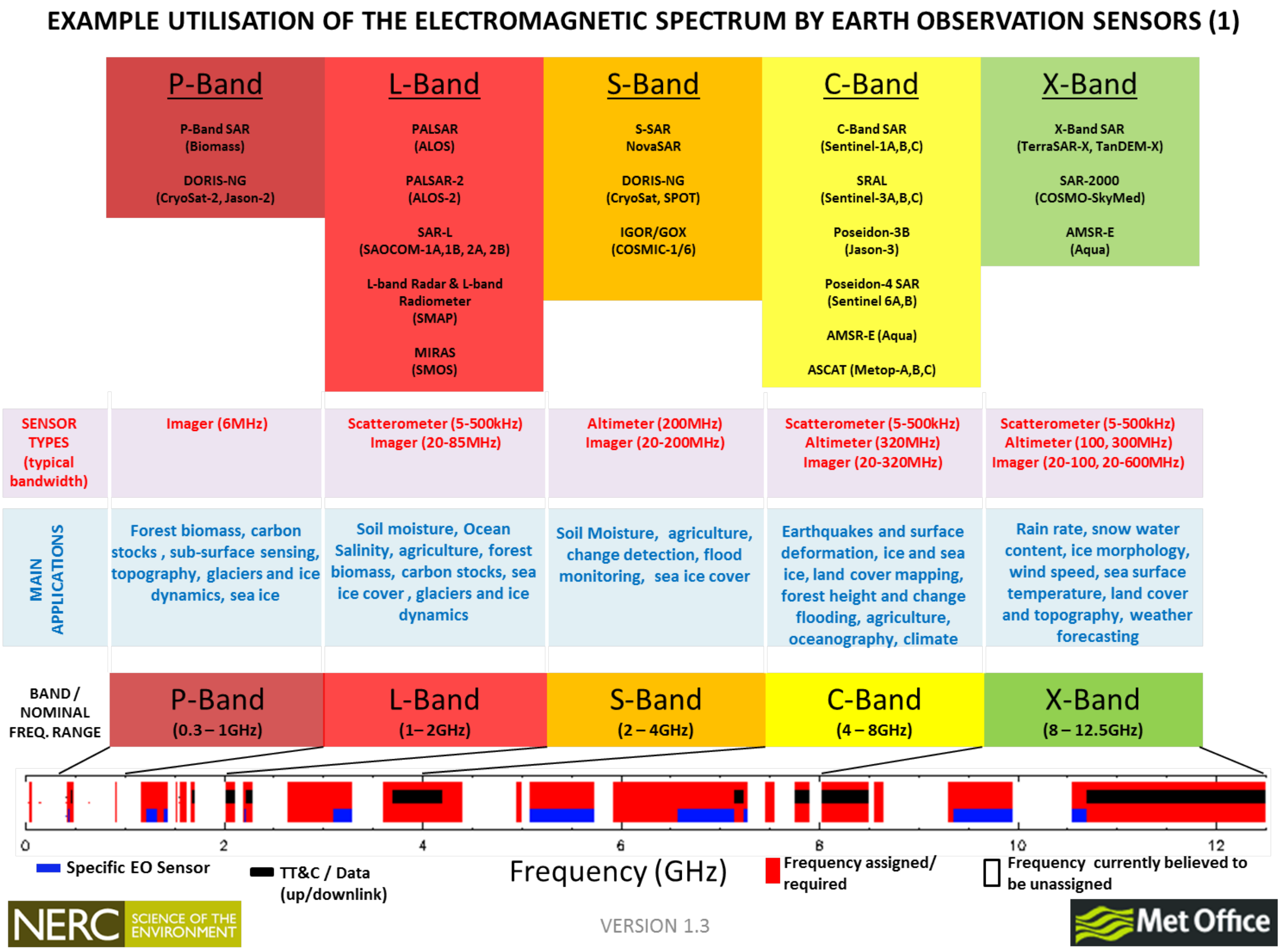


Figure 1: Example utilisation of spectrum by EO sensors up to 12.5 GHz. EO sensor frequencies shown are illustrative but not comprehensive. Telemetry, tracking and control, and up/downlink of data are shown together as TT&C/Data (see Figure 4 also).

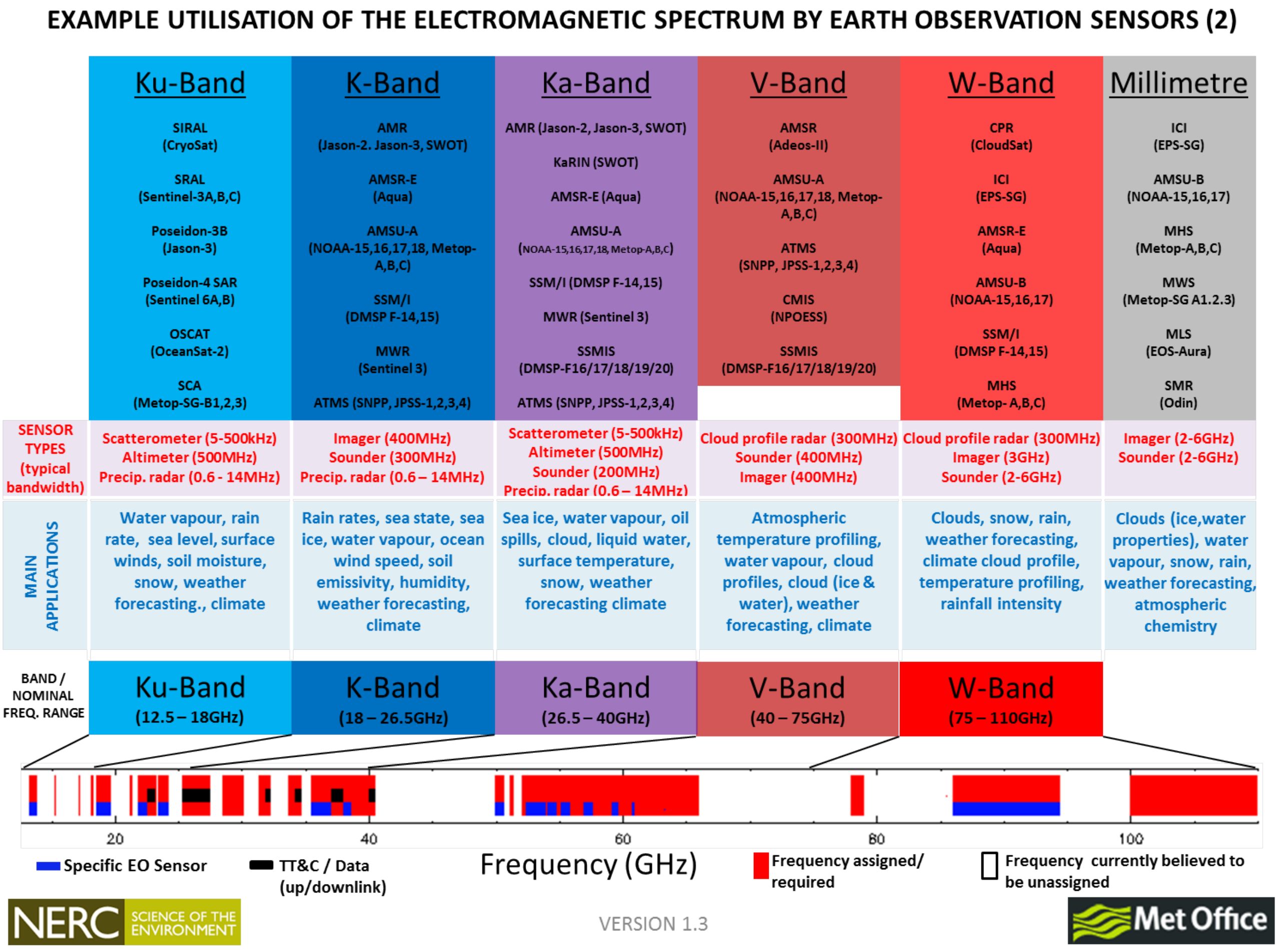


Figure 2: Example utilisation of spectrum by EO sensors from 12.5 GHz to 110 GHz. EO sensor frequencies shown are illustrative but not comprehensive. Telemetry, tracking and control, and up/downlink of data are shown together as TT&C/Data (see Figure 4 also).

### 2.5.1 The active and passive EO use of spectrum: an overview

The heart of EO lies in remote sensing, that is the measurement of an object at a distance using electromagnetic radiation. Therefore the processes that matter are emission of radiation, absorption of radiation and reflection/scattering at a surface or collection of particles. All of these factors dictate the choice of frequencies of individual EO instruments as the object in question will have varying interactions with radiation through the electromagnetic spectrum.

The absorption features of atmospheric gases are particular strong, because of the weak interactions between molecules and the low density, and are particularly localised in frequency because of quantum mechanics. This is important because a satellite has to view the Earth’s surface through the atmosphere and hence for these applications we wish to minimise the atmospheric absorption. On the other hand, if we want to measure atmospheric gases we seek to observe at a range of atmospheric opacities and at frequencies where there is a slope of opacity with frequency.

Figure 3 shows how we can observe atmosphere very well at frequencies above 20 GHz (the plot show lines for a meteorological satellite instruments AMSU-A and MHS flying on the operational Metop-A, B, C satellites. It is also immediately clear why satellite applications for surface sensing (and surface communication) tend to frequencies below 20 GHz where the water vapour influence is lower (note the log scale for opacity). Finally the figure implies that simultaneous observation at multiple frequencies is required to separate out the different contributions.

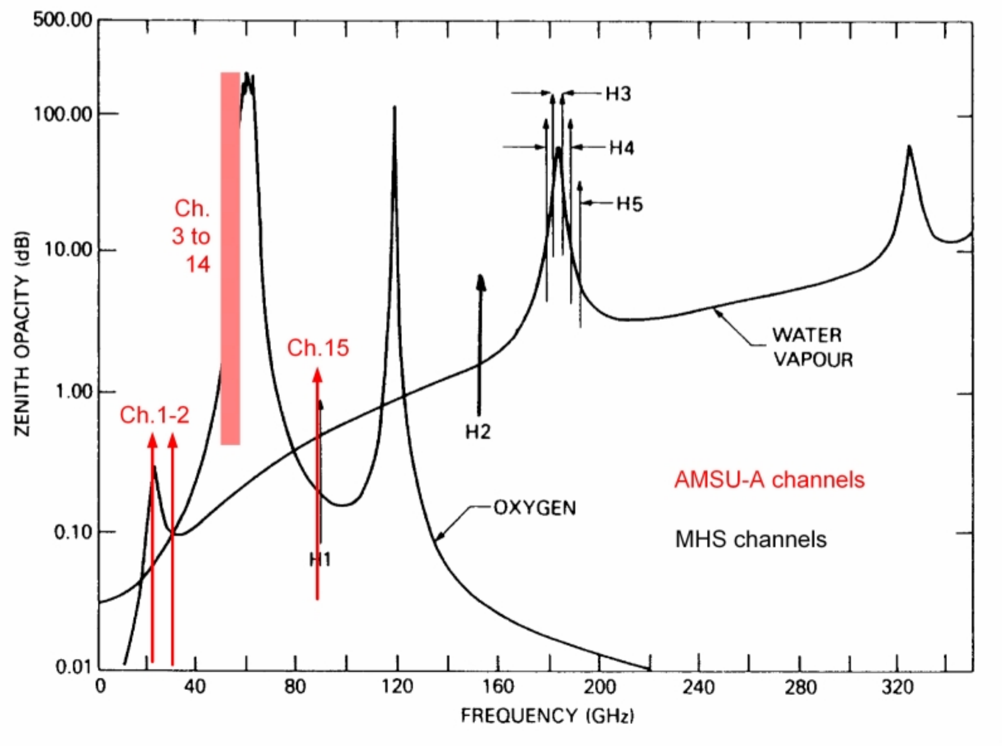


Figure 3: Atmospheric opacity as a function of frequency (courtesy of Eumetsat).

Atmospheric particles also attenuate signals both because of their absorption characteristics and their ability to scatter radiation. The scattering efficiency of a collection of cloud particles or raindrops depends on the particle size relative to the wavelength of the radiation; rainfall droplets are larger in mean size than cloud particles. Therefore active radars obtain more information on clouds if they operate at high frequencies such as 94 GHz whilst rainfall radars are more sensitive to low frequencies such as 13 or 37 GHz.

EO instruments sense the surface through both passive and active instruments. At microwave (and radio) frequencies, the signal relies on the fact that any surface with a temperature emits radiation in proportion to that temperature. This temperature-related signal decreases to lower frequencies. However, the signal is also modulated by the nature of the surface, i.e. the material and so maybe larger for some materials than others; this is the emissivity of the surface which can also vary with frequency). Salts in water emit more strongly below 5 GHz and hence L-band sensors are better equipped to make passive measurements of sea surface salinity than C-band sensors.

The importance of object size and the size of scattering surfaces relative to wavelength is particularly significant for active radar sensing of the surface. The effect is usually illustrated with respect to trees as in Table 2 but applies also to objects on the ground such as buildings and cars. Hence the ESA UK-led BIOMASS mission is implementing P-band SAR in space in order to obtain accurate carbon biomass estimates and also to be able to measure topography below dense vegetation. Multi-wavelength SAR will enable the full vertical extent of vegetation to be quantitatively defined.

**Table 2: Sensitivity of active radar to forest tree structure**

| Band | X | C | L | P |
|---|---|---|---|---|
| Example Wavelength (cm) | 3 | 5 | 25 | 70 |
| Main scattering objects | leaves, twigs, small branches | leaves, small and secondary branches | Primary and secondary branches, thin trunk, some ground returns | Main branches, trunks, ground. Returns |

The wavelength of radiation also determines the depth of penetration of radar into soil, ice and snow. Therefore the choice of frequency must also be aligned to the object. For climate studies, this has an important consequence, namely continuity of observations at specified frequencies in order to obtain consistent data sets over decades.

### 2.5.2 Active imaging (SAR) radar for terrestrial surface, ice and ocean imaging and dynamics

The use of imaging radar (synthetic aperture radar) to observe the surface of the Earth is a strong growth area for the UK science base, for the space industry and for international efforts. This is because of its high sensitivity to the strength and change in scattering from objects on the surface whilst also providing high spatial resolution and observations despite the presence of clouds. Support of SAR radars has been a priority for the UK Space Agency strategically and a priority for UK space instrument providers. **As well as support from UK (and other European) public funds for research and operational missions operating at C band and P band, the UK government has specifically and financially supported the development of NovaSAR operating at S band.**

Although satellites typically carry only a SAR instrument with only one band each (power, mass and hence cost constraints), a full range of bands below 10 GHz is used for different applications. As explained earlier, this is because of the differential response of terrestrial objects such as vegetation (in particular forests) and soil properties such as moisture to the active frequencies. It is also because of the differential penetration of soil and snow/ice surfaces at each band. Therefore there is an increasing synergistic use of satellite data from different SAR missions.

C band has traditionally been used in Europe and Canada, and is now operational in the EC Copernicus system. The choice of C-band SAR as Sentinel 1 shows its importance to European governments from within the portfolio of the new operational EO satellites. L band SARs are flown by Japan and potentially Argentina. X band sensors are flown commercially, for example by Germany. S band sensors are due to be launched soon. Commercial companies in the UK make use of as many of these sources as possible, the driver being particularly high spatial resolution which is more easily achieved at low frequencies (a law of Physics). **A scientific focus will be on new P-band**

**BIOMASS mission which is led by the UK and will provide quantitative measurements of biomass for climate science, REDD+ treaty compliance and potentially set a new basis for carbon markets.**

Table 4 shows typical applications for science, commercial and societal benefits of SAR (and is repeated in each section for each instrument class). GEO is the Group on Earth Observations (https://www.earthobservations.org/index.php) which is recognised as bringing together national governments to bring societal benefits from sustainable EO systems. The number of crosses indicates the level of benefit on a relative scale.

SAR systems are typically used over land although there are ocean applications.

Table 3: Example SARs currently operating in space

| Instrument | Wavebands | Frequencies & bandwidths | Main EO Parameters |
|---|---|---|---|
| **P-Band SAR (Biomass)**<br><br>P-Band Synthetic Aperture Radar | P-Band | 435MHz (6 MHz bandwidth) | Forest biomass, carbon stocks, sub-surface sensing, topography, glaciers and ice dynamics, sea ice vegetation structure and type. |
| **PALSAR (ALOS)**<br><br>Phased Array type L-Band Synthetic Aperture Radar | L-Band | 1270MHz (14-28MHz bandwidth) | Land surface albedo, ice sheet topography, land topography, surface imagery (fire), sea ice cover & thickness, ice dynamics |
| **PALSAR-2 (ALOS-2)**<br><br>Phased Array type L-band Synthetic Aperture Radar-2 | L-Band | 1270MHz (14-28MHz bandwidth) | Soil moisture at surface, fire fractional cover, sea-ice cover, fraction of vegetated land, oil spill cover, land cover, sea-ice type, sub-surface soil moisture, wave directional energy frequency, dominant wave direction, ice dynamics |
| **SAR-L (SAOCOM 1A,1B,2A,2B)**<br><br>L-Band Synthetic Aperture Radar | L-Band | 1.275GHz (50MHz bandwidth) | Soil moisture at surface, fire fractional cover, sea-ice cover, fraction of vegetated land, oil spill cover |
| **NovaSAR-S**<br><br>Phased Array type L-band Synthetic Aperture Radar-2 | S-Band | 3.1-3.3GHz (100MHz bandwidth) | Flood monitoring, agricultural monitoring including soil moisture at surface, land use mapping, disaster management, maritime surveillance |

| | | | |
|---|---|---|---|
| **SAR-S (NISAR)**<br>S-Band Synthetic Aperture Radar | S-Band | 3.162 – 3.237GHz (~100MHz bandwidth) | Sea-ice cover, fraction of vegetated land, fire fractional cover, oil spill cover, snow water equivalent, soil moisture at surface |
| **C-Band SAR (Sentinel-1)** Also referred to as "SAR-C" | C-Band | 5.405GHz (100 MHz bandwidth) | Monitoring: Earthquakes and surface deformation, disaster (oil spill cover, sea-ice cover, fire-fractional cover), forest height and change, flooding, snow water equivalent, soil moisture at surface, fraction of vegetated land, land surface topography, snow status (wet/dry), glacier motion, ice and sea ice extent, dominant wave period, land cover, maritime surveillance, agriculture, oceanography, climate |
| **X-Band SAR**<br>**(TerraSAR-X, TanDEM-X)**<br>X-Band Synthetic Aperture Radar | X-Band | 9.65GHz (300MHz bandwidth) | All-weather monitoring of land surface and coastal processes, agriculture, geology and hydrology, maritime surveillance, infrastructure monitoring including damage assessment, topographic mapping and digital elevation models |
| **SAR-2000**<br>**(COSMO-SkyMed)**<br>Synthetic Aperture Radar 2000 | X-Band | 9.60GHz (~300GHz bandwidth *TBC) | Oil spill cover, sea-ice cover, snow water equivalent, sea-ice type, maritime surveillance, fire fractional cover, infrastructure monitoring including damage assessment, topographic mapping and digital elevation models |

**Table 4: Typical applications for science, commercial and societal benefits of SAR**

| | |
|---|---|
| Science | P (specific): estimating forest biomass and carbon stores, reducing huge uncertainties in carbon emissions from tropical deforestation. UK lead scientist (Shaun Quegan, NCEO, University of Sheffield) for ESA BIOMASS mission<br>Monitoring forest and peat cover, deforestation, burnt scars (e.g. Shaun Quegan's group, NCEO, University of Sheffield)<br>Monitoring volcanic deformation, lava flows (e.g. NERC COMET group)<br>InSAR for surface displacement, strain accumulation, rifting in earthquake zones. Detection of new faults (e.g. NERC COMET group)<br>Monitoring thinning, movement of glaciers (e.g. NERC CPOM group, BAS)<br>Observation of ice sheets, ice flows, melt ponds (e.g. NERC CPOM group)<br>Sea ice extent (e.g. NERC CPOM group) |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Flood extent detection (e.g. University of Reading) | | | | | | | | |
| GEO societal benefits | Disaster management<br><br>Floods<br>Earth quakes<br>Volcanic eruptions<br>Subsidence<br>Landslides<br>Burn scars<br>Post –disaster damage assessment<br>Oil spill detection | Health | Energy<br><br>Subsidence / ground movement etc in oil and gas fields<br>Natural seep detection for off-shore exploration | Climate<br><br>Carbon cycle/ biomass<br><br>Sea ice<br>Ice sheets | Agriculture<br><br>Land cover, crop type | Ecosystem<br><br>Land cover<br>Condition indicators (partic. forests) | Biodiversity<br><br>Habitat mapping<br>Habitat condition | Water<br><br>Hydro-logical mapping<br>Soil moisture<br>Flooding<br>Snow | Weather |
| Impact in related societal benefit area | xxxxx | | xxx | xxxxx | xxx | xxxx | | xxxxx | xxx |
| Commercial systems and services | See matrix below for commercial service offerings<br>In addition SAR systems are a key priority for UK Space hardware companies (eg development of NovaSAR) | | | | | | | | |

| Product | Defence and intelligence | Oil/gas/ minerals | Civil engineering | Insurance | Aviation | Maritime monitoring | Forestry and agriculture | Public safety | Land administration |
|---|---|---|---|---|---|---|---|---|---|
| High resolution imagery | √ | | | √ | | | | | |
| Vessel detection, tracking | √ | | | | | √ | | √ | |
| Oil spill detection | | | | | | √ | | | |
| Change detection | √ | | √ | √ | | | √ | √ | |
| Digital elevation models Topographic mapping | √ | √ | √ | √ | √ | | | | √ |
| Surface movement monitoring | | √ | √ | √ | | | | √ | |
| Sea ice monitoring, iceberg detection | | | | | | √ | | √ | |
| Environmen tal mapping, crop type, | | | | | | | √ | | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| forest type, condition | | | | | | | | | |
| Surface water, flood maps | | | | | | | | √ | |
| Fire risk | | | | | | | | √ | |
| Soil moisture | | | | | | | √ | | |

### 2.5.3 Active altimeters for ocean, lake and ice height

Altimeters are highly accurate instruments which have principally been used for measurements of ocean and ice elevation. They are not imaging but instead are available currently along an orbit track; future concepts are aiming to develop across-track scanning altimeters.

Altimeters over ocean are the greatest source of satellite observations for studying the physical ocean, both directly and through the use of models. The time series of altimeter data provides a fundamental stream of data for climate change (Essential Climate Variable), acting as a proven measure of sea level change. This ECV (sea level change) is reported internationally to all governments through the Intergovernmental Panel on Climate Change.

Altimeter data, merged into models (assimilation), is a core component of oceanography models used operationally in weather prediction systems and in ocean forecasting systems for industry and for defence. It is possible to obtain sea-surface height (ocean topography), significant wave height, sea-surface wind speed, sea-ice thickness, and information on the geoid by analysis of the measurements series and precise orbit parameters.

The Cryosat satellite for ice determination is a high profile, UK-led mission which is leading the way in observations designed to observe Arctic (and Antarctic ice). Because of rapid changes in polar ice, this mission has received extraordinary attention from UK media (9 high profile stories in the last five years on outlets such as the BBC); polar science is receiving attention from UK industries interested in Arctic developments.

Altimeters require synergistic use of multiple active bands (typically two, but increasingly three) in order to achieve the necessary accuracy (correction of ionospheric effects), and also the use of companion passive microwave radiometers to correct for atmospheric water vapour (see below).

Altimeters are typically used over ocean, large lakes and rivers, sea ice and ice sheets.

**Table 5: Example active altimeters currently operating in space**

| **Instrument** | **Wavebands** | **Frequencies & bandwidths** | **Main EO Parameters** |
|---|---|---|---|
| **POSEIDON-3B (Jason-3)** | C-Band | 5.3GHz | Sea level, Sea surface dynamic topography, ocean circulation, significant wave height, coastal sea |

| | | | |
|---|---|---|---|
| Positioning Ocean Solid Earth Ice Dynamics Orbiting Navigator | Ku-Band | 13.575GHz | level (tide), sea state |
| **Poseidon-4 SAR** (Sentinel 6A,B)<br><br>SAR Radar Altimeter | C-Band<br><br>Ku-Band | 5.41GHz (320MHz bandwidth)<br><br>13.575GHz (350MHz bandwidth) | Sea level, gravity, topology, ocean winds, currents, significant wave height, glacier topography, land surface topography, coastal sea level (tide), sea-ice thickness |
| **SRAL (Sentinel-3A,B,C)**<br><br>SAR Radar Altimeter | C-Band<br><br>Ku-Band | 5.41GHz (320MHz bandwidth)<br><br>13.575GHz (350MHz bandwidth) | Significant wave height, sea level, glacier topography, land surface topography, coast sea level (tide), sea-ice thickness, geoid, ocean dynamic topography, lake height |
| **SIRAL (CryoSat-2)**<br><br>SAR Interferometer Radar Altimeter | Ku-Band | 13.575GHz (320MHz bandwidth) | Ice sheet elevation, sea ice thickness, glacier topography, significant wave height, ocean dynamic and bottom surface topography. |
| **KaRIN (SWOT)**<br><br>Ka-band Radar INterferometer | Ka-Band | 35.75GHz (200MHz bandwidth) | Oceanography including sea state |

**Table 6: Typical applications for science and societal benefits of active altimeters**

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Science | Sea level change, sea ice thickness, height of large lakes s in the context of global change research | | | | | | | | |
| GEO societal benefits | Disaster management | Health | Energy | Climate<br><br>Sea level rise<br><br>Sea ice thickness | Agriculture | Ecosystem | Biodiversity | Water | Weather |
| Impact in related societal benefit area | | | | XXXXX | | | | XX | XXXXX |
| Commercial systems and services | Significant interest in both sea level rise and sea ice coverage/thickness but little current commercial market for systems and services | | | | | | | | |

Altimeters are used continuously over ocean and ice/snow. Due to increasing skill in analysing altimeter observations, there is increasing use of altimeter data over lakes and large rivers.

### 2.5.4 Active scatterometers for near-surface winds and soil moisture

Scatterometers are similar to altimeters but concentrate on multiple views to determine absolute backscatter and deduce wind speed. Over the oceans this is the primary means to obtain winds as there are few ground stations (for obvious reasons). Over land there has recently been an increased use of scatterometer data to deduce soil moisture. Scatterometers typically operate at C band and Ka or Ku band.

Near-surface winds are essential for weather forecasting and for studies of extreme storms such as typhoons and hurricanes. As noted in the introduction, weather forecasting has a direct value to research science as the products (forecasts, and hindcast analyses) represent a vast source of model data to the environmental community.

Scatterometers operate over ocean.

**Table 7: Example active scatterometers currently operating in space**

| Instrument | Wavebands | Frequencies & bandwidths | Main EO Parameters |
|---|---|---|---|
| **ASCAT (Metop-A,B,C)**<br><br>Advanced Scatterometer | C-Band | 5.255GHz | Wind vector over surface, soil moisture at surface, snow water equivalent, wind speed over surface, snow status (wet/dry), sea-ice cover |
| **OSCAT (OceanSat-2)**<br><br>OceanSat Scatterometer | Ku-Band | 13.73GHz | Sea surface wind vector, snow water equivalent, snow status (wet/dry), wind vector over surface, sea-ice cover, wind speed over surface, soil moisture at surface |
| **RapidScat (ISS)**<br>Rapid Scatterometer | Ku-Band | 13.4GHz | Sea surface wind vector, snow water equivalent, snow status (wet/dry), wind vector over surface, sea-ice cover, wind speed over surface, soil moisture at surface |
| **SCAT (HY-2A,B,C,D)**<br><br>Scatterometer | Ku-Band | 13.25GHz | Sea surface wind vector, snow water equivalent, snow status (wet/dry), wind vector over surface, sea-ice cover, wind speed over surface, soil moisture at surface |

| | | | |
|---|---|---|---|
| **SCA (Metop-SG-B1,2,3)**<br><br>Scatterometer | C-Band | 5.3GHz | Sea surface wind vector, large-scale soil moisture, soil moisture at surface, snow water equivalent, wind speed over surface, snow status (wet/dry), sea-ice cover |
| **WindRAD (FY-3E,G)**<br><br>Wind Radar | C-Band<br><br>Ku-Band | 5.3GHz<br><br>13.265GHz | Sea surface wind, surface soil moisture, surface wind speed (over ocean only), wind vector over surface (ocean only), snow water equivalent, soil moisture at surface, snow status (wet/dry), sea-ice cover, sea-ice type, |

**Table 8: Typical applications for science and societal benefits of active scatterometers**

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Science | Sea-surface wind; also surface soil moisture in the context of global change research | | | | | | | | |
| GEO societal benefits | Disaster management | Health | Energy<br><br>Off shore renewables | Climate<br><br>Sea surface wind<br>Soil moisture | Agriculture | Ecosystem | Biodiversity | Water<br><br>Soil moisture | Weather<br><br>Unique for measuring global sea surface wind speed and direction |
| Impact in related societal benefit area | | | xx | xxxxx | | | | xx | xxxxx |
| Commercial systems and services | Little current direct commercial market for systems and services | | | | | | | | |

### 2.5.5 Active radars for clouds and precipitation

Active radars for cloud and precipitation have provided some of the great advances forward in the last fifteen years for understanding weather and climate-related processes. These radars so far use the 13.5 GHz, 36 GHz and 94 GHz frequencies where continuity of observations are essential for science. The recently launched GPM mission provides the first satellite observations of rainfall structure and intensity over the mid-latitudes including the UK. The new Earthcare mission will operate at 94 GHz and is the focus of a European-Japan collaboration which is led by the UK.

The use of multiple bands (simultaneously; known as synergy) is required in order to observe both cloud and precipitation; low frequencies are more sensitive to rain, high frequencies are more sensitive to cloud. So Ku-band is more suited to heavy rain, Ka-band is more sensitive to light rain (from stratiform clouds) and W-band provides information on clouds including convective systems.

The use of multiple frequencies also gives information on rain droplet size which affects the development and intensity of rainfall.

Radars can operate over ocean and land.

Table 9: Example active radars currently operating in space

| Instrument | Wavebands | Frequencies & bandwidths | Main EO Parameters |
|---|---|---|---|
| **CPR (EarthCARE)**<br><br>Cloud Profiling Radar | W-Band | 94.05GHz | Vertical cloud profiles, vertical motion, cloud ice (total column), cloud ice properties, melting layer depth in clouds, freezing level height in clouds, cloud base height |
| **DPR (GPM Core Observatory)**<br><br>Dual-frequency Precipitation Radar | Ku-Band<br><br>Ka-Band | 13.6GHz<br><br>35.55GHz | Vertical profiles, accumulated precipitation, cloud liquid water total column, precipitation intensity at surface, cloud liquid water, melting layer depth in clouds, freezing level height in clouds |

Table 10: Typical applications for science and societal benefits of active radars

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Science | Key science interest.<br>EarthCARE, for example, will advance our understanding of the role that clouds and aerosols play in reflecting incident solar radiation back into space and trapping infrared radiation emitted from Earth's surface. These observations are much-need to improve climate predictions and weather forecasts. | | | | | | | | |
| GEO societal benefits | Disaster management | Health | Energy | Climate | Agriculture | Ecosystem | Biodiversity | Water | Weather |
| Impact in related societal benefit area | | | | xxxxx | | | | | xxxxx |
| Commercial systems and services | Little current direct commercial market for systems and services | | | | | | | | |

### 2.5.6 Passive remote sensing using GNSS

There are now complex uses in the space science sector of remote sensing using signals available for other purposes, e.g. using Global Navigation Satellite Systems (GNSSs) as part of the Earth Exploration Satellite Service (EESS). For example:

Radio occultation is a relatively new technique but rapidly maturing technique for performing atmospheric measurements. Currently used mainly as a weather forecasting tool, it also has the potential to be harnessed in monitoring climate change. The technique involves a low-Earth orbit satellite receiving a signal from a GNSS satellite such as GPS or Galileo. This signal is refracted as it passes through the Earth's atmosphere, and the magnitude of this refraction provides information on the temperature and water vapour concentration in the atmosphere. The relative position between the GNSS satellite and the low-Earth orbit satellite changes over time, allowing for a vertical scanning of successive layers of the atmosphere.

GNSS reflectometry involves making measurements of the reflections from the Earth of navigation signals from GNSSs such as GPS or Galileo. Applications include ocean roughness determination for meteorological services such as wind retrieval and sea state services, and scientific interests in, for example, gas transfer and climate modelling. Other potential applications include snow and ice monitoring, soil moisture and biomass. UK scientists and industry have provided the first demonstration of this through the UK's TechDemoSat-1

**Table 11: Example passive remote sensors using GNSS currently operating in space**

| Instrument | Wavebands | Frequencies & bandwidths | Main EO Parameters |
|---|---|---|---|
| **GRAS (Metop-A,B,C)**<br><br>GNSS Receiver for Atmospheric Sounding | L-Band | 1228MHz<br><br>1575MHz | Height and temperature of tropopause, atmospheric temperature, specific humidity, integrated water vapour, height of top of PBL |
| **IGOR (TerraSAR)**<br><br>Integrated GPS Occultation Receiver | L-Band | 1228MHz<br><br>1575MHz | Height and temperature of tropopause, atmospheric temperature, specific humidity, integrated water vapour, height of top of PBL |
| **ROSA (Megha-Tropiques)**<br><br>Radio Occultation Sounder of the Atmosphere | L-Band | 1228MHz<br><br>1575MHz | Height and temperature of tropopause, atmospheric temperature, specific humidity, integrated water vapour, electron density, height of top of PBL |

### 2.5.7 Passive microwave imaging radiometers

The applications of passive imaging radiometers are wide-ranging based on sensitivity of the observed signals to surface temperature and soil misiture, atmospheric water vapour, rainfall, snow and sea ice. The low influence of clouds ensures that these instruments are very useful and gaining in their applications.

The most significant instruments sense discrete channels between 6 G Hz and 183 GHz.

The applications of such instruments have previously been mostly to ocean and atmosphere but increasingly they are used over land.

**Table 12: Example passive microwave imaging radiometers currently operating in space**

| Instrument | Wavebands | Frequencies & bandwidths | Main EO Parameters |
|---|---|---|---|
| **MWR (Sentinel 3)**<br><br>Microwave Radiometer | K-Band | 23.8GHz (400MHz bandwidth) | Tropospheric water vapour (timing delay for altimeter pulse correction) |
| **SMAP (SMAP)**<br><br>Soil Moisture Active Passive | L-Band | 1.41GHz (24MHz bandwidth)<br><br>Active SAR: 1.26GHz (30MHz bandwidth) | Sub-surface soil moisture, surface soil moisture, sea surface salinity |
| **MIRAS (SMOS)**<br><br>Microwave Imaging Radiometer using Aperture Synthesis | L-Band | 1.4135GHz (20MHz bandwidth) | Sub-surface soil moisture, surface soil moisture, sea surface salinity |
| **AMSR-E**<br><br>**(Aqua)**<br><br>Advanced Microwave Scanning Radiometer-EOS | C-Band<br><br>X-Band<br><br>K-Band<br><br>K-Band<br><br>Ka-Band<br><br>W-Band | 6.925GHz (350MHz bandwidth)<br><br>10.65GHz (100MHz bandwidth)<br><br>18.7GHz (200MHz bandwidth)<br><br>23.8GHz (400MHz bandwidth)<br><br>36.5GHz (1000MHz bandwidth)<br><br>89.0GHz (3000MHz bandwidth) | Snow status (wet/dry), soil moisture at surface, snow water equivalent, snow cover, precipitation intensity, water vapour, cloud liquid water, winds, sea surface temperature, land surface temperature |
| **AMR (Jason-2, Jason 3, SWOT)**<br><br>Advanced Microwave | K-Band | 18.7GHz (200MHz bandwidth)<br><br>23.8GHz (400MHz | Altimeter data to correct for water vapour and cloud cover. |

| | | | |
| --- | --- | --- | --- |
| Radiometer | K-Band<br>Ka-Band | bandwidth)<br>34GHz | |
| **SSMIS** (DMSP-F16/17/18/19/20)<br>Special Sensor Microwave Imager Sounder | K-band<br>K-band<br>Ka-Band<br>V-Band<br>V-Band<br>V-Band<br>V-Band<br>V-Band<br>V-Band<br>V-Band<br>V-Band<br>V-Band<br>W-Band | 19.345 GHz (355 MHz bandwidth)<br>22.235 GHz (401 MHz bandwidth)<br>37.0GHz (1580MHz bandwidth)<br>50.3GHz (380MHz bandwidth)<br>52.8GHz (389MHz bandwidth)<br>53.596GHz (380MHz bandwidth)<br>54.4GHz (382MHz bandwidth)<br>55.5GHz (391MHz bandwidth)<br>57.29GHz (330MHz bandwidth)<br>59.4GHz (239MHz bandwidth)<br>60.79GHz (BW up to 106 MHz)<br>63.28GHz (2.7MHz bandwidth)<br>91.655 GHz (1418MHz bandwidth) | Cloud liquid water total column, snow cover, cloud liquid water, cloud ice total column, sea and land surface temperature<br>[Note: SSMI also has bands above 100 GHz at 150 GHz and 183 GHz, typically with BW of up to 1.6 GHz] |
| **ICI**<br>**(Metop-SG-B1,2,3)**<br>Ice Cloud Imager | Millimeter | 183.31GHz (4 to 14 GHz bandwidths)<br>243.2 GHz (2.5 GHz bandwidth)<br>325.15 GHz (3 to 19 GHz | Cloud ice (total column), cloud ice effective radius, cloud ice, integrated water vapour, specific humidity |

| | | | |
|---|---|---|---|
| | | bandwidths)<br>448 GHz (2.8 to 14.4 GHz bandwidths)<br>664 GHz (8.4 GHZ bandwidth) | |

Table 13: Typical applications for science and societal benefits of passive microwave imaging radiometers

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Science | Very significant science interest in soil moisture and ocean salinity measurements in the context of global change research.<br>Measurements contribute to development of Essential Climate Variables. Complementary to infrared (e.g. for sea surface temperature). | | | | | | | | |
| GEO societal benefits | Disaster management | Health | Energy | Climate | Agriculture | Ecosystem | Biodiversity | Water | Weather |
| Impact in related societal benefit area | | | | xxxxx | xx | | | | xxxxx |
| Commercial systems and services | UK interests in instrument development for public sector operational systems, e.g. for EUMETSAT | | | | | | | | |

Passive microwave imaging radiometers operate continuously over both ocean and land. Radio-frequency interference from ground sources is a significant source of noise for these instruments and limits some of the applications in coastal zones and over land.

### 2.5.8 Passive microwave sounders for the atmosphere

The applications of passive microwave sounding are largely in weather forecasting based on their ability to provide information on temperature and humidity. Uses of these instruments are often in combination with infra-red instruments on the same platform. The combination provides the level of accuracy required for quality weather forecasting.

Sounders cover frequencies from 20 to 200 GHz (wavelengths 1.5 to 15 mm), operating in absorption bands split in several channels of bandwidths from a few MHz to some GHz (see Figure 1 which shows the AMSU-A and MHS bands). The application fields depending on the exploited frequency bands: nearly-all-weather temperature profile from oxygen bands (e.g., 54 GHz, 118 GHz); nearly-all-weather humidity profile from water vapour bands (e.g., 183 GHz); cloud liquid water path and rainfall are also observed.

Microwave sounders are “Workhorse” instruments for weather forecasting and are observing the atmosphere globally.

Table 14: Example passive microwave sounders currently operating in space

| Instrument | Wavebands | Frequencies & bandwidths | Main EO Parameters |
|---|---|---|---|
| **ATMS (SNPP, JPSS-1,2,3,4)**<br>Advanced Technology Microwave Sounder | K-Band<br>Ka-Band<br>V-Band<br>W-Band<br>Millimeter | 23.8GHz (270MHz bandwidth)<br>31.4GHz (180MHz bandwidth)<br>50.3 - 57.6GHz (12 bands)<br>89.5GHz (5000MHz bandwidth)<br>165.5 – 183.31GHz (5 bands) | Nearly-all-weather temperature and humidity sounding, cloud liquid water total column, specific humidity, integrated water vapour, accumulated precip., cloud ice total column, precip. Intensity at surface, cloud liquid water, atmospheric temperature |
| **MHS (Metop-A,B,C)**<br>Microwave Humidity Sounder | W-Band<br>Millimeter | 89.0GHz (2800MHz bandwidth)<br>157GHz, 183.31GHz, 190.311GHz (2200 MHz max bandwidth) | Nearly all-weather specific humidity, integrated water vapour, precip. Intensity at surface, cloud ice column |
| **AMSU-A (Metop-A, B, C)**<br>Micro-Wave Sounder | Millimeter | 23.8 GHz (nominal BW: 270 MHz)<br>31.4 GHz (nominal BW: 270 MHz)<br>50.3, 53.6, 54.4, 54.9, 55.5, 57.2 GHz (max BW: 400 MHz)<br>89.0 GHz (max BW: 6 GHz)<br>165.5GHz, 183.31GHz | Nearly all-weather atmospheric temperature<br>Cloud liquid water total column, specific humidity, integrated water vapour, precipitation intensity. |

Table 15: Typical applications for science and societal benefits of passive microwave sounders

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Science | Measurements contribute to development of Essential Climate Variables. Complementary to infrared sounders<br>Microwave radiance data from have become key elements of the historical climate record and need to be continued into the future to sustain a long-term record. Atmospheric temperature sounding data play an important role, along with radiosonde and aircraft data in re-analyses of temperature and other upper-air variables. Uncertainties in the measurement of humidity are much larger than in the measurement of temperature and scientific work continues to reduce uncertainties in the measurements. | | | | | | | | |
| GEO societal benefits | Disaster management | Health | Energy | Climate | Agriculture | Ecosystem | Biodiversity | Water | Weather |
| Impact in related societal benefit area | | | | xxxxx | | | | | xxxxx |
| Commercial systems and services | UK interests in instrument development for public sector operational systems, e.g. for EUMETSAT | | | | | | | | |

### 2.5.9 Passive microwave limb sounders for atmospheric chemistry

For completeness, we include atmospheric chemistry instruments which view the horizon of the Earth is so-called limb viewing mode. This enables them to view the higher atmosphere above 5 km, principally for atmospheric chemistry although successful trials have recently been carried out to assimilate data into weather forecasting models.

The instruments usually have channels above 100 GHz although older instruments did use the 60 GHz oxygen line still used by the microwave sounders noted in the previous section.

Table 16: Example passive microwave limb sounders (for atmospheric chemistry) currently operating in space

| Instrument | Wavebands | Frequencies & bandwidths | Main EO Parameters |
|---|---|---|---|
| **MLS (EOS-Aura)**<br><br>Microwave Limb Sounder | Millimeter<br><br>Terrahertz | 118GHz (9 sub-bands) 190GHz (6 sub-bands)<br><br>240GHz (7 sub-bands)<br><br>640GHz (9 sub-bands)<br><br>2500GHz (5 sub-bands) | Chemistry of the middle atmosphere (upper troposphere, stratosphere and above): Ozone, OH, specific humidity, halogen compounds, $N_2O$, $HNO_3$, ice water content |
| **SMR (Odin)**<br><br>Sub-millimeter | Millimeter | 118GHz<br><br>486 – 544 GHz (4 bands) | Chemistry of the middle atmosphere: $O_3$, specific humidity, halogen |

| | | | |
|---|---|---|---|
| Radiometer | | | compounds, $N_2O$, $HNO_3$ |
| JEM-SMILES (International Space Station)<br><br>Sub-millimeter Radiometer | Millimeter | 625-650 GHz | Chemistry of the middle atmosphere: chlorine (ClO); short-term mission |

### 2.5.10 Satellite communications for Earth Observation

Figure 4 shows our best understanding of the use of spectrum for command control uplink and downlink, and for data downlink. Space agencies and industry are better placed to communicate the effective use of these frequencies and their overall value. Our point would simply be that the entire suite of EO satellites is downlinking data through these frequencies which gives them high value for us. Downlink capacity is limiting the efficient use of some satellites, a problem that needs to be addressed.

**UTILISATION OF THE ELECTROMAGNETIC SPECTRUM BY EARTH OBSERVATION & SPACE RELATED TELEMETRY, TRACKING & CONTROL, & DATA UPLINK/DOWNLINK**

| Application | Orbit | Timescale (Current /future) | Bands |
|---|---|---|---|
| Telemetry/Telecommand and Ranging | GSO/NGSO<br>GSO/NGSO | current/future<br>current/future | 2 025 – 2 110 MHz<br>2 200 – 2 290 MHz |
| Instrument raw data downlink | GSO<br>NGSO<br>GSO/NGSO<br>GSO/NGSO | current<br>current/future<br>future<br>Future | 1 675 – 1 710 MHz<br>7 750 – 7 900 MHz<br>8 025 – 8 400 MHz<br>25.5 – 27 GHz |
| Low rate direct dissemination to user stations | GSO | current | 1 675 – 1 710 MHz |
| High rate direct dissemination to user stations | GSO/NGSO<br>NGSO | current<br>future | 1 675 – 1 710 MHz<br>7 750 – 7 900 MHz |
| Data dissemination (EUMETCast) via commercial GSO satellites | GSO | current/future | 3 700 – 4 200 MHz<br>10.7 - 12.5 MHz |
| Data Collection Systems | GSO/NGSO<br>NGSO | current/future<br>future | 401 – 403 MHz<br>460 – 470 MHz |
| Search and Rescue | GSO/NGSO<br>GSO/NGSO | current/future<br>current/future | 406 – 406.1 MHz<br>1 544 – 1 545 MHz |
| Space Communication | **Space Communication Notes**:<br>TT&C (up)<br>TT&C (down)<br>TT&C, Payload Data (up)<br>TT&C, Payload Data (down)<br>TT&C, Large volume Payload Data (up)<br>TT&C, Large volume Payload Data (down)<br>Deep space TT&C, Large volume payload data (up)<br>Deep space TT&C, Large volume payload data (down)<br>Future plans & manned lunar missions | | <br>2025 – 2110 MHz<br>2220 – 2300 MHz<br>7145 – 7235 MHz<br>8400 – 8500 MHz<br>22.55 – 23.15 GHz<br>25.5 – 27 GHz<br>31.8 – 32.3 GHz<br>34.2 – 34.7 GHz<br>37-38 & 40-40.5 GHz |

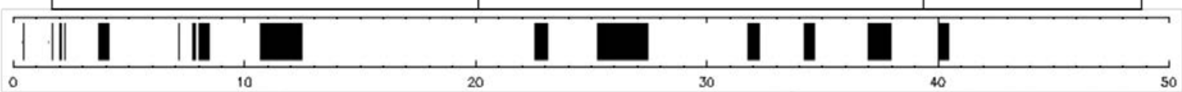


Figure 4: Utilisation of the spectrum for EO and space-related telemetry, tracking & control, and data uplink/downlink.

## 2.6 Question 17

*Question 17: For each of the space science applications you provide, please could you indicate how UK consumers and citizens benefit from their use? Where possible please also provide an indication of the scale of the benefits (either qualitatively or quantitatively).*

For satellite EO data and indeed for UK environmental science, it is important to recognise that much of the benefit to UK consumers and citizens occurs through both direct national interests and through the significant UK share of benefits driven by international actions. Quantitative values are more easily evidenced at international level and some figures are given here for the major societal benefits to which the EO value chain contributes (as part of an overall science effort). There are also estimated national benefits particularly for jobs and growth which can be found in the UK Industry's Innovation and Growth Strategy (IGS) for Space. Further work needs to be done to establish the methodologies in UK government for valuing activities and work is on-going, for example in the UK Space Agency, to agree processes.

What is clear is that environmental science plays a crucial role in the EESS value chain. Instruments, missions and applications start in the scientific domain and progress to provide operational and commercial systems and services. This can be clearly illustrated with the progressive development of EESS in Europe. Scientific endeavours from ERS-1, through ERS-2 to ENVISAT have now resulted in 6 series of operational Copernicus Sentinel missions aimed at supporting and providing evidence for environmental and security policy across Europe; the current EC investment over the next spending period is 3.8 billion Euros. The net economic and societal benefits of the Copernicus have been estimated by Booz and Co to be ~€30bn by 2030 giving a benefit to cost ratio of ~3.7[6]. More recent studies suggest an even better return on investment with every €1 invested in Copernicus generating up to €10 in return[7].

Nationally, the IGS report looks for growth in the UK space sector of £40 billion by 2030 with identified EO markets in maritime surveillance and maritime environment monitoring, disaster and emergency response, polar infrastructure, and climate and environmental services (including carbon markets, insurance and agriculture). Upstream EO companies such as SSTL have already contributed significantly through exports of EO instruments and platforms to China, Taiwan, and the US.

A major benefit to UK citizens is in the domain of societal benefit as illustrated by the international environmental response. The UK science community has played a leading role in the treaties regarding ozone depleting substances and refocussing of the related industries. Estimates of global benefits are of the order of $214 billion in economic terms (cost/benefit ratio of 2:1 approximately). Cost/benefit ratios increase to 11:1 when health is accounted for, for example an estimated reduction worldwide of 19.1 non-melanoma cancer cases and 1.5 million melanoma cancer cases.

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6 Cost-Benefit Analysis for GMES, European Commission: Directorate-General for Enterprise & Industry Booz and Co, London19th September 2011

7 Reported at “Copernicus- Sentinels Serving Society and the Environment”, Conference organised by Greek Presidency of the Council of the European Union, the European Space Agency, and the European CommissionMay 2014

The societal benefits of the ozone case are relatively well-established. A similar benefit clearly exists for climate change where the Stern review, commissioned by the UK Chancellor of the Exchequer, estimated the benefits of action on greenhouse gases at £2.5 trillion. The evidence from EO data directly informs current UK perceptions and policy decisions which then influence international actions. Further work is required to map the cost/benefits for the UK and the science contribution but it will clearly be large.

EO data are playing an increasing role in monitoring and informing response to natural hazards, for example in aviation following on from the Eyjafjallajökull volcano eruption in 2010 which IATA estimated cost the aviation industry $1.8 billion (http://airlines.iata.org/analysis/volcanic-ash).

## 2.7 Question 18

*Question 18: From your perspective, what high level trends will affect the space science sector in the coming years?*

**For the next decade, we foresee driving trends for EO arising from the following sources: climate data; natural hazards; deforestation and REDD+ (and similar activities); demands from the applications industry for increased coverage from SAR data; demands from science and industry for higher temporal as well as spatial resolution; large increases in downlink requirements arising from higher spatial resolution and more sophisticated instruments.**

We expect an increased demand for climate quality, consistent data records which can be used for confirmation of long-term and short-term change, alongside attribution of causes. The recent apparent decline in Arctic sea ice and changes in global temperature rise illustrate very well the high level interest and response of government and public. There remain big decisions to be made through the COPT process and other political initiatives. As well as high level usage, scientifically existing EO data records are increasingly used for evaluation and interpretation of climate models as evidenced in the IPCC 5th Assessment Report. These needs will also increase the importance of the operational Copernicus and Meteorological (Eumetsat and NOAA) satellites which the UK contributes to and from which it derives benefit. There are strong drivers for consistent use of frequency for satellite programmes to enable these consistent data sets to be built.

The need for carbon monitoring, carbon accounting and the response in carbon markets continues to drive activity in deforestation alongside political activities. The UN's Reducing Emissions from Deforestation and forest Degradation plus conservation (REDD+) programme is an example of efforts to monitor and balance financially national carbon emissions using observations of carbon stocks. Frequent coverage is required and the through-cloud capabilities of SAR make it attractive for these applications.

Natural hazards such as flooding, volcanoes and earthquakes are amenable to satellite observations. Increasing the frequency of coverage, the spatial resolution of instruments and the near real-time availability of data will allow much more effective response to these events.

Records of long-term change have historically been built from sounders and imagers. We see the demand for imager data increasing rapidly as these longer-term data sets are used for both science and commercial purposes, particularly for the land surface and cryosphere.

**Combining these factors we see evidence for a large increase in EO satellite numbers, particularly in constellations of small satellites and in desire to implement geostationary satellites (for example for passive microwave) in order to address the temporal frequency of coverage.** Similarly, we observe a growth in research and commercial SAR systems and there is no sign of that trend decreasing. In S-band SAR, there has been an international impetus with the UK, USA-India and China all planning launches in the next 5 years.

**It is clear that many missions, including the new Sentinels, are limited by download capacity**, thus limiting the satellites from recording continuously along the orbit track of each satellite. These limitations have been present historically but are now exacerbated by the increase in spatial resolutions and number of channels of EO sensors. Increasing the download ability would increase the economic benefits and efficiency of the satellite operations by significant margins.

## 2.8 Question 19

*Question 19: For each of the space science application(s) your organisation uses or provides, what are the a) current trends; and b) likely future drivers of demand for spectrum?*

*Please include in your response:*

- *the scale of the demand drivers;*

- *the reason for additional demand (e.g. higher resolution radar data rates/bandwidth required) and whether this increased demand is for data delivery or for the taking of measurements;*

- *whether increased demand can only be met at specific frequencies and why;*

- *any variations in demand drivers by geography (i.e. regional or global), and why;*

*and*

- *whether future demand is expected to be temporary or intermittent, and the reasons for this.*

*In your response, please provide any evidence which supports your position on the drivers of demand (e.g. forecasts, studies and statistics).*

There are three main drivers at the moment which are increasing demand significantly in terms of usage of microwave and radio spectrum. The first is the requirement for long-term missions serving both the operational needs of programmes such as Copernicus /commercial EO and the scientific needs for data sets which document environmental change. The commercial and science policy drivers urge consistency in data set production. The second driver is the gain from increased temporal coverage through multiple satellites in constellations, through international agreements to secure co-operating satellites or from geostationary satellites. The third driver is the need for increased bandwidth for downlink of data from the entire EO satellite suite.

The first two considerations do not in themselves require additional frequency usage. Rather the demand is ever increasing reliance on consistent, long-term (safeguarded) bands for EO satellites without radio frequency interference (RFI), and without a primary need for an increase in bands below 100 GHz. There may be an increased usage of such bands for alternative EO missions, e.g. rainfall radar at C and X band.

The third driver is better commented on by space agencies and industry who deal more directly with use of downlink bandwidth. There is a need for increased downlink capacity in any case.

Above 100 GHz, EO developments are likely to focus on specific allocated bands which are not yet used by EO sensors. Millimetre wave radars for 130-134 GHz and 237.9-238 GHz are needed for ice and snow clouds. Microwave limb sounders are suited to the region 290-360n GHz for enhanced sensitivity to ozone. Upper atmosphere chemistry missions are targeting the terahertz region (0.8 to 4.7 THz – but at discrete frequencies within this range).

## 2.9 Question 20

*Question 20: Taking into account the drivers you have identified in your response to Question 19 above, what (if any) challenges is your organisation concerned about in meeting potential future demand? Please provide the information by application and band, along with any supporting evidence, if available.*

As for Question 19, our concerns are firstly to ensure that the vital measurements currently undertaken by EO sensors in this frequency range are safeguarded for the future. Secondly we need to continue to represent and work towards satisfying the drivers for increased downlink capacity so that EO sensors in space can be utilised more efficiently. The downlink capacity is clearly generic.

## 2.10 Question 21

*Question 21: Are there any future developments, such as the radio astronomy SKA, that could reduce the demand for space science spectrum in the UK?*

No reduction is demand for space science spectrum is foreseen at the current time by our community or by the EO sector as we understand it. The bands we are concerned below 100 GHz with are either bands which have been consistently used by the EO sector or else are bands with high profile, significant missions dedicated to them. Essentially the unique function of EO satellites is to observe globally and regionally in an accurate and repeatable fashion; this cannot be replicated by other techniques which have their own strengths but more locally.

## 2.11 Question 22

*Question 22: Do you have any comments on the list of potential mitigations we have identified? What likely impact would each of the mitigations have on spectrum demand? To what extent do you believe that these mitigations apply only to certain applications?*

Many of the sub-questions in question 22 are best directed at engineers in space agencies and industry. However, from our knowledge we can say the following.

**RFI appears to be a considerable problem for some EO sensors already**, especially when due to unregulated sources (very strong RFI) but also generally from cities or industrialised countries. There are already EO missions operating in protected spectrum at L band which have been compromised over land and near coasts because of these effects. RFI has also been reported at C and X band.

As far as we understand it, EESS receiver filtering is already implemented where possible. Clearly and R&D effort can always try to improve this filtering and we would support this work which must be long-term. However, we would note that **simulations of allowed RFI need much improvement in terms of agreed and accurate process**, understanding of the translation from city to city or country to country, and **testing in the field**, i.e. using satellites and local observations given problems already observed. There also needs to be an excellent assessment of suggested technology improvements.

Likewise there is research into new single processing techniques. We support further study of these but implementation **needs to be subject to demonstration of the success of the technique** prior to large scale implementation as for receiver filtering.

A global database of science satellites and frequencies would need to include the precise orbit and observation patterns of the sensors which are not fixed, particularly for satellites which observe in a tasking mode. **Therefore the database would need to be dynamic**, i.e., updateable in realtime. It seems unlikely that other spectrum users would link to such a database and implement it robustly in realtime.

Greater geographic sharing of spectrum is a good principle for ground-based activities, e.g. for fixed site radars (NERC operates two such radars) but not for mobile radars. However, this does not apply to EO satellites where the missions are undertaking global measurements on the whole.

## 2.12 Question 23

*Question 23: What other mitigation opportunities do you foresee that we should consider? For what applications are these likely to be applicable and what scale of improvement are they likely to deliver?*

We do not foresee any other mitigation opportunities at present and we would be happy to support an expert workshop in this area. Any solutions seem more likely to arise from engineering solutions rather than system concepts at this stage.

## 2.13 Question 24

*Question 24: Beyond the activities already initiated and planned for the space science sector (e.g. as part of WRC-15), do you think there is a need for additional regulatory action that may, for example, help your organisation to address the challenges it faces?*

*In your response, please indicate what type of action you consider may be needed and why, including any evidence to support your view.*

We believe that there is a need for a UK position which safeguards satellite frequencies and also takes action on RFI in protected bands where observed.

We also think that there is merit in assessing the levels of RFI that actually occur at ground level and above, and developing a standard process for this (Including simulations) which is agreed by all parties.

We are not experts in regulatory action but would be happy to support Ofcom in achieving appropriate actions in the areas we have outlined.

# 3 Remarks

We are very pleased to have been able to respond to the Ofcom review. We recognise that this is an important process and look forward to a constructive dialogue with Ofcom in the future.

The spectrum at less than 100 GHz is vital for EO missions that utilise specific frequencies for Space science research, services and commercial activities; these frequencies are used because of the fundamentals of electromagnetic radiation interacting with land surface objects, ice, ocean waves, clouds, rainfall and atmospheric gases. The societal, public policy and commercial benefits of EO are large and growing.

The science and commercial drivers are focussed on consistent access to protected frequencies rather than expansion of the frequencies exploited; there are plans to increase exploitation of allocated space bands above 100 GHz.

Alongside secure allocation of frequencies, the EO sector is most concerned with measures to increase downlink capacity and with the removal of RFI which appears to be already interfering with some EO sensors (although using protected bands).