Impact on UK from pollution of spectral wavebands used for Meteorological Observing

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UK government has to date invested £136million, with commitment to invest a further £63million, in observing the environment using instruments operating at microwave frequencies, This investment provides the information used to support and advise UK government policy on Climate Change, the Environment and International development as well as in providing services in support of National Security, UK Public Safety and UK infrastructure. If these observations were lost through interference from un-natural sources there are no alternative bands or techniques that can be employed. This could set back UK capabilities by up to 10 years. Hence, for the UK to achieve the benefits from the investment made any changes to the international Radio Regulation 5.340, which currently protects the microwave frequency bands, must be resisted

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1. Introduction

Observing the state of the atmosphere is fundamental to the process of producing weather forecasts or climate predictions and the majority of improvements in forecasting accuracy over the last 15 years have come from using data obtained by satellites. Half of these gains can be attributed to use of instruments operating in the microwave (1-200GHz) frequency bands due to their unique ability to provide information in and below clouds, which is impossible in any other frequency band.

So far these bands have been absolutely protected from both intentional and unintentional active emissions under international Radio Regulation 5.340 which prohibits all emissions in these specified bands. Despite this, some commercial users have been pressing for this regulation to be relaxed, or even dropped, allowing active emissions in these bands and the setting of higher out-of-band interference limits.

Interference corrupts the observed data which can render it useless. The effects of this would be two-fold:

- Setting back current capability up to 10 years through loss of vital data, wiping out recent gains
- Slowing the rate of future improvements that would have been expected through further exploitation of the data. New technology and observing techniques may eventually overcome the impact of the lost data, but this is by no means certain, and may be at considerable cost.

Any relaxation of the current regulations must be resisted as the effects on the UK's current and future operations would significantly reduce:

- capability to support and advise UK Government policy on Climate Change, International Development issues and the Environment,
- the accuracy of services provided in support of national security and consequent implications for the UK public and infrastructure.

2. Impacts - Policy Advice

Climate Change
G8 Gleneagles Communiqué re-affirmed previous commitments to *'strengthen international cooperation on global Earth observations'* and welcomed the adoption of the implementation plan for the Global Earth Observation System of Systems (GEOSS.) Operational meteorological satellites are an integral component of GEOSS - all of which are carrying microwave sensors that would be threatened by any change to RR 5.340.

Continuity of observations is key to monitoring and assessment of natural and man-made climate change and reducing the uncertainties in future predictions. It has been satellite microwave observations that have been used to finally prove to the last sceptics that man-made global warming is a reality. Corruption of microwave observation data would undermine credibility in the data and therefore these scientific results. Loss of confidence would also seriously impact ability to provide definitive advice on likely impacts of climate change and hence government policy for their mitigation.

International Development
Increased uncertainties in weather forecasting and climate prediction would also reduce confidence in the advice given on UK international policy relating to Disaster Risk Reduction and Environmental Sustainability. With a growing awareness of the links between natural disasters, socioeconomic development and poverty outcomes, reduced accuracy of predictions would impact government aims and ability of achieving the Millennium Development Goals.

Strategic international priorities for the UK would similarly be affected, either sustainable development for poverty reduction and protection of the environment or support for British nationals abroad. The UK's global forecast model is the best in the world – as demonstrated during Hurricane Katrina in 2005 when (through the FCO) better forecasts were delivered to UK citizens living in the US than they were able to receive via anyone else, including the US. Reduced/corrupted observations would degrade the UK's world leading capability and would clearly have a high impact upon services provided for overseas aid agencies such as to DfID (e.g. forecasts for the Southeast Asia Tsunami, Pakistan earthquake, Mozambique and Venezuela floods).

3. Impacts - National Security

Defence
The ability of the Ministry of Defence to develop its Network Enabled Capabilities (NEC), which links sensors, decision-makers and weapon systems, would be significantly impacted, delaying plans of using weather for military advantage. To support NEC there needs to be a Recognised Environmental Picture (REP) based upon the timely provision of accurate Environmental Information (EI). Battlefield management is becoming more sophisticated, so in order to achieve superiority in theatre and to reduce collateral damage our forces need appropriate EI to be provided in the right place at the right time to allow commanders to make the best informed decisions.

Civil Contingency
Meteorological advice and data are provided to emergency services, government departments and agencies involved in dealing with a Chemical, Biological, Radiological and Nuclear Incidents (CBRN) release. The accuracy of forecast information and advice provided during major incidents, e.g. the London Bombings and Buncefield Oil Fire, would be reduced with greater uncertainty of affected areas. Evacuation and mitigation for larger areas could plainly have very major financial & public safety implications, running to £billions. In addition;

- UK society will suffer as public and relevant agencies either receive less warning time to take appropriate mitigating actions or receive more false alarms of severe weather
- Utility companies will be less prepared to restore power supplies affected.
- Poorer weather forecasts would reduce confidence levels and shorten the lead times for warnings of likely strong winds, bucking the recent trend for providing better-targeted and earlier warnings.
- Rather than improving short range warnings of events like the flash flooding of Boscastle in 2004, loss of microwave observations would significantly delay capability to predict these events.

National Infrastructure

- Local government and the Highways Agency costs to keep the roads clear will increase, either from weather related accidents or through unnecessary gritting due to greater uncertainty of forecast road conditions.
- The CAA and aviation industry as a whole could see a significant safety, economic and environmental impact. The effect on worldwide flight delays and flight routing / fuel burn alone would amount to billions of pounds.
- Security of supply of energy and preparedness for disruption would all be lessened with an unacceptable burden placed on the UK economy from the energy sector.
- Likelihood of meeting the Kyoto greenhouse gas emission targets reduced even further.
- Current and future plans to improve management of weather-related disruption to the UK rail network would be considerably delayed.

4. UK Government Investment

The UK investment in environmental observations in the 1-200GHz frequency range is of the order £136million, with commitment of at least £63million over the next 15 years. Much of this could be at risk if interference were permitted that corrupts data.

The UK Government has invested heavily in environmental observations over the last 30 years, both for operational and research programmes, with by far the largest investment being in satellite observing. UK contributions to EUMETSAT this financial year alone will be £26million, covering the geostationary satellite programme (MSG, MTG), European Polar System (METOP) and the optional programme (JASON-2).

For this report the focus with satellites is on the EUMETSAT EPS programme as it includes most of the microwave instruments that would be affected. EPS, which is part (~5%) of the European component of the Global Observing System, is a series of polar orbiting satellites flying in constellation with those of the USA that will provide the bulk of operational global atmospheric observation data for the next 15 years. Since it was approved in 1998 the UK has invested ~£100million in EPS and is committed to a total investment of ~£200million by 2021 (out of total across Europe of €1.8billion) Of this investment at least 15% can be considered for provision of the microwave sounding instruments AMSU/MHS. Impacts of Radio Frequency Interference in any of their channels would put this investment at risk – potentially for complete loss.

(Note: The US equivalent programme spend on NPP/NPOES is currently budgeted at $13.5billion, with microwave instruments CMIS and ATMS comprising at least ~$2billion of this. Any RFI impact on European systems will have an equally serious impact on the US systems – affecting NOAA (civil) users as well as the US Department of Defense)

Previous investments by the UK in satellite hardware have included the AMSU-B instruments (which are still operational). In addition to this, considerable effort has been spent in researching use and exploitation of microwave sensor observation data – considering calibration, algorithm development and assimilation techniques.

Satellites are not however the only investment. Ground based systems using microwave sensors are equally vital and have also seen significant investment by the UK over the last 30 years. These are dominated by the weather radar network but also include wind profilers, cloud radars and temperature sensors. Unlike satellites, where costs are shared by EUMETSAT members, the costs for ground based systems fall to the UK alone. The total investments are shown in the table below.

		UK Investment made to date	UK Committed future investment (over next 10-15yrs)
EPS		£ 15M	£ 15M
AMSU		£ 12M	-
Exploitation of satellite data		£ 6.5M	£ 5M
Weather Radar	Hardware	£ 30M	£ 15M
	Development	£ 50M	£ 10M
	Support & Maintenance	£ 20M	£ 15M
Wind Profilers		£ 2M	£ 1.5M
Cloud Radars		£ 220k	£ 1.4M
Temperature sensors		£ 750k	£ 1M
	Total	**£ 136 million**	**£ 63 million**

These investments in environmental observations have been made by the UK government with the expectation of benefits to society to come through improved weather/environmental services. An external assessment of benefits to the UK from the services operated through / provided by, the Met Office was put at £1.5billion per annum. With a Met Office annual budget of ~£150million this represents a 10:1 benefit to investment ratio - an established ratio used in many socio-economic studies for the value of meteorological services.

Annexes

- Technical Annex A: Background discussion of Impacts
- Technical Annex B: Observing systems operating in microwave frequency bands
- Glossary

Technical Annex A: Background Discussion of Impacts

1. Introduction

The passive and active remote sensing bands used by the Met Office to acquire key observational data are coming under increasing pressure from active use that can result in harmful interference that can corrupt the data or render it useless. The effects of this on the Met Office's current and future operations could have a significant impact on the services that it provides to its customers and the general public.

The Met Office must ensure that it provides comprehensive information to the regulatory authorities on its use of the spectrum and the potential impact on its services and customers of changes, to assist them when making policy decisions affecting the use of the spectrum. The costs and benefits of the various uses of the spectrum are increasingly being used when assessing their relative merits. It is therefore important that as much information as possible on these aspects is provided.

The passive bands have been absolutely protected from intentional or unintentional active emissions under international Radio Regulation 5.340 which states that all emissions are prohibited in these specified bands. Despite this, some active users have been pressing for this regulation to be relaxed, or even dropped, allowing active emissions in these bands and the setting of higher out-of-band interference limits. The scientific use of the passive bands is currently protected by having hard limits on the level of unintentional out-of-band interference in each band. However, some active users are arguing that they should be allowed to transmit in these bands up to these hard limits. They have already succeeded in the 24GHz band where temporary active use of the band has already been granted for SRR (Short Range Radars) for cars, with a limited market penetration to reduce the impact on passive users. Despite a clear statement from the European Commission that the temporary use of the 24GHz band for SRR was not to be used as a precedent for future active use of the passive bands there are concerns that this may now be happening. It has been suggested that having hard limits on interference in the passive bands may not in the passive user's best interests as they could be regarded by active users as a target that was available for exploitation instead of encouraging them to limit unwanted emissions. There are concerns that the alternative approach involving impact studies based on current passive usage could preclude future passive usage that requires lower interference limits. Future developments using more sensitive sensors and techniques could lead to improvements in forecasting accuracy with significant consequential benefits. In practice it is also unlikely that interference levels would be reduced if hard limits were to be removed. The relative merits of the two approaches to the protection of the passive bands are not clear and further discussions within the meteorological community and with the regulatory authorities are needed. Access to reliable information to back up any positions will be essential.

The frequency bands required for passive remote sensing have already been rationalised, and the use of some bands for remote sensing has or will cease, releasing spectrum for alternative use. As a consequence, the scope for reducing the requirement further is limited.

This report focuses on the particular use of passive bands by Earth Exploration Satellite Service (EESS) in operational meteorology, climatology and numerical weather prediction (NWP). However, use of active microwave bands is also referenced for completeness. It assesses the impact of radio-frequency interference (RFI) on observing capability, its subsequent impacts on forecasting capability/services and the resulting impact on our customers. It considers both current and future potential impacts based on review of known information from existing investigations/trials and our expert knowledge of the forecasting process (observations through to services)

2. Impact on Observations

Observing the current state of the atmosphere is fundamental to the process of producing forecasts, whether they are shorter term weather forecasts or long term climate predictions. The Met Office strategy for observing is to adopt the concept of an Integrated Observing System (IOS) – a holistic approach where observations from many different systems using different technologies are considered complimentary to each other and part of one total system. Demands for efficiency have led to this approach where overlaps in observing capability are minimised, i.e. each system is designed as part of the total system with minimum redundancy of capability built in.

Due to the huge investment and commitment made by the UK government in meteorological/ oceanographic satellite systems (~£26million per annum through the Met Office), these form the baseline of the IOS with ground-based and in-situ systems being used to fill any gaps in capability and to provide ground truth calibration. We have recently closed a supplementary observing network because of the capabilities now offered by microwave satellite systems. Low redundancy/capability overlap does mean that loss of any one sub-system potentially causes large gaps in capability which cannot readily be filled.

Whether satellite or ground based, there is a common impact – any RFI can cause sensor channels to be lost, a recent example being AMSR over Europe at 10.7GHz. These cases are obvious, but lower level RF pollution/interference is detected in each band as noise, either continuous or intermittent, resulting in reduced accuracy (higher errors) and reliability. With automatic processing, any/all errors would be assimilated as 'accurate' data into numerical models – with resulting propagation of errors into forecasts.

Technical Annex B provides the breakdown of satellite and ground based systems, the frequency bands in which they operate and the geophysical parameters observed.

3. Impact on Met Office Capabilities

Sensitivity of every channel/band to varying levels of RFI cannot readily be assessed. This would need extensive research & investigation to run each scenario for each band for our models for a comprehensive range of weather conditions which would be extremely time/resource consuming. Hence, in this report we are considering only the case that RFI in any one band would mean the total loss of that band.

The nature of the weather, and therefore meteorological analysis/forecasting, means that the impact of data availability, or loss cannot be predicted in advance of an event. On some days data voids can be tolerated without major impact – on others, especially during severe weather events, data voids can have significant consequences on forecast accuracy. The 'Great Storm' of October'87 is an example of this. Lack of humidity profiles over Biscay meant the developing storm system was not adequately captured by the models and so the forecast track and its impacts on the UK were missed. The UK was fortunate that the storm hit at night otherwise many more lives would have been lost! Nonetheless, this was a high profile failing of the system for which a public inquiry was set up - with one of the outcomes being the recommendation for increased satellite coverage in the microwave region - for 'all-weather' observations.

Passive microwave satellite observations are unique as they provide information in and below cloud which is impossible in any other frequency band. In this section we consider the impact on NWP and climate research of loss of each frequency band. The exact purpose of each band is only briefly summarised with the main focus being how much forecasts are degraded if each individual band is lost.

3.1 Impact on NWP

For operational weather forecasting (1-14 day range) the forecasting process is heavily reliant on numerical weather prediction (NWP) with increasing automation involved in producing forecasts and with less input from human forecasters. This automation has only been possible with high resolution, more accurate NWP models fed by higher resolution (spatial & temporal) observation data. The degradation or loss of crucial observation data therefore has a direct impact on the NWP analysis and subsequent forecasts. Results from a recent NWP impact study (S.English, 2006[1]) show some disturbing results.

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[1] NWP Technical memo FRTR484, Met Office

The study of data denial experiments presents its findings in terms of the change to root mean square of error (RMSE) as a result of removing satellite microwave data. In this way it is possible to compare the value of microwave observations relative to all gains in the last decade.

It is found that microwave observations, as with all satellite data, have their largest impact where other data sources are sparse, so most especially in the southern hemisphere. However impact is also significant and valuable in data rich areas. In the southern hemisphere loss of microwave observations would take forecast accuracy back 9 years for mean sea level pressure (pmsl), 12-15 years for 500 hPa geopotential height and 14 years for 250 hPa winds. This is close to an order of magnitude greater impact than that arising from radiosondes, especially at shorter range, and microwave observations supply about 60-70% of the impact of all satellite data.

In the tropics, microwave observations are less important, largely because of the value of satellite cloud track winds that are available from geostationary based visible and infrared instruments. They only provide about 40% of the total satellite data impact and comparable impact to radiosondes (more impact at 250 hPa, less at 850 hPa). The impact for low altitude winds equates to just 2-3 years but for high level winds the microwave data remain very important with a detriment corresponding to about 12 years. In the northern hemisphere the detriment arising from loss of microwave observations correspond to 6 years for winds and geopotential height and 4 years for pmsl. This varies from 60-90% of the impact of all satellite data.

These potential losses would be catastrophic to NWP as there are no alternatives!

While the study demonstrates the overall affect of microwave sensors on NWP it also attempts to assess the impact of individual frequency bands. The practical use of microwave bands is that they are used together in groups and some frequencies are important to more than one group. These groups often form the basis for a single instrument measuring at several frequencies (e.g. AMSU).

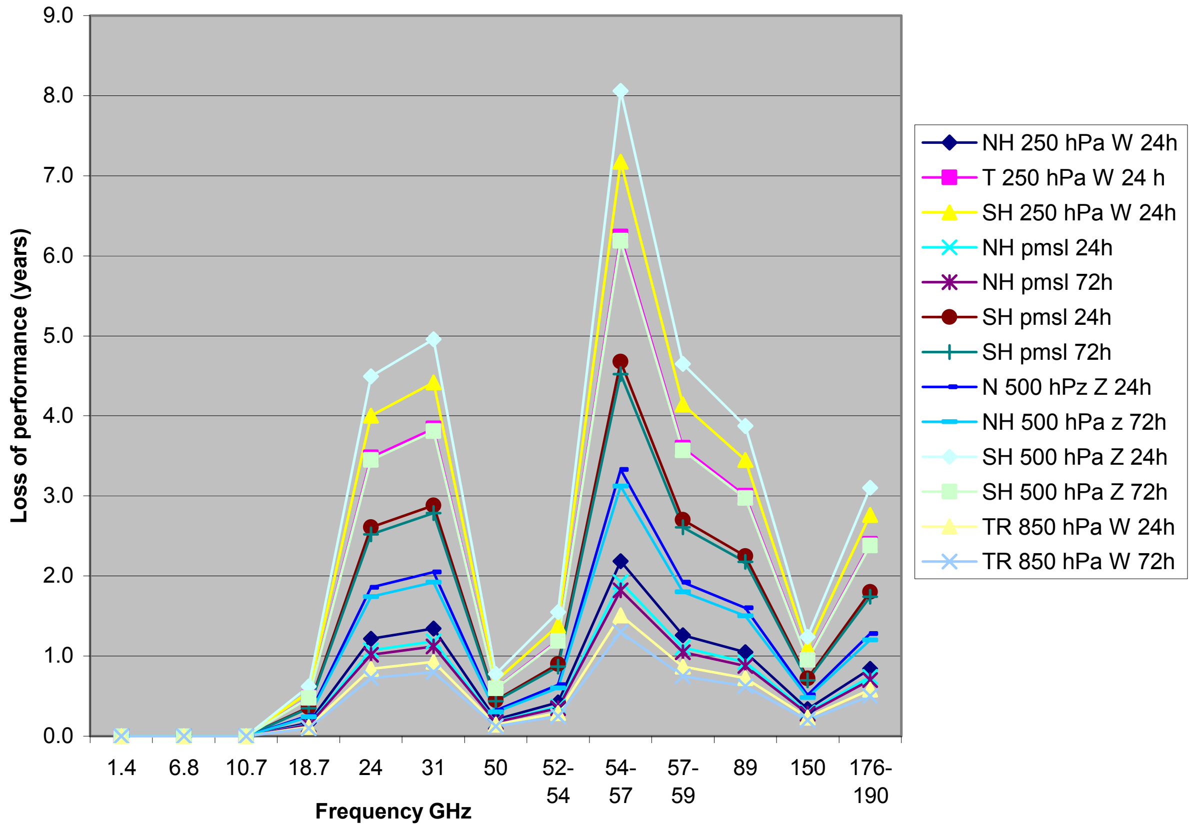

Figure 1. Loss of Global NWP Performance vs lost frequency band

In figure 1. an estimate of the loss of performance of the global NWP system is given if a particular frequency is lost due to RFI. So, for example, loss of the key part of the oxygen band above 54.5 GHz alone would give a degradation equivalent to nearly 6 years of improvement in the tropical and southern hemisphere upper level wind accuracy. However the adjacent window channels, often considered to be less vital, would give a degradation in the same parameter of 3.5 years.

In terms of the fields considered to be most important the loss of any one of 24 GHz, 31 GHZ, 54-57 GHz, 89 GHz or 176-190 GHz would degrade NWP performance by over 2 years in data sparse regions and by 3-6 years in the most sensitive regions. NWP performance has improved very significantly in the last ten years with faster computers, more sophisticated data assimilation methods, the effective exploitation of new satellite data and higher resolution NWP models. Therefore returning to performance even 2 years ago is significant. The loss of more than one band takes is not additive but loss of several channels or bands would quickly lead to losses of performance equivalent to over 10 years in some regions.

The impact of such data is where a significant part of the expected improvements in the next decade will come from. It is hard to estimate exactly how much forecast accuracy will improve in the future due to increased exploitation of satellite data. It is perhaps best to estimate this based on improvements over the last 12 years. 12 years ago the impact of satellite data was very small as only coarse resolution retrievals from the old TOVS system and cloud track winds and scatterometer with very limited coverage were available. The Met Office has invested in future observing systems such as the Infra-Red Atmospheric Sounder Interferometer (IASI) and the GNSS Receiver for Atmospheric Sounding (GRAS) instruments on the European polar system satellite, METOP (METeorological Operational satellite). It is anticipated that these and other new observing systems such as the Global Precipitation Mission (GPM), the Soil Moisture and Ocean Salinity Mission (SMOS), the Advanced Technology Microwave Sounder (ATMS) and the Conical Scanning Microwave Imager Sounder (CMIS) will mean that satellite data continue to provide a significant proportion of future NWP improvement in the next 12 years.

3.2 Impact on Climate monitoring/prediction

Passive microwave observations provide a unique capability for monitoring of the global climate that cannot be achieved from the more sparse in situ observing networks, or from infra-red sounders that are sensitive to the presence of cloud. Owing to the global interdependence of economies, security, and food and water supply, climate any where in the world is relevant to UK interests, and therefore research must take a global view.

These observations contribute to the top level objective of the Met Office to sustain a world-class climate prediction capability to give an authoritative assessment of natural and man-made climate change and their impacts.

Specific impacts of loss of passive microwave observation data are:-

Sea-ice extent (18-19GHz, 37GHz)

There are no suitable alternative observations of sea ice extent. Trends in surface temperature over the last decade have been largest over the Northern Hemisphere high latitude regions, where the loss of sea-ice has important environmental implications. Sea-ice observations are critical for scientists to:

- Use atmosphere-only models to simulate recent climate and therefore understand the processes that control it, especially at high latitudes.
- assess sea-ice schemes used in coupled ocean-atmosphere climate models that are used to predict future climate change.
- Monitor changes in high-latitude climate where sea-ice extent is a sensitive indicator of change.

The loss of sea-ice observations would severely limit our ability to understand, simulate, monitor, and predict future changes in high-latitude climate, and therefore also those regions sensitive to arctic climates including the UK and Europe.

Atmospheric temperature (50.3, 53.73, 54.96, 57.95GHz)

Passive microwave observations have been used to show that temperatures in the lower atmosphere are warming alongside temperatures at the earth's surface. Until now, there has been doubt that temperatures in the lower atmosphere are rising, a doubt which climate sceptics have leapt on as proof that global warming is not happening. At the global scale it is now clear that no major discrepancy remains.

Due to the large uncertainties inherent in the various data types this resolution has only been possible through scrutiny of all available observations. Without the passive microwave observations this would not have been possible, and the evidence base for climate change would be weakened.

Integrated column water vapour (18.7, 22.2, 37, 85.5GHz) + Upper troposphere water vapour (89, 150, 176-190GHz)

The importance of water vapour to climate cannot be overstated. It is the principal method of atmospheric energy transport, and is the dominant greenhouse gas. Much controversy in climate research concerns the representation of clouds and water vapour within climate models. Passive microwave observations of water vapour through the troposphere are vital in order to validate climate models, understand key water vapour processes and therefore reduce uncertainty in future predictions.

The passive microwave observations of integrated column water vapour are the only robust observations of increases in atmospheric water vapour in recent decades, in line with warming at the surface, providing further evidence for the magnitude of recent climate change.

Precipitation (Oceans, 10.6, 19.3, 22GHz. Land, 37, 85GHz)

Patterns and variability of global precipitation have major economic and social impacts, flooding and drought can disrupt commerce, industry, and agriculture, jeopardise water supplies and increase the incidence of disease. It is therefore imperative that global precipitation is routinely monitored. The loss of passive microwaves would limit precipitation observations to rain gauge observations at land stations only. Due to the large spatial variation in rainfall patterns this would severely limit our ability to rigorously validate precipitation within climate models.

3.3 Impact on Forecaster Capabilities

As has already been stated, modern forecasting relies heavily upon accurate forecast models with the forecaster 'adding value' to the raw model output to produce as accurate a forecast as possible to the customer. Hence any degradation of the quality and reliability of the model output from its current level would have a serious impact on the forecaster and therefore the customer.

Much of the raw model data is used to run other specialised forecasting models and tools (ie. NAME, TDAs, radar propagation, Site Specific Forecasts, surge model) and confidence in the reliability of model forecasts (and a knowledge of their weaknesses) is essential to forecasters both in the public and defence areas. Should the reductions in forecast accuracy suggested by the recent NWP impact study occur forecasters would have to 're-learn' the strengths and weaknesses of all aspects of the model output and also the knock-on effects on forecasting tools. For example the forecast information and advice provided by EMARC during the London Bombings and Buncefield Oil Fire would have been of reduced quality, and our ability to meet our responsibilities as one of the Worlds nine Volcanic Ash Advisory Centres (advising international aviation of the location and movement of clouds of volcanic ash) would be seriously impaired.

<u>Severe Weather Events</u>

The loss/degradation of sounding information input into forecasting models would therefore have a large impact on operational forecasting, especially in relation to rapid/major cyclogenesis e.g. the Great Storm of 1987, Boxing Day Storm of 1999

The Storm Tide Forecasting Service (STFS), set up after the east coast flooding disaster of 1953, plays a pivotal role in flood prevention around the coasts of England, Wales and Scotland. Bearing mind that it is the 'very poor' forecasts that have the highest impact on this service, any degradation in model quality and reliability would lead to a much increased risk of surge flooding events being missed and hence an increased risk to life and property – just one missed forecast resulting in the Thames Barrier not to be raised could lead to the whole of central London being flooded at a cost that must run into billions of pounds.

Tropical Cyclone Forecasting
Tropical cyclones are amongst the most powerful and destructive meteorological systems on earth. Globally, 80 to 100 develop over tropical oceans each year. Many of these make landfall and can cause considerable damage to property and loss of life as a result of high winds and heavy rain. In recent years, the Met Office has taken an active role in improving the forecasts of these weather systems.

The impact on Tropical Cyclone forecasting through the degradation of satellite information is likely to be great, as the introduction of such data streams into forecasting models, together with model developments, have lead to year on year improvements in forecasting the track of cyclones in both hemispheres. Bearing in mind that the effect of data loss in the model will be greatest over the data sparse areas of the Southern Hemisphere (taking forecast accuracy back between 9 and 15 years) we would see a corresponding downturn in the accuracy of Tropical Cyclone forecasts.

Our ability to accurately forecast the track of Hurricane Katrina in 2005 (when we delivered better forecasts to UK citizens living in the US than they were able to receive via the US met. services) has resulted in a paying contract to supply hurricane forecasts to the Foreign and Commonwealth Office throughout this years hurricane season, with the possibility that this service will be extended to cover all cyclone affected areas of the world. A decrease in model accuracy would clearly have a high impact upon these new services and those provided for overseas aid agencies such as to DfID (e.g. forecasts for the Southeast Asia Tsunami, Mozambique and Venezuela floods).

4. Impacts on Customers

The Met Office trading fund framework document sets out our role as the UK National Met Service in providing met and climate services to enhance the effectiveness of our Armed Services, contribute to the safety of the public and marine safety, and meet the needs of civil aviation, commerce and industry. These services are reliant on accurate weather forecasts and any degradation in NWP capability and, just as significantly, any deceleration in its rate of improvement, would have serious financial and operational consequences for our key customers. Below, the impact of RFI on our customers is assessed by sector.

4.1 Defence

Defence operations, both in the UK and overseas, have a critical dependence on the operating environment. This is reflected in an investment of approximately £34M per annum on environmental information (EI) services to Defence from the Met Office, on top of the underpinning capability furnished through the National Met Programme. Almost all of our defence-focussed R&D is aimed at exploiting enhanced NWP capability through the development of decision-making tools taking input data from NWP. Delivery of improved EI guidance to the front line will migrate away from the forecaster brief to more automated means, directly into mission planning and support systems. This demands the highest levels of accuracy from NWP at increasing resolutions,

4.1.1 Battlefield Tactics.
Weather is considered in every facet of military planning, global deployment, and system design and evaluation. With improvements in environmental situational awareness, the military is rapidly shifting its tactical and strategic focus from "coping with weather" to anticipating and exploiting atmospheric and space environmental conditions for military advantage. New and improved data from satellites will significantly accelerate this transformation.

Weather affects every air mission, from an air drop of humanitarian aid to bombs on targets. Ground forces exposed to the elements are hampered by extreme temperatures, winds, dust, rain, and snow. Accurate weather forecasts and warnings allow the Army to prepare for these conditions and move its weapons and equipment cross-country when required. The Navy uses ocean surface wind and wave fields for ship routing, with better data and forecasts, the Navy will avoid costly unnecessary sorties and have more time in areas of certain impact.

4.1.2 Impact on defence aviation.

Most military jet fighters of today consume fuel at an alarming rate and do not have the option of orbiting at height for several hours in the hope that the weather may improve. Neither do they possess all of the landing aids found in modern passenger aircraft, and they are therefore even more dependent on accurate weather forecasts than their civilian counterparts as described in section 4.4.

4.1.2.1 **Cost of failed missions due to bad weather**. In a study at RAF Valley in Anglesey over the period Aug 02 to Jun 03, 534 out of 17,231 aircraft training sorties (i.e. ~ 3%) were aborted due to bad weather (i.e. target obscured by cloud, precipitation or fog). As Valley's Hawk trainer costs £4000 per hour to operate, and each sortie lasts about an hour, this equates to approx £2.1 million. In fact this is likely to be a significant underestimate as each sortie may involve two or three aircraft. Apply this to all airfields, and it becomes apparent that any reduction in forecast accuracy of target weather through a reduction in NWP capability could cost tens of millions of pounds, present greater risks to pilot safety and increase the costs/duration of pilot training and mission execution.

4.1.2.2 Accuracy of airfield warnings. Short-range forecast advice such as the issue of thunderstorm warnings is essential to flight safety and the safety of ground support personnel involved in aircraft refuelling operations.. Forecasters rely heavily on accurate lightning detection and radar rainfall information to provide these warnings, without these data the frequency of false alarms and missed events would increase and station operations would be become less efficient..

4.1.3 Tactical Decision Aids (TDAs).
TDAs are used to identify windows of opportunity and plan which weapons, sensors and type of manoeuvre are appropriate for a particular mission. TDAs have a critical dependence on the quality of the input NWP data, especially in the boundary layer. Any degradation would reduce TDA performance and increase the number of mission failures..The increasing exploitation of microwave satellite data are integral to improvements in NWP (particularly the specification of the surface temperature & soil moisture) required by the Defence user, Without these improvements the advantage of information superiority over our adversaries could be lost.

4.1.3.1 **Noise predictions**. Noise prediction forecasts are a requirement at a number of MOD bases in order to help them plan detonations/firings without falling foul of H&S law or the local populace. Noise propagation is sensitive to the low level vertical profiles of wind and temperature and any degradation to model data in the boundary layer, and above for long range predictions, will have a significant impact on accuracy.

4.1.3.2 **Artillery firings**. The accuracy of artillery firings is highly sensitive to meteorological errors. In a study of AS90 gun firings with typical range 23km and maximum altitude 6.3km, it was found that a 10 degree error in the forecast wind direction, or a 5 knot error in forecast winds or a 2.5K error in virtual temperature would lead to radial miss distance of over a 100metres from the intended target. When such targets are located in densely populated areas, the potential for large numbers of civilian casualties is clear to see.

4.1.4 Radar propagation.
Any decrease in the ability of NWP models to resolve the temperature and humidity profile of the atmosphere and make predictions of radio frequency anomalous propagation, essential for targeting, ship self-defence and communications less accurate.

4.1.5 Chemical, Biological, Radiological and Nuclear Incidents (CBRN).
CBRN plume drift forecasting has a critical dependence on local wind flow and deposition (e.g. via precipitation). Any degradation in the quality of the raw NWP used to create Chemical Downwind Messages for Middle East locations would directly impact the accuracy of these messages and endanger life..

4.1.6 Search and Rescue.
In the UK about 14,000 search and rescue incidents occur annually. About 8,000 of these incidents lead to deployment of some type of resource (RNLI/helicopter *etc.*). 5,600 people were actually rescued and 316 lives were lost. Ninety percent of these incidents occurred within 3 km of the coast.

Any deterioration in NWP operational models affecting winds, surface waves and near surface currents would **significantly** decrease the quality of the drift predictions and local weather needed to optimise these coastal search and rescue operations. The consequent likely increase in the number of lives lost is open to question but is likely to be between 1% and 10%. An increase of 1% would mean 3 additional lives lost per year and a 10% increase would equate to 30 lives.

4.2 Public Weather Service

4.2.1 Chemical, Biological, Radiological and Nuclear Incidents (CBRN).
The Met Office provides meteorological advice and data to emergency services, government departments and agencies involved in dealing with a CBRN release. Accurate meteorological and dispersion advice during a major incident (for example a nuclear detonation) is dependent on accurate NWP to predict local variations in wind speed, direction and precipitation (to wash out toxic particles). Getting this right could plainly have very major financial benefits, running to £billions or more.

4.2.2 Foot and Mouth outbreaks.
The Met Office has the lead responsibility for providing meteorological and dispersion advice during a Foot and Mouth epidemic. Predicting the potential spread of the virus requires detailed wind flows and other meteorological data for driving dispersion models. Any degradation in NWP would significantly decrease the confidence with which forecasts of disease spread can be provided, and lead to less confidence in the targeting of an area over which culling or vaccination is required. It is estimated that the cost of the 2001 outbreak was £2.5 billion for compensation for slaughtered animals (a total of 6 million animals were culled) and £3.1 billion for losses to agriculture and the food chain. Even a reduction of just 1% in the number of animals culled through improved detection and targeting could lead to savings of tens of £millions in a future outbreak.

4.2.3 Weather-related road congestion.
One source estimates that the total economic cost of road congestion is some £20bn *per annum.* Highways Agency research indicates that 25% of congestion is caused by “accidents and incidents”. Further research points to 20% of this 25% being attributable to adverse weather. An approximate cost of weather-related congestion is therefore £1bn *pa.* This ignores the human cost of bad weather (*e.g.* injuries due to road accidents attributable in part to bad weather). It is hard to quantify the effects that poorer NWP-derived weather forecasts would achieve, but even assuming it to be as low as 5% of the £1bn cost would be £50m. And this is before any attempt is made to financially quantify the human cost.

4.2.4 Wind storms and Flooding events.
Human and economic loss from severe weather events, in particular windstorms, is significant and (due to climate change) growing. The following example statistics indicate the scale…

Storms and floods typically contribute over 90% of the costs of extreme weather each year. Historically windstorms have been the primary cause of insured losses due to natural events in Europe, although since 1990 flood damage has also emerged as significant. Since 1970 there have been 55 severe windstorm events, resulting in total insured losses of £24bn (€35 bn). Seven very severe storm events account for 64% of this total. In the UK in 1987, hurricane-force winds caused over £1.2bn in property damage, giving rise to 1 million claims in a single day. Volatility of losses has been exacerbated by the clustering of very severe storms, with three in 1990, and three more in 1999. There is a slight upward trend in the number of windstorm events.

And scientific evidence points to climate change significantly increasing the costs of storm damage. Recent evidence suggests that warmer temperatures could increase the severity, as well as the number, of storms. By the 2050s, insurance claims for storms in average years could have doubled from today’s value of £400m *pa* and in extreme years, today’s value of £2,500m *pa* could have tripled.

Flooding also accounts for significant loss. Research commissioned by Defra estimates that five million people and 1.8 million residencies plus 140,000 commercial properties (overall, some £220bn of assets) are at risk of flooding in England and Wales. About half of the total asset value is located in the Environment Agency Thames Region. The annual cost of flooding is estimated as £0.7bn exclusive of uninsured damage.

Storm wind damage – provision of early warnings
Loss of microwave observations would setback the forecast accuracy of winds by 6 years and surface pressure by 4 years, and increase the likelihood of 'busts' i.e. very poor forecasts. Poorer weather forecasts would reduce confidence levels and shorten the lead times for warnings of likely strong winds, bucking the recent trend for providing better-targeted and earlier warnings. UK society will in turn suffer as public and relevant agencies have less time to take appropriate mitigating actions e.g. utility companies will be less prepared to restore power supplies affected.

Flash flooding
On 16 August 2004 the village of Boscastle in Cornwall was flooded. Eight inches of rain fell in 24 hours, most of which fell in a concentrated period of five hours. The result was two million tonnes of water flowing through the centre of Boscastle. There was no loss of life, but damage to property was estimated to be in the region of £500 million.

Flash flooding occurs after intense localised rainfall events usually associated with thunderstorm activity, usually in urban areas where surface drainage of rainfall is inhibited by the ground surface (typically tarmac or grass). The radar network represents the first line of defence against loss of life and property resulting from flash flooding. Indeed, it came into being partly as a direct consequence of the 1952 Lynmouth flood when 30+ people lost their lives. Radar is the only means we have of detecting these events in real-time and is likely to remain so for the forseable future as satellite rainfall measurements do not have the accuracy, spatial resolution or frequency in time in order to resolve dangerous rainfall patterns.

Any decline in NWP performance would only serve to delay required increases in the precision and reliability of rainfall forecasts that would allow the Met Office to issue flood warnings earlier in time for mitigating actions to be taken. Potential socio-economic benefits are difficult to assess, but potentially lives could be saved and damage to property could be reduced (*e.g.* by distributing sandbags) if earlier and more accurate warnings were available.

River flooding
Although river flooding events have a longer lead-time than flash floods, they occur regularly and with significant human and economic loss. The most recent published estimates indicate that the annual direct cost of river flooding in England and Wales is £800m, with an additional annual indirect cost estimated at £400m.

The Environment Agency estimates that it should be possible to save about £3m damage per annum cumulatively for each extra hour of warning lead time that can be provided. In addition, the ability to provide long warnings in excess of 12 hours would permit increased protection of communities by temporary defences, which could provide larger financial and environmental benefits by avoiding the need for civil engineering works.

This would require improved precipitation forecasts (amount, location, time) that enables the intense cores of precipitation that cause flooding to be identified, permitting use of the forecasts in catchment flood models, and thus providing direct input to the flood warning process.

Coastal and tidal flooding events
One million properties are at risk from coastal flooding. This risk is exacerbated by climate change impacts on sea level rise and the increase of storm frequency (which increases storm surge tides and associated winds). The Storm Tide Forecasting Service integrates high resolution atmospheric NWP model with high resolution wave / surge models to provide improved forecasts of near shore and coastal weather related events. Realisation of the benefits of more accurate forecasts provided at longer lead times will be setback if NWP performance is reduced.

4.2.5 Mitigation of damage arising from oil spills.
Oil spillages such as that from the Bahamas registered tanker *Prestige* on 13 November 2002, along the coast of Spain and France, are hugely expensive to clean up. The estimated cost of the clean-up to the Galician coast alone was £1.6bn. Any decrease in ocean modelling capability that affected coastal current predictions and hence the realism of the oil slick drift predictions, would decrease the value of advice given to environmental protection and other governmental agencies. It is hard to quantify in monetary terms what socio-economic loss might be, but it could well be very material given the huge economic (hence human) and environmental cost of such events.

4.3 Commercial

4.3.1 Rail Operations.
Weather-related disruption is a major external risk faced by the UK's national rail network. This might be due to buckling of rails in extreme summer heat, power lines be brought down during high winds, icing of conductor rails or loss of adhesion during autumn leaf-falls etc. Weather-related events directly attributed and recorded within train delay minutes account for about 10% of the national average.

Clearly the assessment of the severity of risk depends upon the quality and timeliness of the weather forecast information supplied. Currently the Met Office provides forecasts for 32 regions of the UK rail network in terms of both a daily forecast of detailed weather conditions and an assessment of the likelihood of particular hazard thresholds being exceeded over the coming 5 days.

More accurate spatial resolution of the occurrence of weather events in the timescale of 0 – 36 hours would be delayed if NWP performance declined. Future improvements to provide probabilistic forecasts that would enable improved asset maintenance decisions to be made, on the timescale of 1 -10 days and outwards to 1 month ahead would be delayed. For example, better predictions of summer temperatures which would be too high for rails to be laid would allow Network Rail to make more efficient decisions regarding the timing and location of critical asset maintenance works. Network closures could be planned so as to avoid those times and locations when and where weather events were predicted to be so severe as to preclude effective maintenance work. There is potential, given further research, for ensembles forecasts to deliver both business benefit to Network Rail and socio-economic benefit to its customers.

4.3.1 Off-shore Oil Industry
Research commissioned by UKOOA and UK HSE has estimated that the likely cost savings to offshore operations such as helicopter operations, rig movements, diver support vessel operations and tanker loadings, from improved meteorological data, could be £10m *pa*. The impact on offshore operations of planned improvements in NWP is likely to be significantly smaller than those envisaged in the report cited. Nonetheless even a 10% increased value to those operations would amount to a saving of some £1m *pa* and equate to 30 lives.

4.3.2 Optimisation of Utility Company Operations
Weather forecasts are a vital part of the information chain that energy companies use to plan and manage their businesses. The weather has a significant effect on patterns of energy demand and on the ability of companies to generate and transport the power required to meet that demand. As forecasts become increasingly accurate, prediction of demand and supply becomes more accurate and this leads to real benefits to the economy in terms of security of supply, efficiency and preparedness for disruption.

It has been shown in the US that if the accuracy of weather forecasts were increased by 1 degree Celsius, the cost of electricity to that nation could be reduced by at least $1bn *pa*. Scaling this down to derive a corresponding potential saving to the UK suggests that, conservatively, electricity costs of the order of £80-100m *pa* could be saved.

It is especially improvements in temperature, wind speed and illumination deficit forecasts that will help the utilities sector deliver measurable socio-economic benefit to the UK economy. Equally, any decline in forecast accuracy of these elements will deliver an unacceptable burden on the UK economy.

4.4 Civil Aviation Authority – Airlines, Airports and Air Traffic Control

Although aviation accidents are rare, weather is often a causal factor and reductions in forecasting accuracy or a deceleration in its rate of improvement will impact on two main areas:-

1. The quality of core services provided through the CAA main contract where the Met Office provides the safety baseline of services for all aviation within UK airspace and through its ICAO designated World Area Forecast Centre (WAFC), global aviation above 24,000ft.
2. Commercial services, where declining forecast quality and less innovation from forecast model improvements will provide poorer support for value-added services. Such services provide financial savings to customers through optimised flight routes, minimised fuel costs, enhanced logistical planning, increased operational efficiency and delay reduction.

Globally, it is estimated that the annual cost of weather to the aviation industry is $4 Billion. Of this, it is estimated that up to <u>$1.5 Billion is avoidable</u>.

4.4.1 Safety : severe weather avoidance
Significant weather is a mandatory part of pilots briefing prior to departure. However, every year there are a number of accidents caused by encountering severe weather en-route.

The US National Transportation Safety Board quote weather factors to be the second most common causal factor of accidents after human error (and ahead of aircraft defects). Others quote that about 20 to 30% of world wide accidents are related to **adverse weather conditions**, which is the major contributing factor to the three largest categories of fatal aircraft accidents. Any deterioration in forecast accuracy will therefore have a negative safety implication, risking human life and property.

Critical to safe operations around airfields is the ability to forecast low cloud and fog. Improved forecasting of these parameters in the future will be delivered, in part, by improved specification of surface temperature and soil moisture from satellite observations. These satellite observations make extensive use of the atmospheric window channels which are under the greatest threat of contamination and protection of these bands is essential to the continuing improvement of forecast of safety critical met parameters.

4.4.2 Economic, social and environmental impacts: delay reduction
As well as having a major influence on an airlines financial bottom line, delays also have a significant economic impact on the UK economy due to the disruption to passengers and freight. Figures from Eurocontrol eCoda for Europe alone give the following figures for Jan 05:

- 25% of all departure delays were caused by weather factors. Of 680,000 flights, 40% were delayed (272,000), of these 25% were attributable to weather (68,000)
- With an average delay of 10 minutes and a average cost of £50 per minute this gives an associated delay cost to European aviation in Jan 05 of **£34M**
- A comparison departure delay figure for 2004 (2 years degradation in NWP) was 28% and hence an associated delay cost of over £35M for Europe alone.

In Europe approximately 22% of air traffic flow management delays are due to bad weather. Such delays have a considerable cost for both airlines and users. A study in the US appraises these costs at more than **3B$ per year**.

Furthermore, one UK based short-haul airline claims that pilots are permitted to add up to an extra ton of fuel on top of that calculated by the flight plan and almost always add a contingency due to a lack of confidence in the calculated fuel burn and forecast weather. Assuming that all pilots add an un-necessary 500Kg per flight, then the estimated cost per annum to the airline in terms of fuel burned carrying un-used fuel is: 0.5 ton x 300,000 flights x 1.5 hrs (average flight) x 2% (per hr) x $300[2] (per ton) **~ $1.3M p.a.** This figure excludes the lost revenue from the cargo that could have been carried instead of the additional fuel.

Reductions in forecast quality therefore promise significant set-backs in the potential for proactive planning, with resulting negative impacts in terms of delay reduction and fuel burn.

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[2] $180 quoted in 2003 - $300 derived by average increase in fuel prices 2003 - 2005

4.4.3 Economic, social and environmental impacts: Flight routing
Minor set backs in upper level wind forecasting will result in significant financial implications for airlines in terms of fuel costs and the environment - emissions of greenhouse gases and other pollutants. The Director General of IATA (International Air Transport Association) was recently quoted (3) as saying that "rising oil prices are making cost cuts critical for airlines; if every flight could save one minute, industry savings of **$4b annually** are possible". The pollution of spectral wavebands used for meteorological observing has been informally discussed with IATA whose view is that any forecast accuracy deterioration is unacceptable.

Some studies have indicated that more accurate wind fields than currently exist could reduce fuel burn for long haul flights by 0.6-2.9%. Yet any reductions in wind forecast quality will lead to deteriorations in flight routing, inflated fuel costs for airlines and greater emission of pollutants. The January 2006 RMS Vector Error for 250 hPa winds for the Southern Hemisphere – where data sources other than microwave observations are sparse and any loss of data will have a greater impact- was 4.2, whereas for January 04 and January 2006 accordingly the errors were 4.35 and 5.5.

4.5 Climate

The Climate Programme of the Met Office, Hadley Centre is a programme to deliver a wide range of scientific results, analyses, information, data and advice which is required to inform government policy in the areas of climate change mitigation (through the UN Framework Convention on Climate Change (UNFCCC), and the UK Climate Change Programme) and adaptation (through the UK Climate Impacts Programme). It is primarily funded by the Department of the Environment, Food and Rural Affairs (Defra, ~12Mpa) and the Government Meteorological Research Program (~3.5Mpa).

The Climate Prediction Programme is not an academic research programme; its work plan and deliverables are driven by Defra's requirements for science to inform UK government policy on climate change mitigation and adaptation. In particular the loss of key passive microwave observations will impact the science underpinning the following key objectives:

- To negotiate commitments under the UNFCCC for the 2nd Commitment Period, including consideration of objectives on stabilisation of greenhouse gases in the atmosphere.
- Anticipate future climate change by planning cost effective adaptation strategies for the UK.
- Contribute effective science to the Intergovernmental Panel on Climate Change (IPCC) reports that reports to the UNFCCC and provides a standard of reference for policy-makers, scientists, and other experts.

5. Summary/Conclusion

Certain passive bands are essential for the operations of the Met Office and must be given the highest level of protection from in-band and out-of-band RFI. In terms of the fields considered to be most important for operational weather forecasting RFI in any one of 23.6-24 GHz, 31.3-31.8 GHZ, 50.2-59.3 GHz, 89 GHz or 174.8-191.8 GHz bands would degrade NWP performance so much that forecast services would be compromised – returning performance to pre 2000 levels in some cases, with future improvements being slowed to ~50% expected.

The above frequency bands are also vital to climate research and prediction with the addition of the 10.68-10.7 GHz, 18.6-18.8 GHz, 22.21-22.5 GHz, 36-37GHz bands. However, there may be scope for greater flexibility in the use of some other bands, subject to safeguards that would enable new passive applications in the future where appropriate

By definition the most serious RFI is that which we can not detect and the full extent of the problem is therefore unknown. Protection of all these above bands for EESS is essential as the unique spectral nature of each means there are no alternatives for making equivalent observations in any other parts

[3] Speednews, Friday Sept 9th 2005

of the spectrum. At present it is the 50.2-59.3 GHz band that remains the most vital source of observations on a global scale.

With such a significant impact on the key forecast products of atmospheric winds, temperature and humidity, the reduced level of service we would be able to provide would be unacceptable to our customers across the whole range of business areas – Government and Industry alike.

Technical Annex B: Observing systems operating in microwave frequency bands.

1. Observations

Attached table 1 lists the microwave frequency bands used by EESS for operational meteorology & climatology including the observing systems for each band and the geophysical parameter being observed.

2. Satellites Systems

2.1 Instruments/Missions

AMSU	on NOAA-15, NOAA-16, NOAA-17, and NOAA-18 (NOAA); METOP-A, METOP-B, METOP-C (EUMETSAT); Aqua (NASA).
MHS	on NOAA-18 (NOAA) and METOP-A, METOP-B, METOP-C (EUMETSAT).
ATMS	on NPP and NPOESS series (NOAA)
CMIS	on NPOESS series (NOAA)
SSM/I	on DMSP F8, F9, F10, F11, F12, F13, F14, F15 (US Department of Defence)
SSMIS	on DMSP F16, F17, F18, F19, F20 (US Department of Defence)
AMSR	on Adeos-II (Japanese Space Agency) and Aqua (NASA)
TMI	on TRMM (NASA)
MIRAS	on SMOS (ESA)
Aquarius	on Aquarius/SAC-D (NASA + CONAE = Argentine Space Agency).
WindSat	on Coriolis (US Department of Defence)

Details on these missions can be found at the WMO/CEOS webpage:
http://www.wmo.int/index-en.html => WMO Space Programme => Online database information => Satellite Systems and User Requirements information (CEOS/WMO database)

2.2 Frequency band use

It is vitally important to note that most bands are sensitive to more than one geophysical variable and therefore channels must be used together to derive a number of different quantities. Therefore there is no one-to-one mapping from frequencies to products. Furthermore most measurements used in meteorology will be direct assimilated in their raw form into the analysis used by Numerical Weather Prediction models. The list below therefore simply indicates the main sensitivity of each band. The frequencies chosen each have unique spectroscopic characteristics for the application each is used for. The spectroscopy is fixed by fundamental physics and is unalterable.

1.4 GHz Soil moisture and ocean salinity
The emission of radiance from the surface only depends on salinity at frequencies below 5 GHz. The strength of the signal increases to about 1 GHz but remains very small. It is only detectable from space between 1 and 2 GHz and thus the 1.4 GHz band is the only choice available.

6.8 GHz Sea surface temperature
Below 10 GHz the atmosphere becomes almost transparent to all radiance except for very heavy precipitation. By 6.8 GHz even the heaviest precipitation has little impact. Therefore there is the only opportunity for a “clean” all weather view of the surface. However below 2 GHz there is also sensitivity to salinity so the highest possible frequency must be used for an unambiguous sea surface temperature. Hence 6.8 GHz is the only viable option. A channel between 2 and 6 GHz would provide some sea surface temperature information but a) less close to land because of diffraction limit with the longer wavelength (hence some ocean areas would be unobservable) and (b) with some small biases due to small salinity variations.

10 GHz: Surface rainfall rate Precipitation over oceans (10.7, 19.3, 22GHz)
Above 10 GHz the effect of rainfall becomes significant on the passive emission but above 18 GHz the effect of water vapour and cloud liquid water mask the emission from the precipitation. Therefore there are two candidate frequencies (10 and 15 GHz) but all investment by space agencies has used the protected frequency at 10 GHz. Satellite data are essential to infer global changes in precipitation due to the strong spatial variability inherent in precipitation, and the lack of in-situ observations over the oceans. Precipitation estimates from microwave emissions measured by SSM/I (19.3, 22GHz) over the oceans have been incorporated in the Global Precipitation Climatology Project (GPCP, Huffman et al. 1997), and the NOAA Climate Prediction Center Merged Analysis of Precipitation (CMAP, Xie and Arkin, 1997). The 10.7GHz channel available on the Tropical Rainfall Measuring Mission's (TRMM) Microwave Imager (TMI) provides a more-linear response for the high rainfall rates common in tropical rainfall. There are no known alternatives for these data

18.7 GHz: Surface windspeed, Sea Ice (+37GHz)
Above 15 GHz the wind induced roughening of the ocean (waves) modifies the surface emission in horizontal polarisation but not in vertical polarisation. Therefore instruments measuring both vertical and horizontal polarisations can give windspeed information except in heavy precipitation. Wind direction can also be obtained if the full Stokes vector is measured due to the anistropic scattering by waves leading to non-zero values in the 3^{rd} and 4^{th} elements of the Stokes vector. The strength of the surface emission changes peaks between 18 and 40 GHz but in this range the (non precipitating) atmosphere is only transparent below 20 GHz. Sea-ice extent is expected to become a sensitive indicator of climate change, and observed trends in Arctic sea-ice extent are consistent with increases in the duration of the summer melting season (IPCC, 3AR, pp. 124-125). Continuous measurements have been derived from the Scanning Multichannel Microwave Radiometer (SMMR, 1978 to 1987), and the Special Sensor Microwave/Imager (SSM/I, 1987 to present). The sea-ice concentrations are an integral part of the Hadley Centre blended sea surface temperture and sea-ice data set (HadISST, Rayner et al. 2003). There is no alternative observation of sea-ice extent.

19.35 GHz: Surface windspeed
(its use now superceeded by the 18.7 GHz band). An alternative to 18.7 GHz but not protected and being phased out.

22-24 GHz: Total column water vapour
There is a water vapour spectral line at 22.225 GHz with a width from 20-24.5 GHz. This is the only water vapour line in the entire spectrum where cloud absorption is weak and thus water vapour can be measured through clouds. The band at 23.6-24.0 GHz measures emission at the side of this band. A number of frequencies have been used to measure water vapour from this feature but space agencies have converged on 23.6-24.0 GHz for all missions so only one narrow frequency band requires protection (though the car radar devices now will pollute this band).

31-37 GHz: Total column cloud liquid water
There is a broad atmospheric "window" from 25 to 48 GHz. However the atmosphere is not really transparent at these frequencies because of significant cloud liquid water emission. The emission from other sources (water vapour, oxygen) reaches a minimum at 31 GHz so space agencies have converged on this frequency, though some older systems used 37 GHz (e.g. SSM/I). Indirect measurement of precipitation over land surfaces is achieved from the higher frequency bands of the SSM/I, and are incorporated in the GPCP and CMAP analyses. Land stations provide an alternative measurement, but cannot offer the comprehensive spatial sampling of satellite observations.

50-59 GHz: Temperature sounding (+118 GHz)
The 50-59 GHz range is a remarkable and unique natural resource. There is a strong emission from oxygen but nothing from ice cloud and little from water vapour. As oxygen is well mixed through the atmosphere (i.e. always about 21% of air is oxygen) air temperature can be inferred from these spectral lines, because we know how much oxygen there is already. This can be achieved even in the middle of a cloud composed if ice (most are). For operational meteorology this is vital information. At no other frequency does such a capability exist. There is a single oxygen absorption line at 118 GHz but ice cloud is having an effect at that wavelength and the effects of liquid water is so strong that even small amounts affect the measurements. To gain profile information the spectrum must be

sampled at a range of oxygen absorption strengths and hence 11 channels are used to cover the low frequency side of the oxygen absorption band. The record of temperatures from the Microwave Sounding Unit (MSU) have been extensively analysed by the international climate community, providing observations back to 1979. Temperatures in the lower atmosphere are warming alongside temperatures at the earth's surface. Until now, there has been doubt that temperatures in the lower atmosphere are rising, a doubt which climate sceptics have leapt on as proof that global warming is not happening. At the global scale it is now clear that no major discrepancy remains. Due to the large uncertainties inherent in both data types this has only been possible through scrutiny of all available observations, through multi-national effort, from both radiosondes and MSU. Since 1998 a follow-on series of instruments (AMSU) have been available, with additional channels that will allow for a more comprehensive assessment of the vertical profile of atmospheric temperature changes, important for diagnosing feedbacks related to the change in temperature lapse rate, and possible impact on the water vapour content of the atmosphere.

89 GHz: Detection of strong convection (e.g. thunderstorms). Integrated column water vapour over oceans (18.7, 22.2, 37, 85.5GHz)

Above 60 GHz the effect of ice cloud becomes significant on the measurements for the first time. There is an atmospheric window between the 50-60 GHz and 118 GHz oxygen spectral features which has the highest atmospheric transmission close to 89 GHz. Thin ice cloud has no impact at 89 GHz but deeper ice cloud supporting large ice particles has a big impact. Therefore 89 GHz is able to distinguish more effectively than any other channel between thin high level ice cloud and thick possibly precipitating ice cloud. At lower frequencies the sensitivity to ice clouds is insufficient. At higher frequencies it is too strong so thinner ice cloud also has an effect.

Water vapour is a key climate variable. In the lower troposphere, condensation of water vapour into precipitation provides latent heating which dominates the structure of the troposphere. Water vapour is the most important greenhouse gas in the atmosphere, accounting for 60% of the natural greenhouse effect under clear skies, and consequently provides the largest positive feedback in model projections of future climate change. Column water vapour estimates from SSM/I have been used to detect trends and inter-annual variability since 1987 that are consistent with expectation given sea surface temperature changes over this time. No alternative available other than surface humidity from ships and buoys.

150-166 GHz: ice cloud detection

At 150-166 GHz there are three equally good frequencies though systems are now converging on 157 GHz for detecting moderate ice cloud likely to have a significant impact on the quality of water vapour information from the nearby water vapour line. It is therefore vital in interpretation of the water vapour line.

176-190 GHz: Water vapour sounding.

The second water vapour line below 200 GHz. It is much stronger than the line at 22.2 GHZ and therefore able to sense not only low altitude water vapour but high altitude water vapour where amounts are usually much less. However as noted the effect of ice cloud is significant and therefore it must be used with 157 GHz or similar to help with ice cloud detection. To gain profile information the spectrum must be sampled at a range of water vapour absorption strengths and hence three channels are used cover the whole spectral line. Water vapour in the mid and upper troposphere account for a large part of the atmospheric greenhouse effect. Changes in upper-tropospheric water vapour in response to a warming climate have been the subject of significant debate, and therefore uncertainty, in climate projections. Due to instrumental limitations, long term changes of water vapour in the upper troposphere are difficult to assess. The short legacy of the AMSU-B instrument has so far limited the use of these data for climate monitoring, but under the warming expected to occur in the coming decades, global observations of the humidity profile can be used to monitor this critical greenhouse gas.

200+ GHz: Integrated ice cloud content

In the 200+ GHz frequency range there is the potential to gain more information on ice cloud as the measurements are sensitive to all sizes of particle thus enabling measurement of integrated ice content. It is still being explored which are the best frequencies to do this and to provide information on ice particle size and habit which is important for climate monitoring and prediction. A proposed ESA mission, CIWSIR, has a range of frequencies under investigation between 200 and 850 GHz.

All uses of the window band on the low frequency side of the 22.225 GHz water vapour line are converging on 18.6-18.8 GHz (i.e. no use of the bands close to 15 GHz, and use of 19.35 GHz band to be discontinued. Similarly at 150-166 GHz all use is converging on 166 GHz and at 85-92 GHz use of 85 GHz is being dropped in favour of all instruments using 89 GHz. Measurement of water vapour has converged on 24 GHz. The most controversial is 30-37 GHz where most applications can rely solely on 31 GHz however for snow applications 36-37 GHz remains very valuable. However the period of development of satellite programmes is 10-15 years and programmes typically last 15 years. Therefore we still have programmes flying and planned to fly whose frequency selection predates agreements to converge on specific frequencies and therefore there is a temporary requirement which is reflected in ITU agreements.

3. Ground based Systems

3.1 Weather Radar

The UK weather radar network consists of 14 C-band weather radars. The network represents a capital investment of about £15M by stakeholders which include the Met Office, The Environment Agency of England and Wales, the Royal Navy, Anglian Water PLC and Scottish Power. Ongoing running costs are about £1M p.a. and investment is running at order £1M p.a. in new radars, new products and applications.

C band is chosen as a compromise between the level of attenuation (by rain) and the cost of the radar installation. S band is actually a superior frequency to use (less attenuation), but the radar cost has historically been prohibitive. The partners in the UK weather radar network could vacate C-band, but would require investment of about £15M in replacement radars. However, it should be noted that C-band weather radars are also operated in France, Belgium, Netherlands and Eire.

In order to detect rainfall at long range (250km) and light rainfall at shorter range, high power transmitters (at least 250kw peak) and very sensitive receivers are necessary. Even so, most signals from rain lie either within or just a few dB above the background noise. The technique is then very vulnerable to any increase in the background noise level at C band or localised interference. Some interference is experienced from time to time - e.g. from marine radars and satellite uplinks. A general increase in the background environmental noise level at C-band of a few dB would compromise the measurements.

The parameters measured by the network are:-

a) rainfall rate (for flood warning, severe weather warning, and general forecasting)
b) reflectivity (for future assimilation into NWP)
c) radial wind speed (for assimilation into NWP and for future detection of severe weather - tornados etc)
d) refractivity (for assimilation into NWP)

The economic value of the network is dominated by a) but c) is seen as providing significant improvements to the next generation of high resolution NWP.

Total sunk costs in the radar network to date (starting from the early development at Malvern, early feasibility studies etc) would be order £30M capital, £20M S&M and £50M development (all at todays prices).

5.6 – 5.65 GHz Weather Radar: Submission to the ECC 57th Meeting of the WG FM by EUMETNET: Subject: Serious concerns of the meteorological community on the possible use of the 5 GHz RLAN band (5470-5725 MHz) by Intelligent Transport Services (ITS). Evidence of interference to operational radars in Poland and Hungary is presented.

3.2. Wind Profilers

The Met Office owns & operates a network of 5 wind profiler radars, 1 at **64MHz**, 2 at **915MHz** and 2 at **1290MHz**. In addition a research radar at Aberystwyth (45MHz) is contracted by the Met Office to provided operational data.

The wind profiler network is an operational component of the Upper-Air network providing Wind measurements for data assimilation, Real-time displays for forecasting/nowcasting. (Known local use; aviation forecasting at Isle of Man & Wattisham; defence forecasting at South Uist.) and provides a certain amount of redundancy/contingency for the upper air observing network during severe weather events.

These radars are relatively low powered systems and thus the returned signals are very weak. Therefore the receiver is required to be very sensitive to detect these signals, sometimes as low as -25db. Interference/pollution is generally a relatively strong signal compared to the atmospheric signal and thus dominates the return signal. If the interfering signal is identified as noise then it is ignored by the processing but can have the effect of causing missing winds. However if the signal is coherent the software might select it as a plausible atmospheric signal and thus produce a spurious wind. At present these systems produce a consensus wind measurement every 30 minutes and thus unless the interfering signal is continuous it is likely to have little impact on the measurements. However the future requirements for high resolution data (5 minutes) for Nowcasting and Instrument Integration will result in any interfering have a much larger impact on the observations.

These systems are vertically pointing, non-scanning, Doppler radars and thus surface based interference/pollution are unlikely to have an impact on the measurements unless located close to the instrument.
Recent threat has been at 1.2 GHz from the Galileo Satellite system. This threat has resulted in a 2 year study to determine the impact of these systems on the wind profiler technology. These studies have determined that interference is likely, especially for systems located at lower Latitudes where the satellites are located within the beams of the wind profiler radars. However the effects in the wind measurements are most likely to cause missing rather than spurious winds. This threat and the issues is well documented within the Radio Communication Agency (OFCOM)

3.3 Cloud Radars

The Met Office has performed extensive research and development work with a **78GHz** FMCW cloud radar in collaboration with the RAL. Planned work for 2006 is to upgrade this system to a **94GHz** operational 'proto-type', which is an assigned frequency for the cloud radar technology.

Currently there are no operational cloud radar systems operated by the Met Office in the UK but plans are to include them as a component of the integrated observing system for future profiles of temperature and humidity - providing a 'low cost' system capable of measuring multiple cloud layers

These radars are relatively low powered systems and thus the returned signals are very weak. Any interference or pollution is likely to have a high impact on the measurements. Where data is being used for Nowcasting (i.e. real-time displays) it is likely the intermitted interference can be ignored by the user or even removed by advanced signal processing. However it might be difficult to remove/ignore continuous, coherent signals which resemble a cloud layer. For future integration of remote sensing systems, the automated identification of the correct atmospheric signal will be fundamental to the measurement process. At high temporal resolution (< 1 min) all signals will be considered relevant and thus any interference is likely to have a significant impact on the measurements.

3.4 Microwave Radiometer

The Met Office has performed extensive research and development work with a Radiometrics Microwave Radiometer which has channels in the bands from 22-30GHz and 51-59GHz.
At present we use 12 channels in these bands, centred on the following frequencies, each with a bandwidth of 400MHz:

GHz	GHz	GHz
22.235	30.00	54.94
23.035	51.25	56.66
23.835	52.28	57.29
26.235	53.85	58.80

Planned work for 2006/07 is a competitive procurement of a ‘proto-type’ operational Microwave Radiometer. Frequency channels would be similar, but not identical, to those given above. In the future, we are likely to use more channels in the same bands (probably including one at 31.4GHz), and possibly using channels in other passive bands at 89GHz and around the 183GHz water vapour line.

There are no operational ground based Microwave Radiometer systems in the Met Office at present. However, development work is ongoing to satisfy requirements for ground based Temperature and Humidity profiles (from a single system) that will provide a component of the integrated observing system for future profiles of temperature and humidity. (Potential for Radiosonde replacement?)

As this instrument is ‘passive’ the impact on the measurements from RFI is likely to be very significant. Any pollution/interference is likely to dominate the atmospheric signals and thus masked the true signal. These systems run continuous & unattended and rely on advanced signal processing to identify the atmospheric returns. Testing to date has demonstrated that in the presence of strong interference it is almost impossible to expect the software to identify the true atmospheric signal, leading to significant spurious results – making the investment worthless.

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Table 1: Frequencies used for Meteorological Observing

No	Passive or Active	Frequency (GHz)	1. Frequency use						2. Threats			3. Impact				Missions/instruments utilising this band	Parameters	Locations (LEO - Low Earth Orbit satellite)
			Current mission	Current data use	Future mission	Future data use	Potential future interest	None identified	Current	Future	None identified	No alternative	Existing investment	Economic cost	Other costs			
1	P	1.37-1.4																
2	P	1.4-1.427			✓	✓			✓	✓		✓				MIRAS, Aquarius	Soil Moisture	LEO
3	P	2.64-2.655																
4	P	2.655-2.69																
5	P	2.69-2.7																
6	P	4.2-4.4																
7	P	4.95-4.99																
8	P	6.425-7.25	✓	✓	✓	✓			✓	✓		✓				AMSR, WindSat, CMIS	Surface Temperature, Soil Moisture	LEO
9	P	10.6-10.68	✓		✓	✓			✓	✓		✓				AMSR, TMI, WindSat, CMIS	Surface Temperature, Soil Moisture	LEO
10	P	10.68-10.7	✓		✓	✓			✓	✓		✓				AMSR, TMI, WindSat, CMIS	Surface Temperature, Soil Moisture, Precipitation (direct)	LEO
11	P	15.2-15.35																
12	P	15.35-15.4																
13	P	18.6-18.8	✓	✓	✓	✓						✓				AMSR,TMI, ATMS,CMIS, WindSat, CMIS	Precipitation (direct), Integrated Column Water Vapour, Cloud Liquid water, 10m Wind speed, Sea Ice	LEO
14	P	21.2-21.4																
15	P	22.21-22.5	✓	✓												SSM/I, SSMIS, WindSat, CMIS	Integrated Column Water Vapour, Cloud Liquid water, Precipitation (indirect via ice column), Temperature Profile (Low trop), Temperature Profile (mid & upper trop), Sea Ice	LEO
16	P	23.6-24	✓	✓	✓	✓			✓	✓		✓				AMSU,ATMS,CMIS	Integrated Column Water Vapour, Cloud Liquid water, Precipitation (indirect via ice column), Temperature Profile (Low trop), Temperature Profile (mid & upper trop)	LEO
17	P	31.3-31.5	✓	✓	✓	✓										AMSU,ATMS	Integrated Column Water Vapour, Cloud Liquid water, 10m Wind speed, Precipitation (indirect via ice column), Temperature Profile (Low trop), Temperature Profile (mid & upper trop)	LEO
18	P	31.5-31.8	✓	✓	✓	✓										AMSU,ATMS	Integrated Column Water Vapour, Cloud Liquid water, 10m Wind speed, Precipitation (indirect via ice column)	LEO

19	P	36-37	✓	✓												SSM/I,SSMIS,CMIS, WindSat	Integrated Column Water Vapour, Cloud Liquid water, Precipitation (indirect via ice column), Temperature Profile (Low trop), Temperature Profile (mid & upper trop)	LEO
20	P	50.2-50.4	✓	✓	✓	✓						✓				AMSU,ATMS,CMIS, SSMIS	Temperature Profile (Low trop)	LEO
21	P	52.6-54.25	✓	✓	✓	✓						✓		✓		AMSU,ATMS,CMIS, SSMIS, Microwave Profilers (ground-based)	Temperature Profile (Low trop)	LEO
22	P	54.25-59.3	✓	✓	✓	✓						✓		✓		AMSU,ATMS,CMIS, SSMIS, Microwave Profilers (ground-based)	Temperature Profile (mid & upper trop), Temperature Profile (stratosphere)	LEO
23	P	86-92	✓	✓	✓	✓						✓				AMSU,ATMS,CMIS, SSMIS	Integrated Column Water Vapour, Cloud Liquid water, 10m Wind speed, Precipitation (indirect via ice column), Temperature Profile (mid & upper trop), Humidity profile (trop)	LEO
24	P	100-102					✓									GOMAS	Temperature Profile (Low trop), Temperature Profile (mid & upper trop)	GEO
25	P	109.5-111.8					✓									GOMAS	Temperature Profile (Low trop), Temperature Profile (mid & upper trop)	GEO
26	P	114.25-115.25					✓									GOMAS	Temperature Profile (Low trop), Temperature Profile (mid & upper trop)	GEO
27	P	115.25-116					✓									GOMAS	Temperature Profile (Low trop), Temperature Profile (mid & upper trop)	GEO
28	P	116.0-122.25					✓									GOMAS	Temperature Profile (Low trop), Temperature Profile (mid & upper trop)	GEO
29	P	148.5-151.5	✓	✓								✓				AMSU,SSMIS	Precipitation (indirect via ice column), Humidity profile (trop)	LEO
30	P	155.5-158.5	✓	✓	✓	✓						✓				MHS	Precipitation (indirect via ice column), Humidity profile (trop)	LEO
31	P	164-167			✓	✓						✓				ATMS	Precipitation (indirect via ice column), Humidity profile (trop)	LEO
32	P	174.8-182	✓	✓	✓	✓						✓				AMSU,MHS,SSMIS,ATMS,CMIS	Humidity profile (trop)	LEO
33	P	182-185	✓	✓	✓	✓						✓				AMSU,MHS,SSMIS,ATMS,CMIS	Humidity profile (trop)	LEO
34	P	185-190	✓	✓	✓	✓						✓				AMSU,MHS,SSMIS,ATMS,CMIS	Humidity profile (trop)	LEO
35	P	190-191.8	✓	✓	✓	✓						✓				AMSU,MHS,SSMIS,ATMS,CMIS	Humidity profile (trop)	LEO
36	P	200-209					✓											
37	P	226-231.5					✓											
38	P	235-238																
39	P	250-252																
40	P	275-277																
41	P	294-306																

49	P	0.00001	✓	✓	✓	✓				✓		✓	✓	✓		Thunderstorm Location	Lightning flash - UK, NAE, Hemishpere	Lerwick, Camborne, Gibraltar + others
42	P	19.35	✓	✓												SSM/I	Integrated Column Water Vapour, Cloud Liquid water, Precipitation (indirect via ice column), Temperature Profile (Low trop), Temperature Profile (mid & upper trop)	LEO
46	P	23.635-24.035	✓	✓	✓	✓				✓				✓		Microwave Profilers	Integrated Column Water Vapour, Cloud Liquid water, Precipitation (indirect via ice column), Temperature Profile (Low trop), Temperature Profile (mid & upper trop)	Camborne
47	P	51.05-51.435	✓	✓	✓	✓								✓		Microwave Profilers	Temperature Profile (trop)	Camborne
48	P	52.08-52.48	✓	✓	✓	✓								✓		Microwave Profilers	Temperature Profile (trop)	Camborne
45	P	58.6-59.0	✓	✓	✓	✓	✓			✓		✓	✓	✓		Microwave Radiometer	Temperature Profile (trop)	Camborne
44	P	59.3-59.7	✓	✓	✓	✓										SSMIS	Global measurements of air temp profile, humidity profile, ocean surface winds, rain overland/ocean, ice concentration/age, ice/snow edge, water vapour/clouds over ocean, snow water content, land surface temperature.	LEO
43	P	85	✓	✓												SSM/I	Surface Sea-ice cover, Surface Snow cover, Humidity profile (column), Wind speed over sea surface, Integrated Column Water Vapour, Cloud Liquid wate, Precipitation (indirect via ice column), Temperature Profile (mid & upper trop), Humidity profile (trop)	LEO
A	A	0.432 - 0.438																
B	A	1.215 - 1.300	✓	✓	✓	✓				✓			✓	✓		Wind Profilers	Wind Profile - Horizontal & vertical components (low trop)	Dunkeswell, Wattisham
C	A	3.100 - 3.300																
D	A	5.250 - 5.570																
E	A	8.550 - 8.650																
F	A	9.500 - 9.800																
G	A	13.25 - 13.75																
H	A	17.2 - 17.3																
I	A	24.05 - 24.25																
J	A	35.5 - 36																
K	A	78 - 79																

L	A	94 - 94.1			✓	✓								✓		Cloud Radar	Cloud top height, Cloud base height	Camborne
M	A	133.5 - 134																
N	A	237.9 - 238																
O	A	0.046	✓	✓	✓	✓							✓	✓		Wind Profilers	Wind Profile - Horizontal & vertical components (Trop/Strat/Meso)	Aberystwyth
P	A	0.064	✓	✓	✓	✓							✓	✓		Wind Profilers	Wind Profile - Horizontal & vertical components (Lower & higher Trop)	South Uist
Q	A	0.915	✓	✓	✓	✓				✓			✓	✓		Wind Profilers	Wind Profile - Horizontal & vertical components (Lower Trop)	Camborne, Isle of Man
R	A	1.215	✓	✓	✓	✓				✓			✓	✓		Wind Profilers	Wind Profile - Horizontal & vertical components (Lower Trop)	Dunkeswell, Wattisham
S	A	2.8 – 3.0					✓				✓					Weather Radar	Precipitation (direct) Surface & Profile, Radial Wind profile	Various
T	A	5.6 – 5.65	✓	✓	✓	✓			✓	✓			✓	✓		Weather Radar	Precipitation (direct) Surface & Profile, Radial Wind profile	Various
U	A	0.025 - 0.050					✓									HF Radar	Wave height, Wave period, Swell height	

Glossary

AMSR	Advance Microwave Scanning Radiometer
AMSU	Advanced Microwave Sounding Unit
ATC	Air Traffic Control
ATMS	Advanced Temperature and Moisture Sounder
CAA	Civil Aviation Authority
CBRN	Chemical, Biological, Radiological and Nuclear
CFIT	Controlled flight into terrain
CMIS	Conical Scanning Microwave Imager/Sounder
CPG	Conference Preparatory Group
Defra	Department for the Environment, Food and Rural Affairs
DMSP	Defense Meteorological Space Programme (US)
EA	Environment Agency
EESS	Earth Exploration Satellite Service
EPS	Eumetsat Polar System
EUMETSAT	European organisation for the exploitation of meteorological satellites
GHz	GigaHertz
hPa	Hecta Pascal (pressure unit)
HSE	Health and Safety Executive
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
IOS	Integrated Observing System
IPCC	Intergovernmental Panel on Climate Change
METOP	METeorological OPerational satellite (EUMETSAT)
MHS	Microwave Humidity Sounder
MOD	Ministry of Defence
NOAA	National Oceanographic and Atmospheric Administration (US)
NPOESS	National Polar-orbiting Operational Environmental Satellite System (US)
NPP	NPOESS Preparatory Programme
NWP	Numerical Weather Prediction
OFCOM	Office of Communications
PMSL	Mean sea level pressure
RFI	Radio frequency interference
RMSE	Root mean squared error
RNLI	Royal National Lifeboat Institute
SMOS	Soil Moisture and Ocean Salinity Mission
SSM/I	Special Sensor Microwave Imager
TDA	Tactical Decision Aid
TIROS	Television Infrared Observation Satellite
TOVS	TIROS Operational Vertical Sounder
UNFCC	United Nations Framework Convention on Climate Change
UK	United Kingdom
UKOOA	United Kingdom Offshore Operators Association
US	United States of America
WAFC	World Area Forecast Centre
WMO	World Meteorological Organisation (United Nations Agency)
WRC	World Radio