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Radiocommunication Sector of ITU

Report ITU-R RS.2165

(09/2009)

# Identification of degradation due to interference and characterization of possible interference mitigation techniques for passive sensors operating in the Earth exploration-satellite service (passive)

RS Series

Remote sensing systems

International
Telecommunication
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***Note****: This ITU-R Report was approved in English by the Study Group under the procedure detailed in Resolution ITU-R 1.*

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# REPORT ITU-R RS.2165

# Identification of degradation due to interference and characterization of possible interference mitigation techniques for passive sensors operating in the Earth exploration-satellite service (passive)

(2010)

**Scope**

The report is focused on radio-frequency interference (RFI) to radiometric measurements made by Earth exploration-satellites. The natural noise floor in the bands under consideration is the data being measured. The text first discusses how the measurements are used in meteorological and climatic products. Then, it addresses the detectability of RFI and its potential impact on products. Finally, it discusses some techniques that might be used to mitigate (reduce, not eliminate) the impact from RFI. No mitigation techniques have been identified which can be applied to the microwave sensors and their products to allow RFI without degrading their performance reliability or availability.

NOTE 1 – References to provisions of the Radio Regulations (RR) are based on the RR Edition of 2008.

## TABLE OF CONTENTS

*Page*

*Page*

# 1 Introduction

## 1.1 Passive sensing missions

The "passive sensing mission" is described as the "passive" detection and analysis of naturally occurring, ambient microwave energy (the natural noise floor from the antenna) for the purpose of determining present and future environmental conditions. Environmental products are generated from the output of these predictions. The most critical products are forecasts of weather and climate. These forecasts affect human endeavours.

## 1.2 Content and organization of report

Section 2 describes the meteorological and climatology products developed from the radiometric measurements and their application in numerical weather prediction (NWP).

Section 3 discusses detected radio-frequency interference (RFI) in the products made from radiometric measurements and the impact of RFI on weather forecasting capability.

Section 4 discusses how RFI can be prevented or its impact reduced

Annex A of this paper addresses the science of microwave sensing from black body radiation to the receiver measurement. This material will enhance the understanding of the sensor products and their vulnerability to RFI. Annex B presents a table that relates meteorological data products to the sensor measurements used to produce them. Annex C is a glossary of terms used in the report.

# 2 Overview of passive sensing products

Passive sensors measure the electromagnetic energy emitted and scattered by the Earth and its atmosphere. This energy measured by the sensor varies with the equivalent blackbody temperature of the surface and energy transfers in the intervening atmospheric path. This energy appears as the natural noise floor in the band under consideration.

The word "product" in this paper will refer to a range of products created from microwave measurements. These include data records of the measurements, images derived from the records, plots, forecasts, warnings, etc. However strictly speaking the product is the data record created from the measurements.

The microwave radiometric measurements along with other measurements (e.g. infrared) are converted to data file products such as rain rate, sea surface temperature or soil moisture. Products can be categorized by the media they describe such as the atmosphere, ocean or land. Some of the products are publicly provided while others remain in the government or private domain. Some well known weather products include: hurricane formation and path displays, atmospheric temperature profiles, and water precipitation maps.

## 2.1 Passive sensing products

Passive sensor measurements are converted into brightness temperatures which are mapped in space and time. These brightness temperatures are stored in digital records. In the case of polar orbiting spacecraft, these records typically represent either an entire orbit or portions thereof (Level 1 product). The science of brightness temperatures and its relationship to Earth and atmospheric parameters is explained in Annex A.

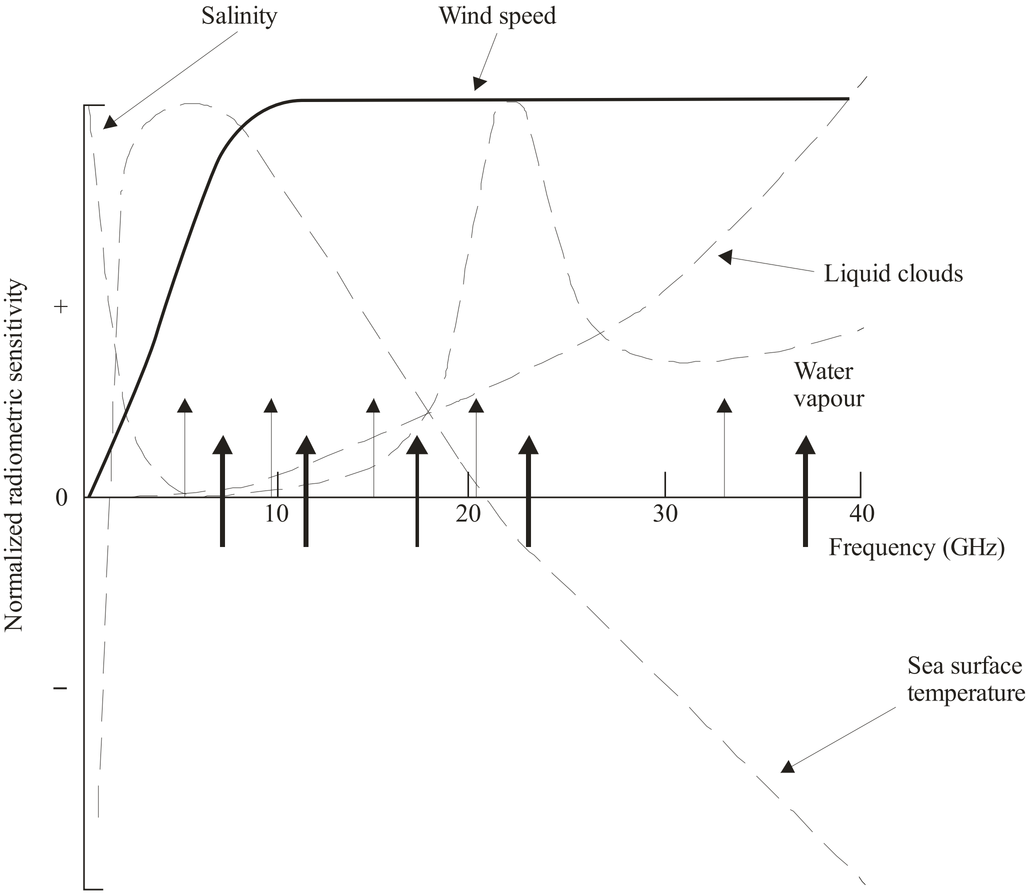
Mathematical algorithms are used with the combination of the brightness temperatures to provide geographic information on meteorological parameters (Level 2 products). In some level 2 products ancillary information is used to generate the products. Such ancillary information includes terrain type, temperature and humidity information from other sensors.

Atmospheric temperature profiles are created from measurements using instruments operating in the 50-60 GHz frequency range. Knowing the barometric pressure and the percentage of oxygen in the atmosphere, the energy measurement of the instrument can then determine the temperature of the air. Similarly at the water vapour lines near 23 and 183 GHz, the temperature is related to other measurements, as well as the barometric pressure, so the water content in the atmosphere can be determined from the measured microwave energy.

Figure 1 illustrates several oceanographic and meteorological parameters and the variance of the brightness temperature for each physical parameter. A particular physical parameter is determined by applying weighting functions or variation schemes to measurements from the several channels to remove the influence of other physical parameters.

FIGURE 1

**Sensitivity of physical parameters in oceanography and meteorology with respect to frequency and the optimum channels as arrow symbols***



Report RS.2165-01

* http://www.profc.udes.cl/~gabriel/tutoriales/index.htm.

Each physical parameter such as salinity, water vapour, wind speed, etc. has a frequency dependent influence on the brightness temperature measurements. Figure 1 is a plot of the relative change in the brightness temperature caused by the physical parameter. The arrows on the frequency axis represent channels where radiometric measurements are made. The measurements are used to characterize the curve for each physical parameter.

The ordinate labelled Normalized Radiometric Sensitivity is $\Delta T_b/\Delta Pi$, where $T_b$ is Brightness temperature and Pi is one of the geophysical parameters in the graph (for example, wind speed or sea surface temperature). Thus, the quantity represents how much brightness changes as one of the geophysical parameter changes. For example, if brightness temperature changes 0.2 K when sea surface temperature changes by 2 K, then ratio will be 0.1. These ratios were plotted as a function of frequency to see how much this ratio is sensitive with the frequencies. The graph provides a visual representation through scaling of the relative values and thus no specific numerical scale is provided.

## 2.2 Product hierarchy and descriptions

The following description applies to a particular meteorological satellite system, (e.g. National polar-orbiting operational environmental satellite system (NPOESS)), which is representative of a typical meteorological system.

Two types of descriptors are in common use to describe products, one is hierarchical the other is more descriptive. Level 0, Level 1A, Level 1B and Level 2 are elements of the hierarchy used to indicate product types from raw (Level 0) to refined (Level 2). A more descriptive lexicon uses the terms raw data, raw data records (RDR), sensor data records (SDR), temperature data records (TDR) and environmental data records (EDR).

***Level 0: Raw data***

Spacecraft carry a suite of sensors designed to detect environmental data either reflected or emitted from the earth, the atmosphere, and space. The satellites store these data and transmit the data to earth stations. These data, before being processed, are called raw data (Level 0).

***Level 1: Satellite data records***

Satellite data records, generally considered as Level 1 data products, are the records of brightness temperatures measured in a few select frequency bands.

These products can be subdivided into three data types:

RDR (Level 1A) – Unmodified sensor's output received from the spacecraft and separated into a record specifically related to the brightness temperature measured on a specific band, where brightness temperature is defined as a measure of the intensity of radiation thermally emitted by an object, given in units of temperature.

TDR (Level 1B) – Antenna brightness temperature calibrated, time-tagged and earth-located.

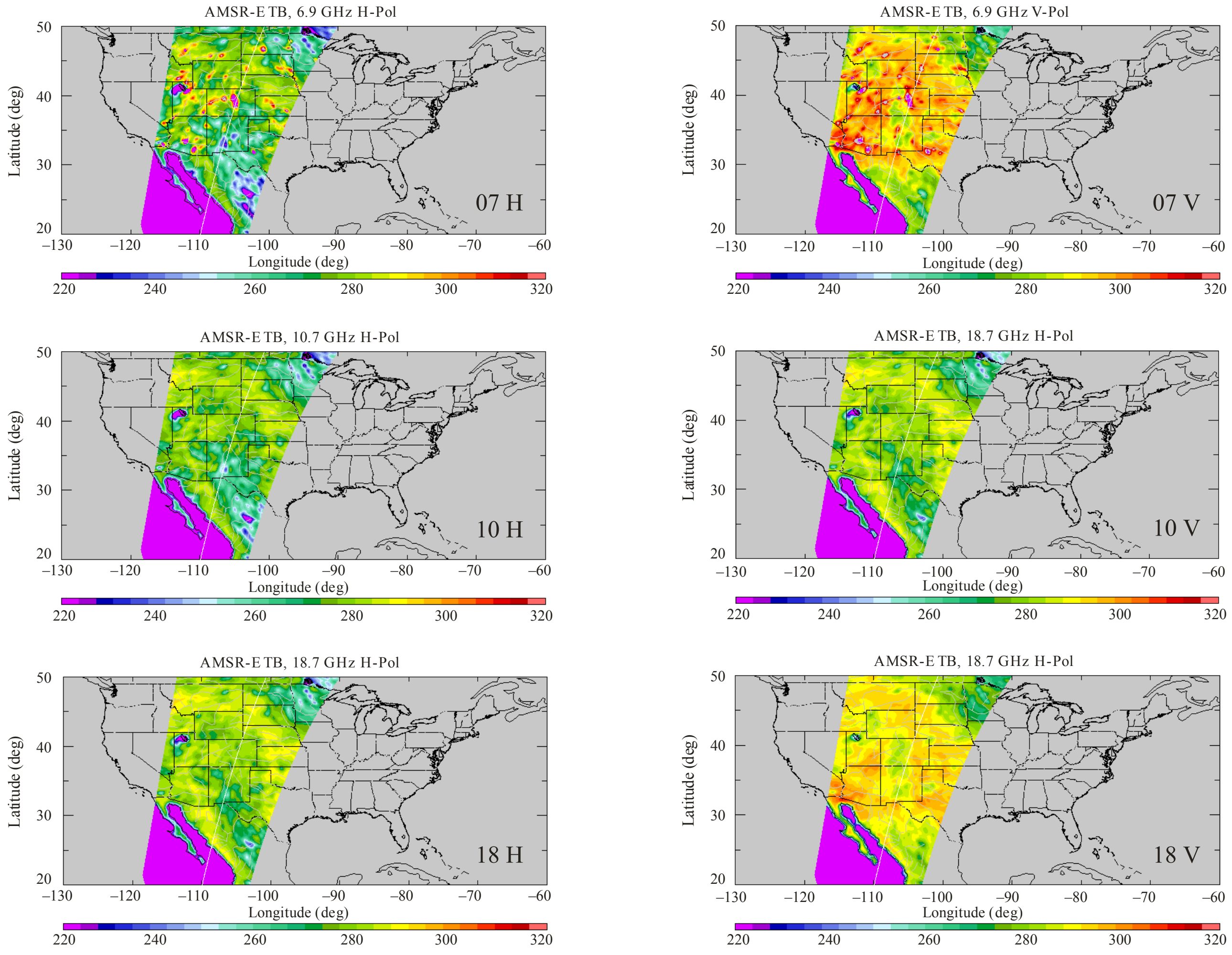
SDR (Level 1C) – Antenna brightness temperatures with antenna pattern correction, calibrated, time-tagged, earth-located.

Antenna pattern corrections are needed because the antenna receives radiation from the entire 4π steradians at varying directional gain values. The measurements must be adjusted to represent only the resolution cell of the sensor.

Figure 2 shows colorized images developed from satellite data records for three passive sensor bands. The left images are obtained with horizontal polarization and the right images with vertical polarization. The image bands from top to bottom are centred at 6.9 GHz, 10.7 GHz and 18.7 GHz.

FIGURE 2

**Images created from satellite data records from three frequency bands and two polarizations from the AMSR-E sensor on the Aqua satellite (Note in the 6.9 GHz images in the two top panels the presence of red areas, which are RFI signals)**



Report RS.2165-02

### *Level 2: Environmental data records*

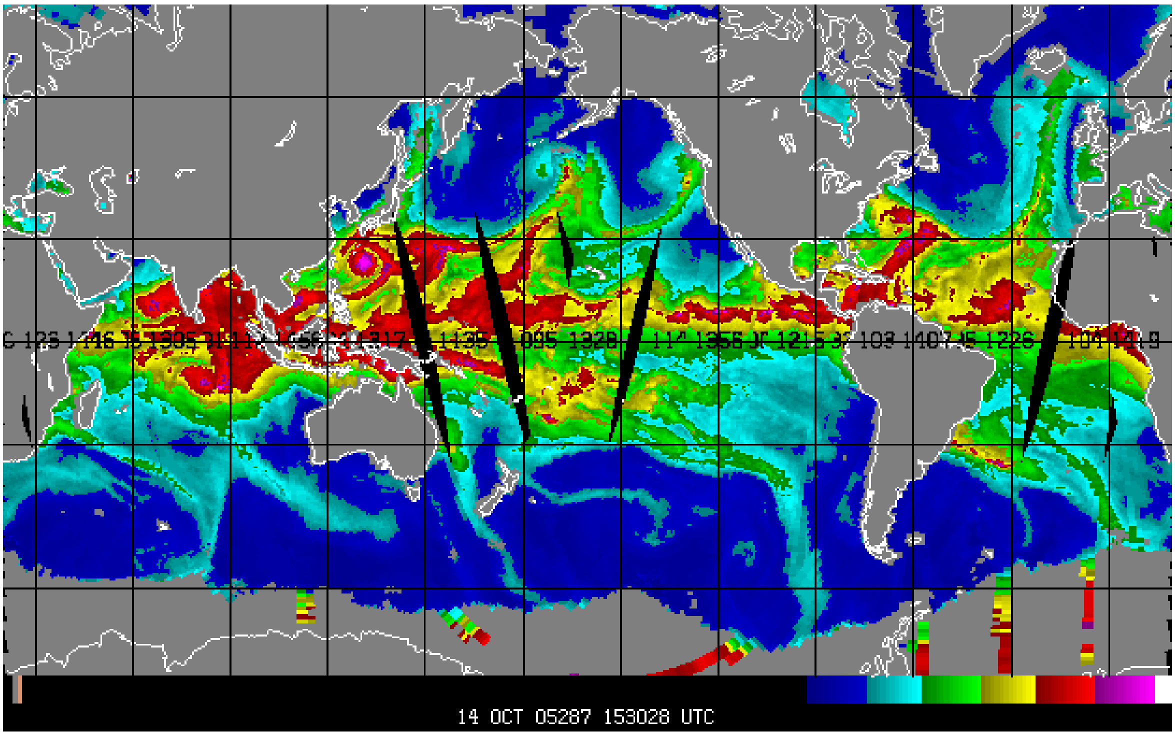
Level 2 products are records of environmental or climatic parameters derived from the Level 1 brightness temperature records. Band selection for the radiometric measurements is driven by the need to interpret the measurements to retrieve the meteorological, oceanographic and land parameters. These products contain meteorological, oceanographic, and land parameters. In some cases the products are generated via a simple equation with the variables consisting of brightness temperatures. In other cases, they result from fairly sophisticated scientific understanding of radiative transfer. Figure 3 is a visualization of a meteorological product made from satellite microwave data. This shows the depth of water/unit area which would result from condensing all the water vapour in the atmosphere in a unit column.

### *Weather, climate, environmental forecasting and archiving products*

These products are made from the environmental data records with the use of computer models or visual inspection of images. The products appear as graphical images, isopleths, research reports, text reports, tables, radio and TV reports, or pictorial images.

FIGURE 3

**Total precipitable water (mm)**
**Composite image created from several satellite data records**



Report RS.2165-03

Applications which are derived from passive sensing measurements include:

1. *Hurricane monitoring
2. Rice production in India
3. Desert expansion in China
4. Sea ice concentration
5. Hydrological products (rainfall, water vapour, snow cover)
6. Tracking ocean circulation patterns
7. *Extreme event forecasting
8. Study of Earth's water cycle
9. Global warming models
10. Crop yield forecasting
11. Identification of potential famine areas
12. Drought analysis
13. Irrigation planning
14. Flood protection
15. Forest fire protection
16. Monitoring of areas prone to erosion and desertification
17. Initialization of NWP.

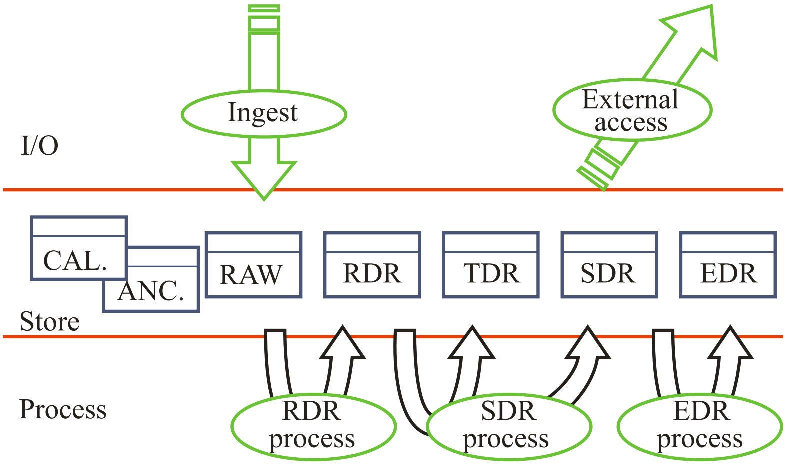
An asterisk (*) is added to products involved in short-term disaster event forecasting.

## 2.3 Product generation process

The data record processing is illustrated in Fig. 4 raw data is received from the satellite then extracted from the transmitted data stream, which contains formatting protocol and possible other interleaved data records "ingested", before being stored as RDRs or Level 1A data. In addition, calibration (CAL) data records and ancillary data (ANC) records are stored for use in subsequent processing. These records can come from spacecraft or local sources.

FIGURE 4

**Data record processing architecture produces all data products**



Report RS.2165-04

The processing architecture produces RDR, SDR, TDR and EDR (Level 2) products. The products are commonly delivered at three progressive levels of processing: RDR process, SDR process, and environmental data record process. TDR are produced as a variant of SDRs in the SDR process.

The "ingest" processor transforms the satellite raw data (Level 0) into a more processing-friendly RDR data set as follows (RDR process):

*Step 1:* Accepts and synchronizes frames of Level 0 satellite data.

*Step 2:* Performs first-level quality control of data stream, filling data gaps as necessary.

*Step 3:* Extracts instrument and spacecraft data from Level 0 data and reformats it into the RDR file format.

*Step 4:* These Level 1A data sets are made available for Level 1B generation under a unique data set name.

Raw data are converted to RDRs by removing the communication protocols, time ordering the information, logging and segmenting the information for further processing. RDRs are made into SDRs by removing the sensor signature and applying calibration data. Applying calibration data recreates the flux distribution at the sensor aperture. The SDR process also creates the TDRs in the same way but without the adjustment for the antenna aperture. This process uses the stored calibration and ancillary data. The EDR process will employ SDRs to estimate the casual bio-geophysical parameters and the EDR records.

The data records created in the SDR and EDR processes are available for external access to produce Level 3 products. Level 3 products are developed from the archived records and from information obtained from other sources e.g. visual images, infrared (IR) images, radiosondes, radar images, etc. These are developed with the aid of computer models and from observation of the images created from the EDRs.

### 2.4 Environmental products and associated sensing bands

Annex B presents a list of various environmental products (Level 2) in three tables, one each for the atmosphere, ocean and, land, respectively. The annex also provides a mapping of products to their associated frequency bands and provides comments on the importance/role of the band.

Some of the consumer products that are derived from the environmental products are weather and climate forecasts, land use records, and sea state measurements.

Climate forecasts and land use records are developed from examining archived data. Past records of measurements when examined in sequence reveal change patterns which in turn reveal such things as the El Niño phenomena, deforestation, ice pack size, desert expansions, snow shrinkage on mountains, changes in trace gasses in the atmosphere, and many other related effects.

Records of specific measurements over the oceans especially in the 1.4 GHz and 6.9 GHz range reveal patterns of sea state and salinity. These patterns show ocean current flows and climate impacts.

### 2.5 Uses of environmental products and NWP model with data assimilation scheme

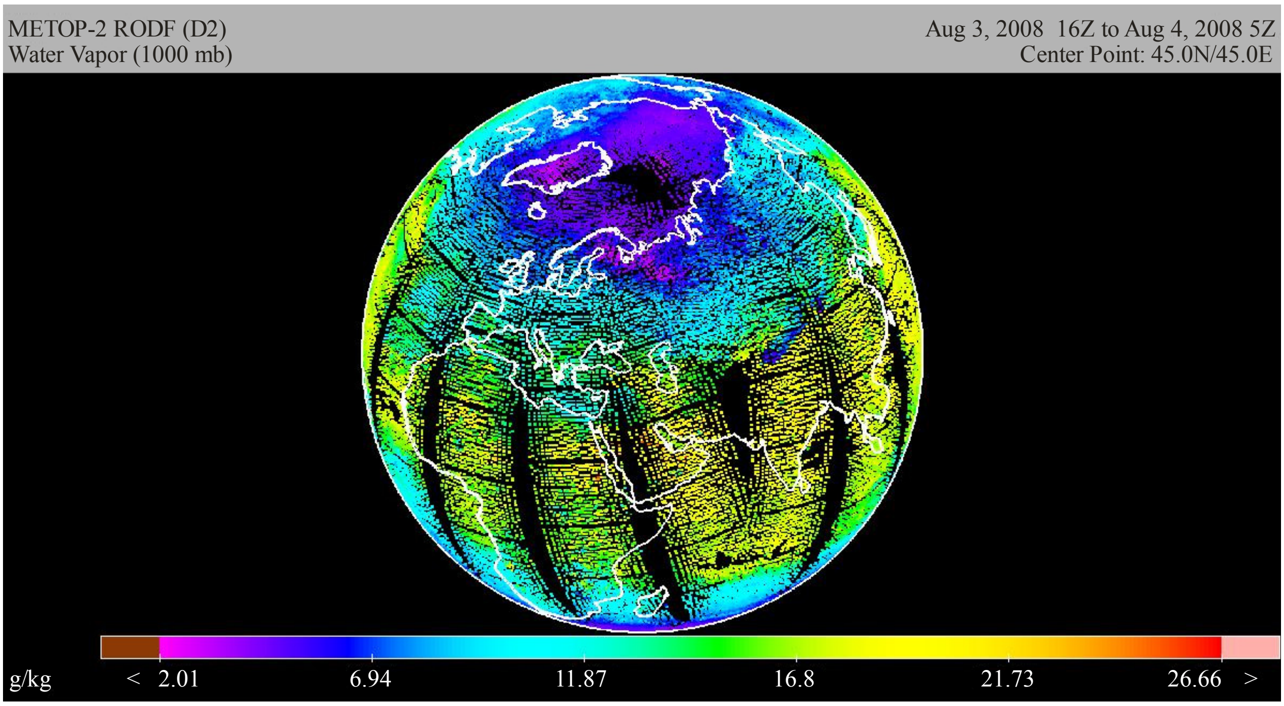
Data record products have two consumers: people and computers. People use visualization software to look at a product during an environmental evaluation. Computers use data records to make other products and also feed environmental models. An example of a product visualization used by people is shown in Fig. 5. This hemispheric depiction of water vapour at approximately the surface of the Earth shows extremely dry regions (blue and indigo) near the pole and the moist counterpart near the equator (yellows and greens). Another feature of this depiction is the banded, orbital swaths showing data gaps in between suborbital scan regions.

Computer use is exemplified by the assimilation of microwave data into numerical weather models assimilation is a key component of the weather forecast process shown in Fig. 6.

NWP is an initial value problem. The atmospheric state is specified at an analysis time, and the equations of motion are integrated out to sometime in the future, currently about sixteen days. The analysis is performed on a regular grid by combining data from all sources. This includes radiosondes, aircraft reports, surface reports, radar, and satellite data. Satellite data are by far the most used, and microwave sounding data is the majority of the satellite data used. The satellite data are assimilated directly into the analysis model using a three dimensional variational assimilation (3DVAR). The 3DVAR uses a short-term (usually six hours) forecast as a background. This is used to establish the state vector, which is composed of the temperature, moisture and ozone profiles, surface temperature and wind speed, and any other variables which are used in a radiative transfer model to simulate what the satellite instrument observes. The difference between the observed and simulated radiances is known in the meteorological community as the “innovation”.

FIGURE 5

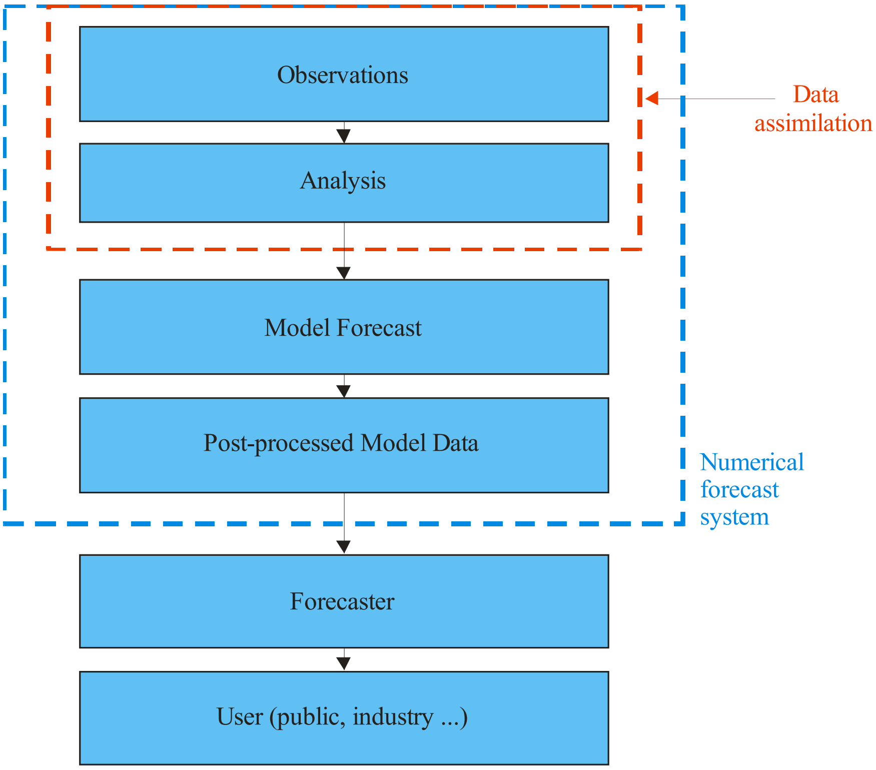
**Visualization of Level 2 product showing water vapour**



Report RS.2165-05

FIGURE 6

**The environmental forecast process**



Report RS.2165-06

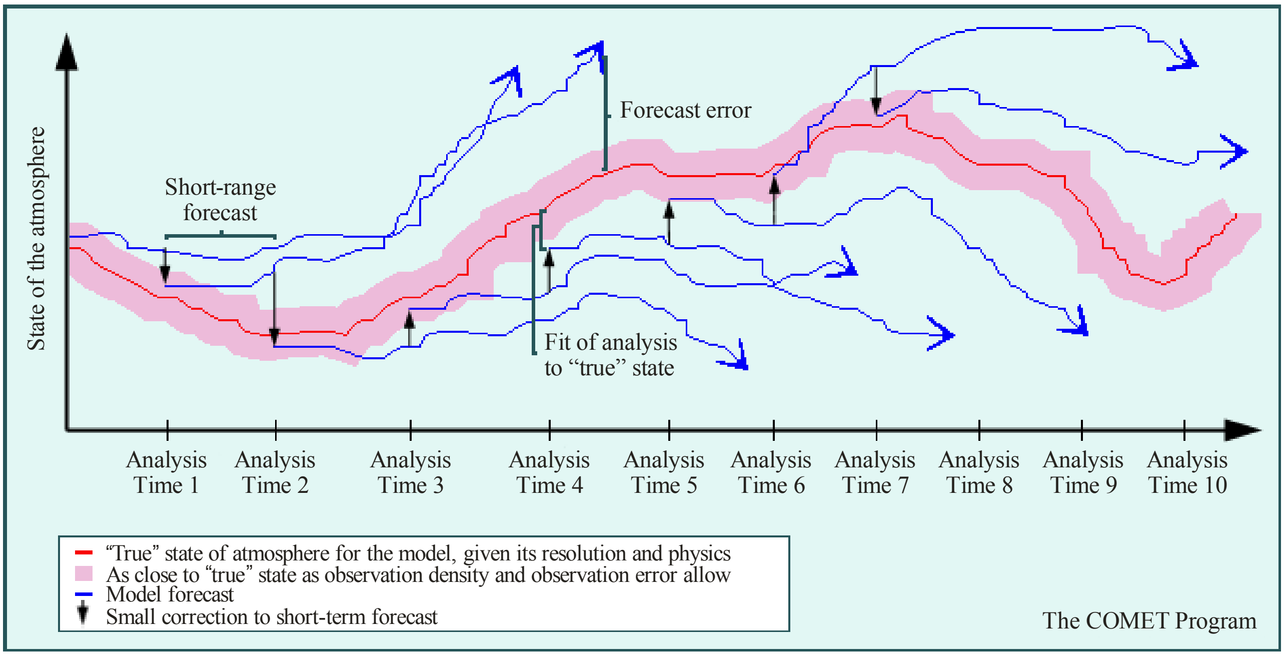
Each assimilation cycle takes six hours of data around the analysis time, and there are four cycles per day, at 00, 06, 12 and 18 UTC. Data are currently being assimilated from NOAA 15, 16, 17 and 18, METOP-A, EOS Aqua, DMSP F13, F14, F15 and F16, GOES 11 and 12, TRMM, GRACE-A, the Cosmic constellation, Envisat, and Meteosat 5 and 8.

Microwave remote sensing is especially important to NWP. Microwave radiation penetrates all but precipitating clouds. Thus microwave radiometers provide information in meteorologically active regions that infrared sounders cannot.

Figure 7 illustrates the process of data assimilation with time. The horizontal axis represents time and is scaled in data analysis periods. The red line bordered in pink is the actual state of the atmosphere. The blue lines are the estimated state of the atmosphere derived from the numerical prediction model. At each time period the atmospheric state is forecast several analysis periods into the future. At the end of each analysis period a new measured state of the atmosphere is assimilated into the model and new forecasts are developed.

FIGURE 7

**NWP tracking of the state of the atmosphere**



Report RS.2165-07

Rather than analysing data directly, the analysis uses observations to make a series of small corrections to a forecast that is generally of good quality. Large discrepancies between observations and the short-term forecast can be used to determine if the data are suspect or erroneous since the forecast is assumed to be good (this is possible even if observations are not rejected outright).

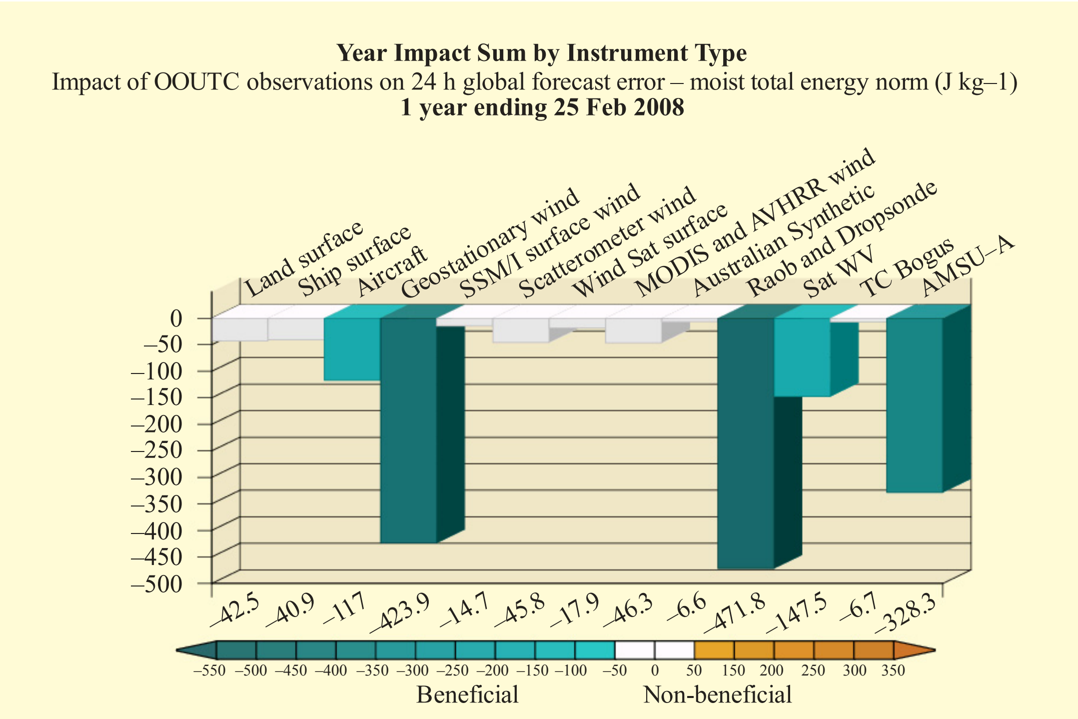
For example, data from a set of the instruments known as the advanced TIROS operational vertical sounders (ATOVS) is composed of information from the passive remote sensors known as advanced microwave sounding units A and B (AMSU-A and AMSU-B) and complemented by the high resolution infrared sounder (HIRS) instruments. ATOVS microwave and infrared information is used to derive vertical profiles of temperature and humidity in the atmosphere. These instruments are carried aboard polar orbiting environmental satellites. The AMSU-B sensor was replaced by the microwave humidity sounder (MHS) in later variants. Following some adjustments radiation measurements from the ATOVS instruments are assimilated directly into numerical atmospheric models using advanced techniques developed for operational use over the last decade. The vertical temperature and humidity profile information is vital to the performance of all numerical forecasting model systems[1].

Figure 8 also shows that the accuracy of the NWP models is heavily dependent upon the inclusion of certain microwave data. For example, information from the advanced microwave sounding unit-A (AMSU-A) system dramatically improves weather forecasts. As shown in Fig. 8 assessments indicate that AMSU-A data was the third most important contributor to reduction in errors in one weather model. These assessments were carried out by one administration.

In turn, national and regional meteorological centres are incorporating microwave data directly in their models. The Italian Meteorological Service, UK Met Office, US National Centre for Environmental Prediction, UK Met Office and the multinational European Centre for Medium Range Weather Forecasting all process AMSU-A data.

FIGURE 8

**Observation impact on short-range forecast error***



Report RS.2165-08

* http://www.nrlmry.navy.mil/obsens/ob_sensar/obsens_main_od.html.

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[1] http://eumetsat.int/Main/What_We_Do/Satellites/EARS_System.

### 2.6 Summary of passive sensing products

Radiometric measurements are transformed into data records and eventually used to develop pictorial images, isometric plots, archived data records, inputs elements of state vectors used by forecasting programs and ultimately, to develop the forecasts themselves. The images are examined to produce local forecasts for consumers, study changes in our environment, document land use, detect environmental changes such as El Niño, etc. Information gained through the examination of these images assists decision makers, warns populations of potential disasters, and warns aircraft of icing hazards.

Over time, the reliance of analysis models has become increasingly more dependent upon these radiometric measurements. The reliability and accuracy of these products has also become more dependent on the radiometric measurements. Therefore, the vulnerability of these products to measurement errors has increased over time. Many factors could corrupt these measurements including RFI so it becomes increasingly important to protect the measurements from RFI.

## 3 Product quality and RFI

Numerous studies have revealed that spaceborne microwave radiometers are subject to detrimental RFI. Since RFI can reduce meteorological and climatological quality in the products, it would be desirable to be able to determine if the input data has been corrupted. Detection of data errors then allows the resulting reduced reliability in forecasts and products to be noted and identified. If errors are actually confirmed, it also provides an opportunity to eliminate the corrupted data from the data set and perhaps allow an estimate of the correct value to be substituted.

This section discusses the detectability of RFI within the products and the impact that RFI would have on the products. Also discussed are some techniques for identifying RFI.

### 3.1 Impact on quality

In its simplest form, a radiometer is a very sensitive microwave receiver, which estimates the brightness temperature of an object by measuring the power level of the received thermal noise. Because the goal of radiometry is to estimate accurately the mean power of the incoming thermal noise, long integration periods (in the order of milliseconds or longer) are desirable in order to reduce uncertainty. Only the mean power estimate after this integration period is of interest, so a traditional radiometer will not record information within an integration period. In addition, the use of large bandwidth channels is desired in order to further reduce uncertainty in the estimate of mean power.

The addition of RFI to the observed channel violates the noise-only assumption and can cause serious problems for a traditional radiometer which is unable to separate corrupted and uncorrupted portions of the observation. Because RFI will always increase the mean power when compared to that of the geophysical background, post-processing of the data can be applied to eliminate abnormally high observations. However, low level RFI can be difficult to separate from geophysical information, making parameter retrievals problematic.

The impact of RFI on meteorological products is not well known because RFI is generally not anticipated unless there is *a priori* reason to suspect it may be present. Such an *a priori* reason would be active radiocommunication services co-allocated with passive services in the passive sensing frequency band or the use by a passive sensor of an unallocated frequency band that is used by active radiocommunication services. Additionally many other known data anomalies that are not RFI could impact the NWP models and are detected in quality control algorithms when model predictions are not accurate. RFI, if present, might be treated erroneously as just another anomaly in the input data or model without specifically being suspected.

### 3.1.1 General factors affecting product quality

Degradation refers to a reduction in the quality of the environmental products. Degradation of product quality as well as communication errors can occur at two locations. The first location is in space where instrument measurement errors can be introduced by the measurement environment, improper calibration, or RFI. The second location is on the ground during ground operations, including the contributions of imperfect algorithms used to convert lower level products to higher level products, and by erroneous geo-location (platform ephemeris) calculated by the navigation program. The degradation due to the second error type can be estimated. The degradation due to first error type, particularly if caused by RFI, may be managed more effectively if it can be minimized and somewhat predicted. However, low level RFI cannot be easily detected because it cannot be distinguished from natural radiation levels. This situation is potentially the most serious problem since degraded or incorrect measurements can be mistakenly accepted as valid measurements.

### 3.1.2 Impact on products

The potential presence of RFI can cause an incomplete data record if the erroneous data can be detected and eliminated. The lost data in the records will reduce the data availability. Each remote sensing function has a data availability requirement on the order of 0.01% to 0.1% and lost data in excess of this percentage could have a severe impact on the data product. The reliability of the forecasts and conclusions derived from the data are degraded. The severity of the impact of this data loss will depend upon the importance of the lost data. Weather systems experiencing rapid changes in intensity may be obscured if their measurable parameters are lost and thus valuable storm data may be hidden.

The quality and availability of the mission data products are generally reduced by RFI in two ways:

– If the "excess" RFI can be detected or identified the data availability will be reduced by the "relative" amount of excess RFI and erroneous data will be deleted or flagged. At least, in that case, the reduced reliability of the products is known if errors are able to be detected.

– If the "excess" RFI cannot be detected, the data product will be "unknowingly" distorted, thereby reducing the quality and accuracy of the data product by some unknown amount.

This unknown misrepresentation of environmental conditions is potentially a greater threat to the forecasting mission than the elimination of erroneous data.

For example, in weather forecasting applications, underestimation of soil moisture results in lowered forecast cloud production and reduced accounting for latent heat transferred to the atmosphere from surface heating. In addition to the detrimental effects RFI will have on short term forecasting and flood prediction, it also affects the quality of long term climatological measurements. Even low levels of RFI that might be large enough to introduce significant errors in short term applications such as weather forecasting are of great concern.

### 3.1.3 Propagation of errors through product levels

Product levels as described in § 2.3 above are developed from radiometric measurements by applying equations that evaluate a land or atmospheric product such as land surface temperature or rain rate from some weighted mathematical combination of radiometric measurements.

It is important to understand the impact of RFI on the quality and reliability of products. Determination of the amount of lost or degraded radiometric measurements in the data set can be used to gauge the quality of the product. To do this, the measurements affected by RFI must be identified.

Generally to relate the effects of RFI propagation to upper level products from radiometric measurements:

Let $F = f(TB_1, TB_2, \ldots\ldots\ldots, TB_n)$

Where F is upper level product (for example, EDR or Level 2 or Level 3 product), which can be expressed by an algorithm $f$, and $TB_1$, $TB_2$, ... $TB_n$ are the radiometric measurements at frequency bands $X_1$, $X_2$, …..... $X_n$, respectively.

Then the error caused by RFI in the product $F$ can be expressed as follows:

$$\Delta F = \left|\frac{\partial f}{\partial TB_1}\right|\Delta TB_1 + \left|\frac{\partial f}{\partial TB_2}\right|\Delta TB_2 + \ldots\ldots\ldots + \left|\frac{\partial f}{\partial TB_n}\right|\Delta TB_n \qquad (1)$$

Where $\left|\frac{\partial f}{\partial TB_1}\right|$, $\left|\frac{\partial f}{\partial TB_2}\right|$, …. $\left|\frac{\partial f}{\partial TB_n}\right|$ are partial derivatives with respect to radiances, $TB_1$, $TB_2$ ……. $TB_n$.

$\Delta TB_1$, $\Delta TB_2$, ………, $\Delta TB_n$ are errors or uncertainties which are introduced by RFI in the specific bands.

Level 2 products are generally derived from Level 1 products through an algorithm which includes a linear equation. For example, the land surface temperature and emissivity are derived from three brightness temperature measurements with the equations (2) and (3):

Land surface temperature

$$T_s = 37.700 + 0.38057 * TB_1 - 0.39747 * TB_2 + 0.94279 * TB_3 \qquad (2)$$

Land surface emissivity

$$\varepsilon_1 = 7.344*10^{-1} + 7.65167*10^{-4} * TB_1 - 4.90626*10^{-3} * TB_2 - 4.96745*10^{-3} * TB_3 \qquad (3)$$

where:

$T_s$: land surface temperature

$\varepsilon_1$: one of three land surface emissivity values derived from these algorithms

$TB_1$: radiometric measurement at 23.8 GHz

$TB_2$: radiometric measurement at 31.4 GHz

$TB_3$: radiometric measurement at 50.3 GHz.

The general format is:

$$T_s = b_0 + b_1 * TB_1 - b_2 * TB_2 + b_3 * TB_3 \qquad (4)$$

If an error occurs in one particular parameter (e.g., $TB_3$), then from equation (1)

$$\Delta T_s = + b_3 * \Delta TB_3 \qquad (5)$$

Where $b_n$, $n$ = 1, 2, and 3 are constants used in the Microwave Integrated Retrieval System (MIRS) products.

These equations show that the error in the Level 2 product is dependent upon the relative importance of the radiometric measurement in the algorithm or the magnitude of the particular coefficient (e.g., $b_n$).

### 3.1.4 RFI detection in the NWP model

Through a series of checks and tests, data are quality controlled to ensure the viability of the information input into the forecast model. This helps to ensure that inaccurate data are adjusted or removed before going into the analysis. As indicated above the model uses innovations to check the quality of the input data as well as the process itself. The process checks for errors that may be caused by the measuring instrument, representativeness errors which are sensitive to the instrument resolution, and observation errors. Many of these errors are anticipated and the system is able to adjust. However RFI is not an anticipated cause of these errors, therefore data errors may not be identified as RFI.

### 3.1.5 Impact of RFI on forecasting

For operational weather forecasting (i.e., a range of 1-14 days) the forecasting process is heavily reliant on NWP with increasing automation involved in producing forecasts and with less input from human weather forecasters. It is to be noted that the NWP performance has improved very significantly in the last ten years through the use of faster computers, the development of more sophisticated data assimilation methods, and the effective exploitation of new satellite data and higher resolution NWP models. Therefore, the introduction of RFI, even low levels, implies the risk of regressing to a performance level corresponding to a situation that took place two years ago.

The degradation or loss of crucial observation data therefore has a direct impact on the NWP analysis and subsequent weather forecasts. A recent NWP impact study yielded some disturbing results.

In a separate study of data denial experiments, each section of the global observing system is removed to assess the impact of loss data in terms of years of improvement loss in recent years. 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).

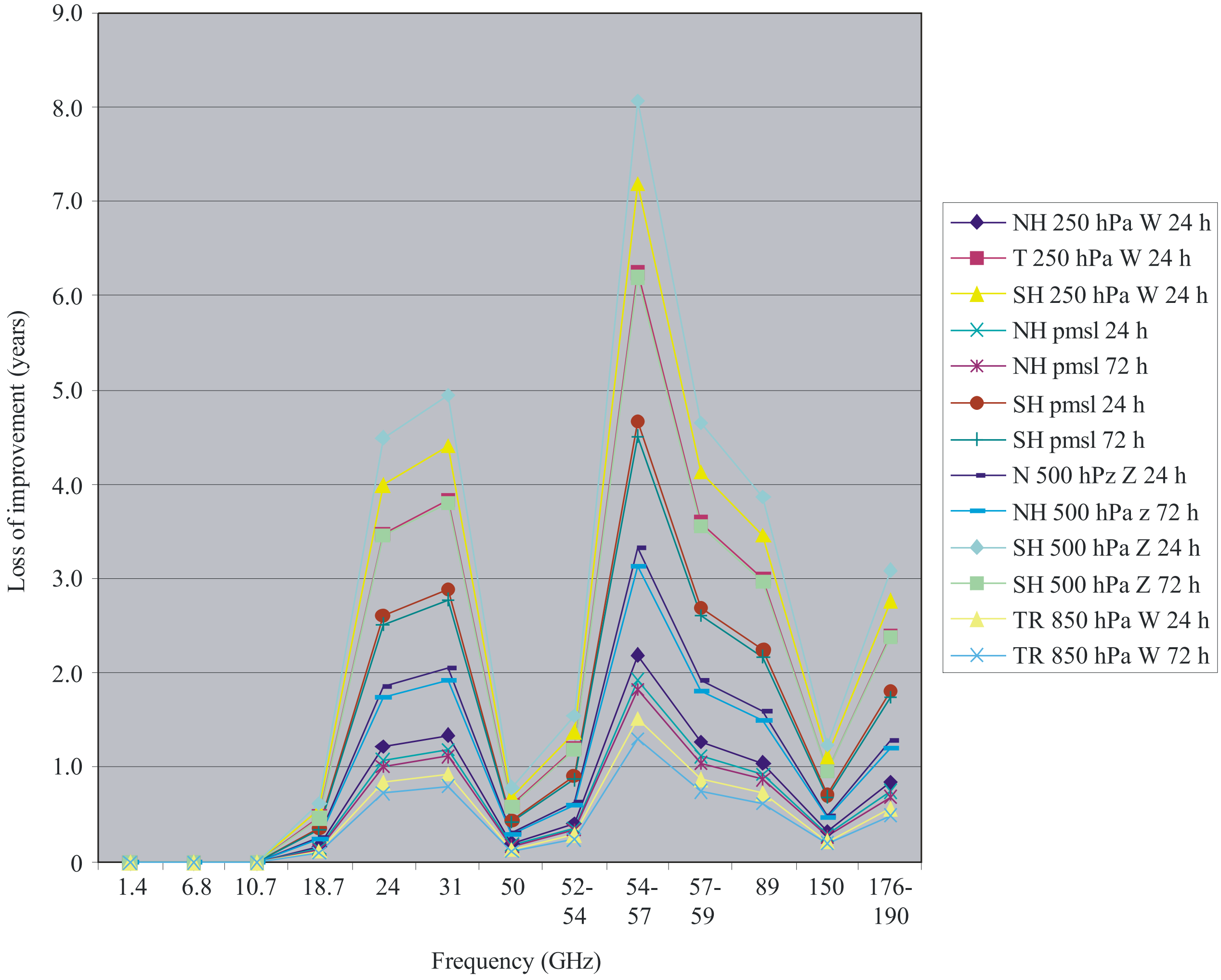
In Fig. 9 an estimate of the loss of performance of the global NWP system is given if a particular frequency is lost due to RFI. For example, the loss of the key part of the oxygen band above 50.4 GHz one would yield a degradation equivalent to nearly 6 years of improvement in the tropical and southern hemisphere upper level wind accuracy. However the adjacent window channel, often considered to be less vital, would give degradation in the same parameter of 3.5 years.

In terms of the measurements considered to be most important the loss of any one of the 24 GHz, 31 GHz, 89 GHz or 176-190 GHz bands would degrade NWP performance by over 2 years in data sparse regions and by 3-6 years in the most sensitive regions. While the loss of more than one band is not necessarily additive, the loss of several channels or bands would quickly lead to losses of performance equivalent to over 10 years in some regions.

Data from these bands are a significant part of the expected improvements in NWP and forecasting during the next decade. It is difficult to estimate exactly how much forecasting accuracy will improve due to increased exploitation of satellite data. It is perhaps best to estimate this possible improvement based on the improvements made over the last 12 years. In 1996 the impact of satellite data was very small as only coarse resolution retrievals from the old TIROS (Television and Infrared Observation Satellite) Operational Vertical Sounder (TOVS) system and cloud track winds and scatterometer with very limited coverage were available. Today the radiances are directly assimilated into the NWP rather than the Level 2 products. In 1998 3-dimensional variational (3D-VAR) direct radiance assimilation of AMSU radiances was implemented producing the second biggest improvement in forecasting skill ever achieved. It is anticipated that future improvement over the next 12 years will be as a result of taking into account a wide variety of remote sensing satellite data (e.g., AMSU, SMOS, ATMS, conical scan instruments, MIS, and IASI).

FIGURE 9

**Loss of performance of NWP system in terms of years of improvement loss estimated for loss of each microwave frequency**



Report RS.2165-09

Passive microwave observations from space provide a unique capability for the monitoring of the global climate that cannot be achieved from the more sparse *in situ* observing networks, or from infrared sounders that are sensitive to the presence of clouds.

## 3.2 RFI identification

### 3.2.1 Near-real time interference detection using quality control methods of weather models

Through a series of checks and tests, data are quality controlled to ensure the viability of the information input into the forecast model. This helps to ensure that inaccurate data are adjusted or removed before going into the analysis. The judgments of trained meteorologists are a critical part of this process. Many factors contribute to data quality, but RFI would be one of the significant factors in contaminating the data accuracy.

In NWP, the data quality is evaluated based upon the differences between the observations and the short-term forecast by the model. The statistical data on these differences (also known as "innovations") provide a good guidance for the data quality of the observations. Figure 10 shows a frequency distribution of innovations which were collected from AMSU channel 6 (54.4 GHz). Approximately 80% of the values are within ±0.1° K and 99% of time these value are falling within ±0.3° K. This distribution curve has a very similar shape of normal distribution curve. For a normal distribution curve about 99.7% of data falls into ±3 σ, where σ is standard deviation. In other words, only less than 0.3% of data will fall outside of this interval. Therefore the innovation values which are greater than 0.3° K are highly suspicious and should be flagged, as possibly being caused by RFI.

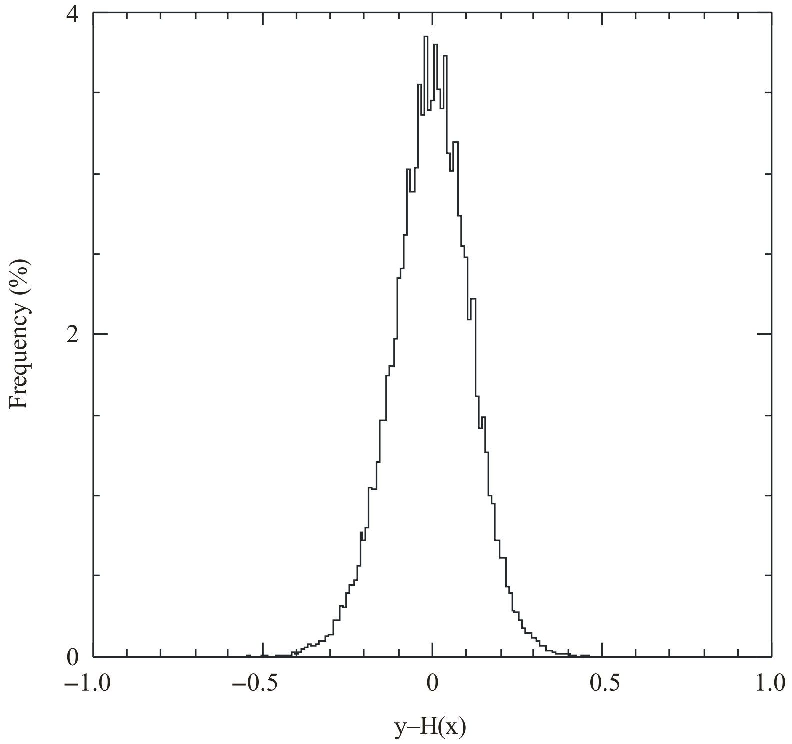
### 3.2.2 Real-time and near-real-time detection of RFI by identifying non-natural properties

#### 3.2.2.1 Procedures for detecting and identifying RFI

The mitigation of interference present in the acquired data set usually requires the identification of the individual measurements that have been contaminated by RFI. Almost all of the procedures for identifying interference regard the interference as additive noise. However this is only an approximation because, at least to some extent, the interference is deterministic, and can be anything from a pure carrier signal to a noise-like signal. Spaceborne passive sensors are often subject to interference from a multitude of emitters on the ground. Thus, even if a single terrestrial emitter may not radiate enough power to adversely affect passive sensor operations, the aggregation of a large number of emitters can. When there is a large number of interfering sources, the aggregate interference is noise-like, and such interference becomes difficult to distinguish from the desired natural measurements, which are also noise-like by nature.

FIGURE 10

**Frequency of innovations in weather model**



Report RS.2165-10

In some cases, data post-processing can sometimes detect the presence of single point interference because it may have different statistics than the natural measurement. As a consequence, the corresponding set of data retrieved through the satellite is considered to be corrupted and not to be processed within the NWP. This situation corresponds to a loss of data due to excessive RFI. The ability to detect and identify man-made interference depends on the degree by which measurable parameters of the man-made interference differ from the measurable parameters of the natural emissions One technique for identifying interference uses separate receivers to measure emission characteristics (such as polarization or narrow bandwidths) that would not arise from natural causes. Data processing can then identify the data known to be contaminated, so that these data can be discarded, modified, or given less weight in the processing algorithm. This technique takes advantage of certain common features of interfering signals that distinguish them from natural emissions. These features include:

1 a narrow-band spectrum relative to the bandwidths of commonly used passive microwave bands,

2 an unusually high degree of linear polarization,

3 an unusually high degree of polarization correlation,

4 a high degree of directional anisotropy.

These four features can be associated with four basic methods for interference detection:

1 sub-band diversity,

2 polarization diversity,

3 polarimetric detection,

4 azimuthal diversity.

Each of these four detection methods provides a means for identifying interference, with the first method, sub-band diversity, offering the additional capability of "data correction". In addition to these four characteristics, the man-made interference has a high degree of spatial, temporal or/and spectral variation. These features can be utilized to separate RFI from the natural emission, which will be discussed more detail in the next section.

However, it is noteworthy that low level RFI will most likely escape detection by conventional filter bank detection methods. The inclusion of extra special receivers and processors to the spacecraft to detect RFI are at the expense of weight, space and power requirements which may only provide a limited improvement in data quality. If the processing were to be performed on the ground, the extra data collected and stored to implement these techniques would require a higher data rate for transmission.

#### 3.2.2.2 Future techniques being applied in the spacecraft

Interference detection techniques that exploit the distinguishing features of interfering signals may be somewhat effective, particularly in bands where primary EESS (passive) allocations do not exist or where the EESS (passive) must share a band with co-primary active services. A simple way to extend the interference detection capabilities of the traditional radiometer is to increase either the temporal sample rate or the number of frequency channels in the system. These approaches can be implemented in an analogue fashion by simple extensions of the traditional radiometer, and the complete data set recorded for post-processing to eliminate interference at finer temporal and spectral resolution.

Redundant measurements in other bands provide measurement diversity. Window channels are measuring surface brightness and provide some redundancy in their measurements. However even though the spatial variability of the measurements may be similar, the brightness temperatures are different between bands. The purpose of measuring in different window bands is to characterize the gradient of the brightness temperature with frequency and not specifically to provide redundancy. However the redundant spatial variability does provide a means to improve data measurements corrupted by RFI.

### 3.2.3 Technique proposed for digital RFI detector

An agile digital detector (ADD) has been developed for a future remote sensing mission to detect RFI at both high and low levels in the microwave radiometer measurements. A digital signal processor provides direct measurements of the probability density function (PDF) of the pre-detected signal. The PDF can be used to detect the presence of unmodulated pulsed RFI.

The sensitivity of the observed brightness temperature to climatically relevant changes is low enough that even quite small biases in the observations, due to RFI, can be detrimental to the mission objectives. For this reason the radiometer's data sampling rate has been increased by several orders of magnitude above the Nyquist rate. The RFI detection algorithm is designed to detect individual samples that differ significantly from the local average value of those nearest neighbouring samples. The detector measures both the 2nd and 4th moments of the pre-detection voltage. The 2nd moment is the conventional measurement made by a square-law detector. The additional 4th moment measurement allows the kurtosis (relative peakiness or flatness of the distribution) of the voltage to be calculated. The kurtosis has been found to be a very reliable indicator of the presence of RFI, even when its power level is extremely low, especially with respect to pulsed RFI signals.

### 3.2.4 Post-processing interference detection

#### 3.2.4.1 Comparison of past records

Data records can be compared to historical records over the same area to expose a bias in the data set. This method is used to correct an entire data set by applying an adjustment to all the data. This technique is only applicable to climate studies. It is applied to data collected over many years and is too slow a technique to be used for weather forecasting. Even for climate studies, it is a means to examine the past and not forecast the future.

Instruments can measure and document the interference in advance. Therefore, when subsequent sensor data are processed, it will be known which data are likely to be contaminated so they can be discarded. In the 1 400-1 427 MHz band, for example, sensors have been flown on aircraft, and interference in certain urban areas has been noted. *A priori* knowledge of interference obtained from these flights (or from special spacecraft) is obtained by mapping the locations of the sources of interference and measuring the characteristics of this interference. The interference environment changes over time, and if this change is sufficiently slow, then an adaptive filtering process can sometimes be used to track the interference.

#### 3.2.4.2 Comparison of measurements

RFI can be detected by comparing measurements between sensing bands or similar measurements within the same band. Measurements on other bands or at different polarities provide redundancy and diversity in the measurements that can be used to recover at least in part the data lost to RFI.

Measurements in the 6.9 GHz frequency range have been determined to be valuable, because of the brightness temperature in this frequency range, but instrument data taken from the AMSR-E has indicated extensive RFI (see Fig. 2). This has provided an opportunity for developing techniques to detect the presence of RFI in the data and to mitigate its impact.

The natural measurements taken at some frequencies may, for those frequencies, be correlated to measurements taken at other frequencies. Interference may then be detected by a comparison of sensing measurements in those bands (for instance, near 10.7, 18.7, 36.5 and 89 GHz) and redundant sensing between polarities (vertical and horizontal).

Detection methods rely on the characteristics of RFI that differentiate it from natural radiation; particularly its high spatial variability and polarization bias (polarization diversity). In the first case, a significantly large increase in the brightness temperature over a small area indicates the presence of RFI. Secondly a bias in polarization indicates RFI. The spatial anomalies are detected by the comparison of the data between sensing channels. Interference is exposed by subtracting the measurement of one channel from another. Similarly the subtraction of the vertical measurement from the horizontal measurement eliminates the natural radiation which has no polarization bias and exposes the RFI, which does have a polarization bias.

The images in Fig. 2 illustrate the effect of RFI and the differences in images between bands and polarization. The high brightness temperatures in the United States of America shown as red are RFI and only appear in the 6.9 GHz images. The difference in the shape of these red areas from left to right indicates differences in polarization.

The data from the images in Fig. 2 are used to illustrate the technique of subtracting images between bands. The technique is limited to high level RFI which causes measurement levels that can be distinguished from natural emissions.

RFI is the only possible cause for the brightness temperature at 6.9 GHz to be significantly higher than at 10.7 GHz. Thus, large positive differences obtained by subtracting the 10.7 GHz brightness temperature (negative spectral gradient) can be used to separate RFI at 6.9 GHz from the natural emission background.

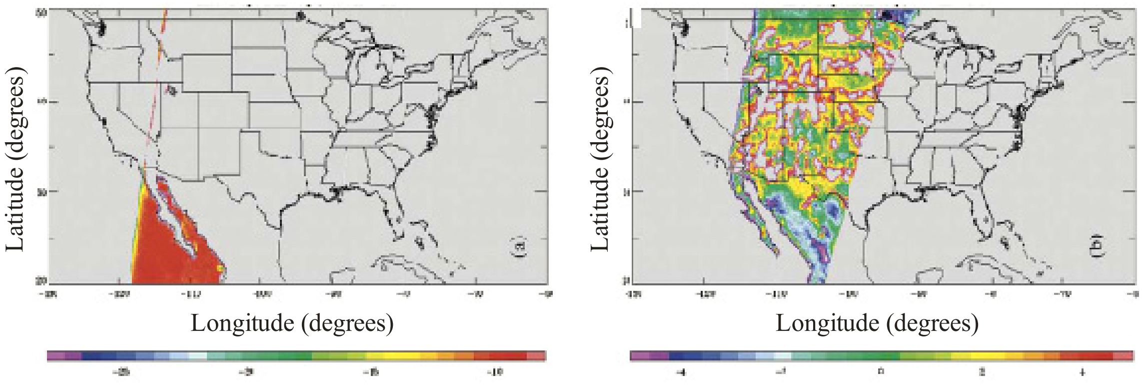
To illustrate the impact of different levels of RFI, images are produced by subtracting relatively uncontaminated radiance measurements at 10.7 GHz from heavily contaminated radiance measurements in the 6.9 GHz band. The difference is mostly the interference. Figure 11 shows processed images where the 6.9 GHz and 10.7 GHz bands have been correlated. Below each figure is a scale of the RFI Index (RI) which is the brightness temperature difference between the 6.9 GHz and 10.7 GHz images. Figure 11 partitions the RI into four ranges, (–30 to –5, –5 to +5, +5 to +10, and +10 to +100). It can be noted that the high level of RI in the lower two images is very detectable. In the upper two images the low level (Fig. 11b) interference is mixed in with the natural differences and in Fig. 11a) it is barely detectable. These low levels of RFI may not be separable from the natural measurement.

## 3.3 Detection and impact of RFI on the mission

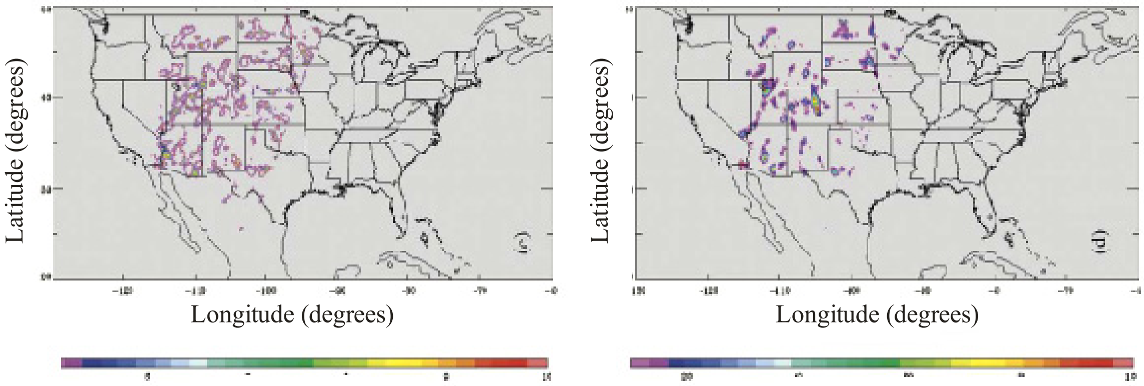
Even extraordinary and sophisticated measures are not able to detect all RFI, especially low level RFI. The detection of “low level” harmful RFI and determining its associated impact is generally impossible. Undetected excess RFI has a potentially greater negative impact on a remote sensing mission because it can lead to erroneous determinations and associated conclusions.

FIGURE 11

**RFI Index in four ranges**



a) Scale –30 to –5 b) Scale –5 to +5



c) Scale +5 to +10 d) Scale +30 to +100

Report RS.2165-11

## 3.4 Summary of RFI detection in products

Detection of RFI errors in the data may be difficult if not impossible depending on the relative change that the RFI causes in the radiometric measurement. Loss of a measurement data due to overwhelming amounts of interference can severely hamper forecasting efforts and can reduce the overall accuracy of the forecasting products. Furthermore, RFI can also detract from progress in forecasting accuracy and even regress forecasting in extreme cases.

High level and persistent RFI will distort the products sufficiently to make the presence of RFI obvious as illustrated in the section above. However, in most cases, it is likely that RFI will only be observable in a few measurements.

On the other hand, RFI that is small relative to the magnitude of the measurement may not be detectable and yet have a significant negative impact on the product.

Detectable RFI may cause the loss of the data set from a band and cause loss of capability in forecast products. RFI affecting only a few measurements can reduce the reliability of the forecasts. Inaccurate forecasts or misrepresentation of some environmental situation such as deforestation could lead to incorrect conclusions by an analyst and incorrect decisions by authorities.

A typical example of wrong measurements in a single band creating errors in many products is the 23.6-24 GHz frequency band, because the band is used in developing multiple products. It was shown in Fig. 9 that loss of an entire band due to excessive RFI could set back forecasting accuracy many years.

Current spacecraft instruments such as the AMSU do not have the capability to check for RFI. The purely passive bands are supposed to be protected from interference by regulations. Newer planned spacecraft instruments are being designed to check for RFI because they are using spectrum that is known to not be free of interfering transmitters. In most of these instruments the spacecraft has used the non-natural and sometimes known characteristics of interference to determine the presence of RFI in the measurements.

Processing algorithms on the Earth will, if RFI is suspected, check for measurements that are out of range or not consistent with other measurements. NWP systems will detect data errors by comparing predictions with measured data and determine that the data is contaminated because the predictions are not reliable. In this case it may not be known that RFI is the cause.

But, despite all these sophisticated mitigation techniques that may be implemented, even if errors can be detected, the data products are compromised by the presence of RFI.

## 4 Interference and impact

By its very nature, human activity today increases the opportunity for interference to occur to microwave sensing measurements. Simultaneous concerns about global warming have heightened awareness of possible risks to life. A reasonable balance between our reliance on emitting devices and incomplete understanding of global climate changes needs to be achieved. For instance, it is not known to what extent incremental increases in microwave brightness temperatures are caused by man-made radiative emissions and thus mask the true nature of trends in atmospheric temperatures.

There is little doubt that society has benefitted from the outgrowth of use of electronic devices, whether it is new medical technology which allows pinpointing unexpected tissue growth or locating a distressed person via global positioning system technology. On the other hand, it is clear that people have benefitted from the passive microwave technology in the realm of improved forecasts (see Fig. 9). The key to a successful balance of these sometimes competing goals is a combination of ITU guidance, industry understanding, and passive remote sensing mitigation through data elimination and real time mitigation.

### 4.1 ITU guidance

ITU provides written leadership for the world and help to resolve inconsistencies among communities. These documents are important not only for the assistance they provide various administrations in guiding their short and long term work but also for the opportunity for change as technology changes the world’s perception of its reliance on devices and its need to understand then mitigate the effects of man-made loads on the global atmosphere and surface.

### 4.2 Industry understanding

The science and application of passive microwave sensing has evolved significantly since its onset in the 1970s. Major international NWP centres use microwave data as a key part of its support of the daily weather forecast. A 2006 survey in the United States of America with 1 465 respondents indicated the average household accesses weather forecasts 115 times per month. It is important to develop an understanding within industry of the importance that passive microwave sensing plays in the daily lives of many humans.

### 4.3 Passive remote sensing mitigation

Mitigation is by definition only a means to minimize the impact of RFI on the microwave measurements and the corresponding products developed from the measurements. Mitigation techniques will not make a sensor less vulnerable to the degrading impact of RFI. The following sections discuss the means to minimize the RFI impact on the products when RFI is known and future techniques to provide an estimate of the measurement if RFI is anticipated and detectable.

#### 4.3.1 RFI prevention through regulation

It is well known that active services operating in the same bands as passive services can cause harmful interference to the passive service operations. For that reason, exclusively passive bands have been allocated both nationally and internationally. These bands are afforded protection not only by these exclusively passive allocations but also by RR No. 5.340. Some ITU-R Recommendations have been adopted which recommend some constraints on active service operations to reduce harmful interference to passive sensors. Some of those Recommendations are also reflected in the regulations, such as RR Nos. 5.556A and 5.562H, which limit the power density at the passive sensor from inter-satellite links.

Development of the microwave spectrum for telecommunications and other active services increases the probability of man-made interference to passive Earth exploration-satellite service (EESS) operations. Continued enforcement of existing radio regulations relevant to passive bands is necessary to permit users of EESS to achieve their objectives.

#### 4.3.2 Data elimination

The most common way of mitigating the impact of RFI is to flag or eliminate from the data set the radiometric measurements that can be detected as contaminated. This way the algorithms that use the measurements can either estimate the missing value or flag questionable results in the output. Algorithms that are using a significant amount of contaminated data can also indicate a reduced reliability in the output. Algorithms that use multiple sets of data for forecasting can place an adjusted weighting factor on knowingly questionable data.

These methods help reduce the impact of RFI on the data products compared to using unknowingly contaminated data but in all cases lost data still degrade the products either by reducing the reliability of the forecasts or contributing to incorrect forecasts.

#### 4.3.3 Real time mitigation techniques

Real time mitigation techniques for passive sensors are very difficult to implement because the signal strength of the desired measured emission and the dynamic range of passive receiver is narrow in comparison to relatively high power man-made RFI signals which can drive the passive receiver to non-linear behaviour or amplifier saturation where no amount of post-processing can improve the data – it must be discarded. On the other hand, it is difficult (if not impossible) to distinguish low power man-made RFI emissions from the real, natural emission measurements which are desired. For low-power RFI emissions, mitigation through the use of fixed filtering (permanent filters to block RFI) degrades the performance of the sensor and has no beneficial impact on the RFI present in the measurement.

Techniques have been developed to recover measurements in the presence of interference. These techniques involve some redundant receivers and processing in an effort to identify and cancel the interference. Techniques differ depending on the characteristics of the interference. The passive receiver has a broad passband and some interfering signals may have a narrow spectrum and can be identified with a series of narrow band filters. Broadband interfering signals that are produced by pulsed signals (e.g. radars) have a different time characteristic than the constant radiation being measured and can be addressed with digital processing techniques.

#### 4.3.3.1 Technique being applied to typical narrow band interfering signals

A multiple sub-band interference mitigation technique has been demonstrated that was planned for the CMIS instrument that was planned to fly on a new satellite. This spectral mitigation algorithm employs an auxiliary receiver that has a number of channels within the sensing band. The mitigation algorithm operates by performing a standard least squares fit to the sub-band data. If all of the sub-bands provide a good fit then no corrections are made. However, if a particular sub-band does not appear to provide a good fit, then the least squares procedure is repeated, with the data from that sub-band deleted from the fit process. This procedure is repeated, removing additional sub-bands until a sub-band combination is found that provides a good fit. Sub-bands can be weighted more heavily in a region of higher than normal expected interference.

The sub-band model can be expected to provide accurate correction for interference falling into one channel, and less accurate correction when it falls into more than one channel. Multiple interfering sources that fall into a single channel would be treated as a single distinct source.

The techniques that were planned for the proposed CMIS instrument are experimental means for handling data contamination due to RFI. Investigation of RFI mitigation techniques will be part of a continuing process to improve the quality of passive sensing data.

#### 4.3.3.2 Technique being considered for broadband interfering signals

Traditional radiometers (i.e., those which directly measure total power integrated over timescales of milliseconds or greater) are poorly-suited to the suppression of rapid time-varying interference. This has motivated the design and development of radiometers capable of coherent sampling and adaptive, real-time tracking of the interference, using digital signal processing.

Future microwave radiometers may employ on-board digital processing for interference suppression. The analogue front end of the radiometer would down convert the received spectrum to a convenient IF, and sample the signal with a high-speed A/D converter. The resulting digital signal would then be processed on-board through time domain and frequency domain blankers to remove interference that exceeds a pre-set threshold.

Using digital technology, a fast Fourier transform (FFT) operation can be performed in real time to obtain a much larger number of frequency channels than is possible using analogue sub-channels. However, the amount of data generated by such a system is also much larger than that of the analogue approaches and would easily exceed the space-to-ground data rates that can be achieved. To reduce the data volume, an interference mitigation processor can be added to the digital receiver to implement simple time and/or frequency domain mitigation algorithms in real time. The resulting interference-free data is then integrated over time and/or frequency to produce a manageable final output data rate.

To detect radar pulses, for example, the digital receiver can maintain a running estimate of the mean and variance of the sample magnitudes. When the magnitude of a sample greater than a certain number of standard deviations from the mean is detected, the receiver blanks (sets to zero) a block of samples beginning from a predetermined period before the triggering sample. In a similar fashion, interference blanking in frequency can be accomplished by means of an FFT operation. However, these techniques result in the deletion of measurements and not the improvement of the individual measurement. It can be said that these techniques improve the entire data set to some degree.

### 4.3.4 Use of redundancy for missing or corrupted data estimation

Several of the techniques discussed above that are used for detection of data corruption require the use of similar data to the measurement and thus provide a close duplicate that may be used for estimating the missing data.

1 Polarization – If corrupted data is detected because of polarization discrimination, the measurement with orthogonal polarization may be a truer measure of the data.

2 Measured data on another channel as illustrated in Fig. 2 between the 6 GHz and 10 GHz channels may be close enough to provide an estimate of the measurement.

3 Measurements in uncontaminated contiguous measurements cells can be averaged to provide an estimate of the actual value.

4 When records are being compared for climate analysis a bias in the data set may be adjusted to align the measurements between records.

## 4.4 Mitigation of RFI risks

There is no known way to replace data lost from excess RFI since passive sensing is generally a “real time mission” that can never be repeated or recaptured for any expired time period.

The impact of known excess RFI may be mitigated through some amount of “real time” redundancy or diversity that generally requires additional spectrum, sensor complexity and processing, all of which increases the cost of the mission and can only provide limited improvements of measured data.

## 4.5 Summary of interference and impact

In data processing RFI is mitigated by flagging suspect data or eliminating it from the data set. Data can be replaced by estimates based upon data points near by but those are not necessarily accurate. In these cases the analysis algorithms are not misled by errors but are reduced in reliability.

Mitigation techniques planned for future spacecraft instruments are based upon knowledge of the interference sources. They rely on the RFI having different characteristics from the natural radiation. The interference is reduced through filtering, nulling, cancelling or polarization selection. However no technique has been proposed that would restore with full accuracy the actual measurement in the absence of RFI. Lost measurements are just that, lost. The instruments do not have the capability to retake the measurement because they are time specific. Most of the techniques mentioned here are still in a research stage and are not yet implemented on any operational satellite, because the results are still preliminary and address a limited number of RFI cases.

Table 1 lists some of the currently known RFI detection and mitigation techniques.

TABLE 1

**RFI detection and mitigation techniques**

| **Frequency band (GHz)** | **RFI detection or mitigation technique** | **Examples of mission or passive sensor** | **Measurement** | **RFI source** |
|---|---|---|---|---|
| 1.4-1.427 | Agile digital detector | Aquarius | Sea surface salinity | High power telecommunication transmission or radars |
| 1.4-1.427<br>6.425-7.25 | Asynchronous pulse blanking and FFT | Hydros | Soil moisture | Wideband sources-radars |
| 6.425-7.25<br>10.6-10.7 | Spectral difference method, principal component analysis | AMSR-E | Soil moisture, vegetation index<br>Sea surface temperature | Narrow-band sources-fixed communication |
| 6.425-7.25<br>10.6-10.7<br>22.21-22.5 | Spatial filter using a dynamic discrete Backus-Gilbert technique | WindSat<br>CMIS<br>NPOESS | Soil moisture, vegetation index | Narrow-band sources-fixed communication |
| 6.425-7.25 | Sub-band diversity | CMIS | Soil moisture, vegetation index | Narrow-band sources-fixed communication |
| 6.425-7.25 | Using a provisional channel | AMSR2 | Soil moisture, sea surface temperature | Narrow-band sources |

Brief description of above RFI detection and mitigation techniques:

1 Agile digital detector

The agile digital detector (ADD) can discriminate between RFI and natural thermal emission signals by directly measuring higher order moments of the signal than the variance that is traditionally measured. The ADD uses high-resolution temporal and spectral filtering methods to selectively remove the RFI that is detected.

2 Asynchronous pulse blanking and FFT

The idea of this technique is to remove incoming data whose power exceeds the mean power by a specified number of standard deviations. Successful performance of this algorithm has been qualitatively demonstrated through local experiments with the digital radiometer. The HYDROS mission team had expressed an interest in possible inclusion of such a digital backend in the HYDROS instrument for the RFI mitigation in L-band. But the system developed can be applied in other RF bands: NPOESS sponsored project using this system at C-band in progress.

3 Dynamic discrete Backus-Gilbert technique

The Backus-Gilbert (BG) technique was traditionally used to enhance the satellite data spatial resolution and/or to improve the sensor spatial coregistration behaviours under a benign RFI environment but was difficult to use in an RFI-ridden condition. However, a new dynamic Discrete Backus-Gilbert (DBG) method has been created for use in RFI noise environments to mitigate RFI effects on the data in conjunction with 4D data assimilation for soil moisture profiles. It resolves a lot of problems with the traditional BG method but still is computationally quite expensive.

4 Using a provisional channel for AMSR2

The provisional channel technique uses two close frequency ranges (6.925 GHz and 7.3 GHz) to measure the same radiances simultaneously. The 7.3 GHz channel is a secondary, which is only used when the primary channel (6.925 GHz) is contaminated with RFI.

All these above listed mitigation techniques have inherent limitations and do not work for every case. Table 2 lists advantages and disadvantages of these mitigation techniques.

TABLE 2

**Advantages and disadvantages of various mitigation techniques**

| Name of technique | Advantages | Disadvantages |
|---|---|---|
| Agile digital detector | Suitable for detecting narrow-band pulsed signals<br>Can detect RFI at low levels – to the radiometric uncertainty<br>No additional analogue detector needed<br>Can be on-board real time technique<br>Could potentially eliminate the effect of RFI on brightness temperatures | Technique only demonstrated for L-band where there are narrow-band unmodulated radars and not shown to be useful for detecting wideband modulated signals<br>Increased temporal sampling rate resulting in large data files<br>Loss of processor results in loss of the channel<br>Places complex equipment on the spacecraft which cannot be maintained<br>Additional processor may provide additional power requirements on the spacecraft |
| Spectral difference method | RFI can be detected and removed relatively easily | Sea and land require different techniques<br>Limited to differences over 5°<br>Not an onboard real-time technique<br>Detection of RFI in one channel is only certain if compared to another uncontaminated channel |
| Sub-band diversity | Can be implemented in near real time on the spacecraft<br>Provides means to estimate uncontaminated measurement<br>Can be implemented with analogue receivers | The inclusion of extra special receivers and processors on the spacecraft to detect RFI are at the expense of weight, space and power requirements which may only provide a limited improvement in data quality<br>If the processing were to be performed on the ground, the extra data collected and stored to implement these techniques would require a higher data rate for transmission<br>Detects only narrow-band interference |

TABLE 2 (*end*)

| Name of technique | Advantages | Disadvantages |
|---|---|---|
| Asynchronous pulse blanking and FFT | Remove incoming data whose power exceeds the mean power by a specified number of standard deviations | The APB approach not shown to be effective in reducing corruption from long-term large scale RFI |
| Using a provisional channel | Uses two close frequency ranges (6.925 GHz and 7.3 GHz) to measure the same radiance simultaneously (7.3 GHz channel is a secondary, which is only used when the primary channel (6.925 GHz) is contaminated with RFI) | Not used in a production environment<br>Neither channel is protected<br>Only one signal is sensitive to the measurement (6.925 GHz) the other signal is there for redundancy<br>Multiple signals means multiple receivers means more expense and higher chance of failure |
| Spatial filter using a dynamic Discrete Backus-Gilbert technique | To enhance the satellite data spatial resolution<br>Can be applied to all microwave bands | Increase noise floor of sensors<br>Extensive computations<br>Need separate RFI detection methods |

## 5 Summary

The use of microwave radiance measurements has become increasingly important in the development of weather forecasts through its increased use in numerical prediction models. The increased inclusion of these measurements in these models has greatly improved the reliability and accuracy of forecasts, and thus contributed to the saving of lives through advanced warnings of severe events. These measurements also are important in contributing to the monitoring of our environment which guides decisions by world leaders.

In most cases the procedures and models that use the radiometric measurements are not designed to detect or mitigate RFI. This primarily is because protection is provided through ITU regulations and RFI interference is not expected. However data corruption in general is expected from other causes and the numerical prediction models and other analysis procedures do monitor results to assess the reliability of the input measurements. It could be RFI that reduces the data reliability although it may not be specifically identified as RFI.

Most RFI mitigation techniques are planned for future systems. Interference mitigation is not applied to current instruments such as the AMSU, SSM/I or AMSR-E. Interference mitigation has been planned for future instruments only in cases where RFI is expected because either the allocated band is shared with other services or the instrument will be designed to operation where there is no passive allocation. In these cases there is generally some knowledge of the RFI source that is used to identify when interference is occurring and then used to mitigate the impact. Expensive and complex systems are needed to identify and mitigate interference and both analogue and digital techniques are planned. Digital techniques show great promise for future mitigation because they can divide the sensor measurement into small time and frequency increments and identify RFI that would not be apparent in the actual radiometric measurement.

Mitigation techniques generally reduce the impact of RFI, however, the quality and completeness of the resultant data products and their associated services are never as good. The mitigation techniques generally require non-trivial resources to first identify the RFI and then mitigate their impact. While RFI mitigation techniques continue to evolve, the importance of sustaining EESS data quality in RFI environments should continue to be emphasized. The present systems with no mitigation techniques installed will continue to be in use for several years. The AMSU/MHS will continue to be used by NOAA until 2015 and by METOP until 2020.

The EESS mission is understandably sensitive to its operational environment, especially RFI. There are mitigation techniques that will minimize impact but will never totally compensate for the loss in data quality, reliability and availability.

## 6 Conclusion

The increased and essential importance of passive microwave sensing in forecasting weather and climate as well as all Earth observation activities totally justifies the need to ensure their operations without degradation due to RFI, either from in-band or out-of-band emissions.

In summary, RFI received by a passive sensor can be classified into three different categories:

1 High levels of RFI that are obviously inconsistent with natural radiation. As such, these can be detected, but the corresponding measurements are lost.

2 Very low levels of RFI below protection criteria, that cannot be detected by on-board passive sensors, and hence do not have impact on the output products.

3 Low levels of RFI that cannot be discriminated from natural radiations and hence represent very serious problem since degraded or incorrect data would be accepted as valid.

In addition, even if it were possible to detect and mitigate RFI, it would result, in all cases, in a severe degradation of the corresponding output products. Therefore no mitigation techniques have been identified which can be applied to the microwave sensors and their products to allow RFI without degrading their performance reliability or availability.

# Annex A

## Science of passive sensing

Passive sensing products are derived from microwave radiometric measurements. In selected microwave bands, the deviation of measured radiometric energy from the theoretical black-body radiation is used to identify meteorological parameters, which are the passive sensor products. All matter reflects, absorbs, and emits electromagnetic radiation at various frequencies. Satellite-borne passive sensors capture the radiation emitted from the Earth and atmosphere. The frequencies at which various types of sensors operate extend from microwave radio frequencies through the infrared to visible light and into the ultraviolet. Objects such as the Earth’s surface, vegetation, water particles, and atmospheric gases radiate at unique frequencies that depend on the temperature of the object. This radiation is called thermal radiation because of its temperature dependence.

A black body is matter that absorbs all electromagnetic radiation incident upon it. None of the incident radiation passes through, or is reflected from, the matter. The object does, however, radiate energy. According to Kirchhoff's Law, the radiated energy from an object in thermal equilibrium with its surroundings equals the absorbed energy, and this energy depends only on the temperature *T*. Since a black body radiates more energy than other matter at a given temperature, it is called a perfect radiator. At microwave frequencies, the Rayleigh-Jeans radiation law governs the intensity of the radiation emitted by a unit surface area into a given direction from a black body. This law can be expressed in many forms, one of which is:

$$E(\lambda, T) = \frac{2kT}{\lambda^2} \tag{6}$$

where:

$E$: the intensity of radiation emitted ($\mathrm{W/m^2 \times Hz^{-1} \times sr^{-1}}$),

$k$: the Boltzmann's constant = $1.38 \times 10^{-23}$ W/(Hz · K),

$\lambda$: the wavelength (metres).

Figure 5 depicts the Rayleigh-Jeans law at microwave frequencies for several temperatures that are in the operating range of microwave sensors. As can be seen, the spectral power density in the microwave region increases with frequency. Therefore, power in the microwave spectrum is relatively low compared to the power in the infrared and visible spectra.

Microwave sensors measure noise, which can be expressed either in terms of power or temperature. Noise is contributed by the radiometer as well as the Earth and its atmosphere. Processing on the ground removes the noise contributed by the radiometer from the sensor data. Ideally, the sensors measure only the power radiated from a "resolution cell" on the Earth's surface. This cell, sometimes called the antenna "footprint," is defined by the intersection of the sensor antenna's main beam with the Earth's surface. The magnitude of this measured power can be calculated as follows. If the radiation source were isotropic, the radiated power per unit area of the surface per unit frequency interval would be:

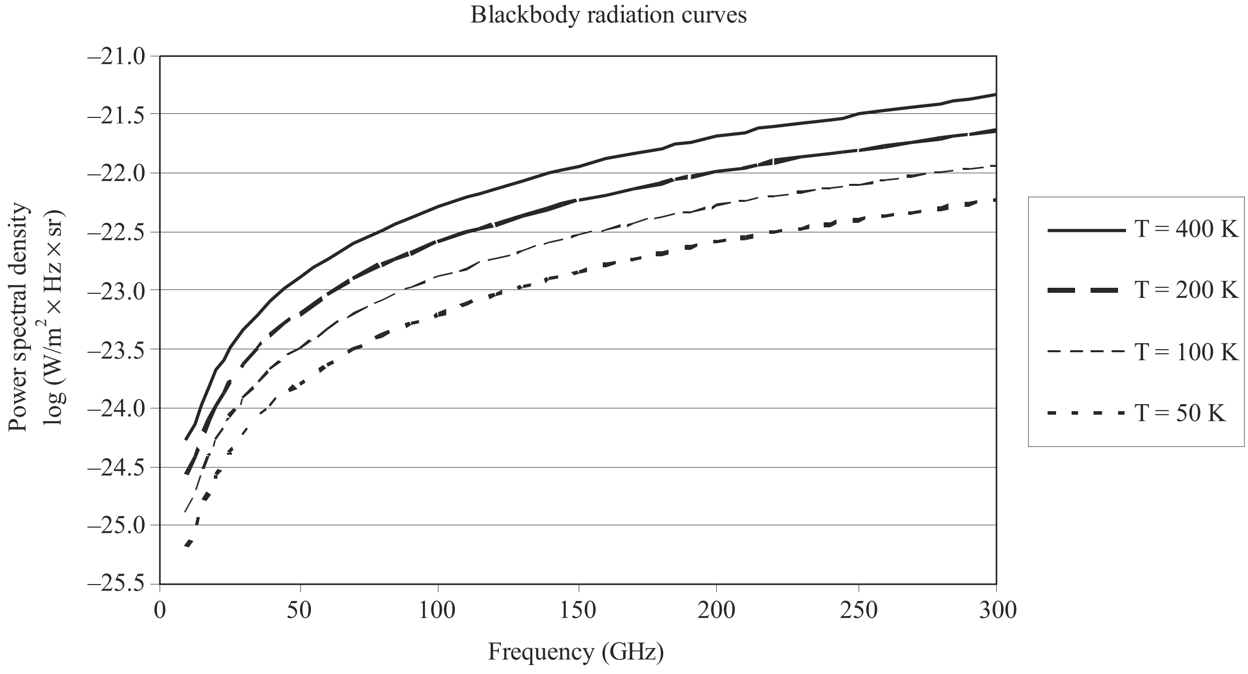
$$4\pi E(\lambda, T) = \frac{8\pi kT}{\lambda^2} \quad (\mathrm{W/m \cdot Hz}) \tag{7}$$

Assume for simplicity that the sensor antenna is nadir-pointing, although it can be shown that the results also apply for antennas pointing off nadir. If *A* is the area of the sensor antenna's footprint on the Earth's surface, then the power per unit frequency radiated isotropically from that area is:

$$4\pi E(\lambda, T)A = \frac{8\pi kTA}{\lambda^2} \quad \mathrm{W/Hz} \tag{8}$$

FIGURE 12

**Rayleigh-Jeans law of radiation**



Report RS.2165-12

Sensor antennas have high beam efficiencies, implying that most (typically about 95%) of the received power arrives from the footprint. In this situation, the antenna gain *G* is related to the antenna footprint area as follows:

$$G = \frac{4\pi d^2}{A} \tag{9}$$

Where *d* is the distance of the sensor antenna from its footprint. Finally, the free-space loss between the footprint and the sensor antenna is:

$$L = \left(\frac{4\pi d}{\lambda}\right)^2 \tag{10}$$

Combining these factors, the power per unit frequency received by the sensor is:

$$\frac{1}{2}\frac{8\pi kTA}{\lambda^2}\frac{4\pi d^2}{A}\left(\frac{\lambda}{4\pi d}\right)^2 = kT \qquad \text{W / Hz} \tag{11}$$

The factor 1/2 accounts for the fact that the sensor is sensitive to only one polarization. Therefore, we find that the radiation power density measured by the sensor is simply *kT* W/Hz$^{-1}$. This says that the sensor is essentially measuring the black-body temperature of the Earth's surface. Of course, this is not completely correct because the Earth is not a black body. The black-body temperature must be modified by the emissivity of the Earth's surface, and by effects of the intervening atmosphere. In addition, even though sensor antennas have high beam efficiencies, radiation nevertheless arrives at the sensor from areas outside the sensor antenna footprint. The latter effect can be accounted for by considering the measured temperature to consist of contributions from all directions relative to the sensor antenna, integrated over 4π steradians:

$$T = \frac{1}{4\pi}\int_{\Omega} G(\Omega)T(\Omega)d\Omega \tag{12}$$

Where $d\Omega$ is an incremental solid angle subtended at the antenna. Processing on the ground adjusts the measured temperature to account for the fact that the antenna beam efficiency is not 100%.

Real objects are not perfect radiators, and can be referred to as gray bodies because they radiate less energy than a black body. The ratio of the energy radiated by an object to the energy of a black body at the same temperature as that object is called the emissivity $\varepsilon$, and has a range of 0 to 1. Emissivity depends on the dielectric constant of the object, surface roughness, temperature, wavelength, look angle, etc. The temperature of a black body that radiates the same energy as an observed object is called the brightness temperature of that object, $T_B$. Disregarding effects of the intervening atmosphere, the physical temperature and brightness temperature are related by:

$$T_{B,N} = \varepsilon T \tag{13}$$

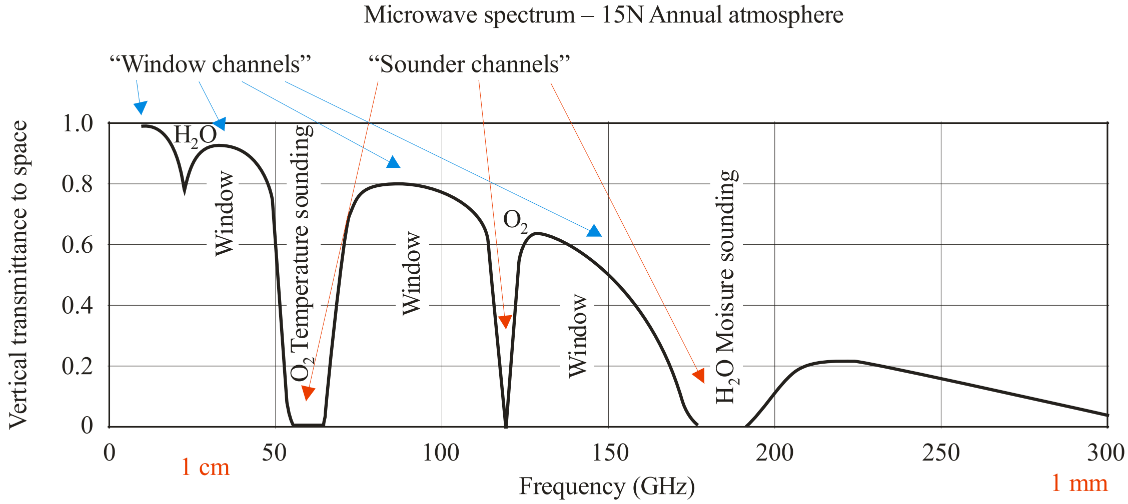
Where $T_{B,N}$ is the brightness temperature neglecting atmospheric effects.

The surface of the Earth is the primary source of thermal radiation in window channels. Oceans and lakes have a low but relatively consistent intensity of radiation. Land areas have higher intensities but these intensities are more variable because of the texture of objects, shape, moisture content, vegetation, and mineral content.

The constituents of the atmosphere (gases and aerosols) modify the brightness temperature further. Radiation transfer through the atmosphere can be classified into multiplicative and additive effects. The multiplicative effect refers to the amount by which energy from the Earth to the sensor is reduced due to atmospheric absorption and scattering. Absorption occurs at those wavelengths at which electromagnetic energy excites atmospheric molecules to different energy states. Atmospheric gases have absorption bands that are specific to the molecule. The $H_2O$ molecule has absorption bands around 22.3 GHz and 183.31 GHz. The $O_2$ molecule has several absorption bands between 50 GHz and 60 GHz and a single band at 118.75 GHz. Areas of the microwave spectrum where the influence of atmospheric gases is minimal, and radiation from the Earth can reach the sensor with little attenuation, are called windows. Frequency ranges where atmospheric absorption is strong are used for sounding. These spectral areas are illustrated in Fig. 13.

FIGURE 13

**Window and sounder channels**



Report RS.2165-13

In addition to atmospheric absorption, scattering from atmospheric constituents also occurs. Scattering is frequency dependent, and its effect is to further reduce the energy at the sensor at high frequencies. Absorption and scattering occur at the same time, so both effects must be considered in deriving meteorological parameters. These multiplicative effects can be accounted for by introducing a loss factor $L_{atm}$ so that the brightness temperature becomes:

$$T_{B,A} = L_{atm} T_{B,N} = \varepsilon L_{atm} T \tag{14}$$

Where $T_{B,A}$ is the brightness temperature considering atmospheric attenuation.

The additive effect refers to thermal emission from the atmospheric constituents themselves. It is more complicated than the multiplicative effects because:

1 it depends on the atmospheric pressure, which in turn is a function of altitude in the atmosphere,

2 emission in lower layers of the atmosphere can be re-absorbed, re-emitted, and scattered in the upper layers.

For simplicity, the additive effects will be accounted for by defining $T_{atm}$ to be the effective brightness temperature of the atmosphere, and adding it to brightness temperature given above, so that

$$T_B = T_{B,A} + T_{atm} = \varepsilon L_{atm} T + T_{atm} \tag{15}$$

Where $T_B$ is the brightness temperature measured by the radiometer.

It is the quantity $kT_B$, not the black-body result $kT$, which is the actual radiated power density measured by the sensor. A more detailed treatment, which sometimes incorporates scattering and emission from rain drops, yields what is known as the radiation transfer equation. Solutions of this equation provide useful information concerning meteorological products.

# Annex B

## Environmental data products

Tables 3 through 5 list the environmental products in three product categories of atmospheric, ocean, and land products. Some of the products are EDRs products. These are the output products developed in three different categories. The atmospheric products represent information about the Earth’s atmosphere such as, water vapour, temperature, gaseous content, etc. Ocean products present information about the surface of seas and oceans. Specifically, such parameters as surface winds, surface temperature, or ice concentrations are represented. Land products represent parameters of the surface of the land such as soil moisture, vegetation, etc.

The first column labelled “product area name” indicates the specific EDR products. Each product is produced by combining the brightness temperature records from various sensing bands.

The product area function column ($2^{nd}$ column) lists the specific parameters that are being used from the brightness temperature records: water refers to frequency bands that are specifically sensitive to water vapour absorption of radiated energy from the Earth, atmospheric temperature refers to bands where radiation from oxygen molecules can be measured, window refers to frequency bands that can detect the Earth's radiation with little effect from the atmosphere, and scattering refers to frequency bands that are sensitive to the scattering effects of liquid or solid water, or surface roughness of the Earth. These are the specific types of Level 1 products used to develop the Level 2 products.

The "passive sensing bands" are listed in the third column by centre frequency. Allocations for emitters are not permitted in this band to preserve and protect the accuracy and integrity of the passive microwave measurements. The column labelled "band evaluation" provides an evaluation of the importance of the band with respect to the environmental product. The entry presents an explanation of the function of the band in the Level 2 product and the relative value of the band compared to other bands that could be used for the same function.

TABLE 3

**Atmospheric data products and associated sensing bands**

| **Product area name** | **Product area function** | **Passive sensing bands (GHz)** | **Band evaluation** |
|---|---|---|---|
| Total Precipitable Water TPW (mm) | Water | 31.4* | Primary band for integrated liquid water. |
| | | 37 | Primary/best use for integrated liquid water. |
| | Window | 19.4 | Primary channel for high liquid. |
| | | 22.3 | Background reference channel for simultaneous retrieval of TWP. |
| | | 23.8* | Background reference channel for simultaneous retrieval of TWP. |
| | | 85.5 | Thin clouds having low water content. |
| | | 89.0* | Thin clouds having low water content. |
| Cloud Liquid Water CLW (mm) | Water | 22.2 | Primary band for integrated water vapour content in high content areas. |
| | | 23.8* | Primary/best use for integrated water vapour content in low content areas. |
| | Window | 19.4 | Principal background channel for use with 22 GHz vapour line. |
| | | 31.4* | Background reference channel, exclusively passive allocation. |
| | | 37.0 | Window channel. |
| | | 85.8 | Window channel at high frequency end. |
| | | 89* | Window channel at high frequency end. |
| Cloud Ice Water | Scattering | 89* | More sensitive to atmospheric water vapour than lower frequencies. |
| | | 150* | More sensitive to atmospheric water vapour than lower frequencies. |

TABLE 3 (*continued*)

| Product area name | Product area function | Passive sensing bands (GHz) | Band evaluation |
|---|---|---|---|
| Particle Size in ice clouds | Scattering | 89* | More sensitive to atmospheric water vapour than lower frequencies. |
| | | 150* | More sensitive to atmospheric water vapour than lower frequencies. |
| Ice Water Path IWP (g/m$^2$) | Sounding for water vapour | 22.2 | Primary band for integrated water vapour content in high content areas. |
| | | 23.8* | Primary/best use for integrated water vapour content in low content areas. |
| | Window | 19.4 | Principal background channel for use with 22 GHz vapour line. |
| | | 31.4* | Background reference channel, exclusively passive allocation. |
| | | 37.0 | Window channel. |
| | Scattering used with 150 GHz to detect large particle size | 85.8 | Window channel at high frequency end. |
| | | 89* | Window channel at high frequency end. |
| | Cloud parameters | 150* | Reference background channel for 183 GHz water vapour, exclusive passive allocation. |
| | Scattering – used to separate surface from cloud scattering | 183 ± 7 | Substitute for IR measurements. Best band for verticalprofile of atmospheric water vapour. Only global source of humidity information in cloudy conditions. |
| | Scattering – used with 150 GHz to identify smaller ice parameters | 230* | Denotes general frequency range and not specific band. |
| Rain Rate (mm/h), this product is derived from the IWP | Sounding for water vapour | 10.5-10.7 | Best for heavy rain rates, especially over low RFI areas such as oceans. |
| | | 18.6-18.8 | Best for moderate rain rates. |
| | | 22.2 | Primary band for integrated water vapour content in high content areas. |
| | | 23.8* | Primary/best use for integrated water vapour content in low content areas. |
| | Window | 19.4 | Principal background channel for use with 22 GHz vapour line. |
| | | 31.4* | Background reference channel, exclusively passive allocation. |
| | | 37.0 | Window channel; good for low rain rates, especially over oceans. |
| | | 85.8 | Window channel at high frequency end. |
| | | 89* | Window channel at high frequency end. |

TABLE 3 (*continued*)

| **Product area name** | **Product area function** | **Passive sensing bands (GHz)** | **Band evaluation** |
|---|---|---|---|
| Atmospheric Temperature | Window providing surface and rain information | 23.8* | Primary/best use for integrated water vapour content in low content areas. |
| | Window providing surface and rain information | 31.4* | Estimate surface temperature gradient used as reference channel for 23.6 GHz water vapour measurement. |
| | Sounding for surface temperature | 50.3* | Measures effect of surface radiation to adjust atmospheric temperature measurements; compliments measurements in; closest window to oxygen temperature sensing frequencies. |
| | Sounding for atmospheric temperature | 57.29 ± 0.322 ± 0.004 (4 bands) | Strongest from $O_2$ at 37 km. |
| | | 52.6-59.3 | Critical band for atmospheric temperature profiling. Atmospheric opacity permits greater sharing at higher frequencies. Provides better vertical resolution than 118 GHz band; less sensitive to cloud effects. Most important band for NWP. |
| | | 57.29 ± 0.322 ± 0.010 (4 bands) | Strongest from $O_2$ at 32 km. |
| | | 57.29 ± 0.322 (2 bands) | Strongest from $O_2$ at 29 km. |
| | | 57.2903 | Strongest from $O_2$ at 25 km. |
| | | 57.2903 ± 0.115 (2 bands) | Strongest from $O_2$ at 19 km. |
| | | 57.2903 | Strongest from $O_2$ at 17 km. |
| | | 55.5 | Strongest from $O_2$ at 13 km. |
| | | 54.94 | Strongest from $O_2$ at 11 km. |
| | | 54.46 | Strongest from $O_2$ at 10 km. |
| | | 54.40 GHz | Strongest from $O_2$ at 9 km. |
| | | 53.596 ± 0.155 (2 bands) | Strongest from $O_2$ at 4 km. |
| | | 52.8 | Strongest for surface air. |
| | Window providing surface and moisture information | 89* | Detects convective structures for tropical storms. |
| | | 86-92* | Reference Windows for 118 GHz temperature sounding to adjust for surface emissions (see Rec. ITU-R RS.515). |

TABLE 3 (*end*)

| **Product area name** | **Product area function** | **Passive sensing bands (GHz)** | **Band evaluation** |
|---|---|---|---|
| Atmospheric Temperature (*end*) | Sounding for Atmospheric Temperature | 118.75 | Isolated spectral line used for limb sounding in upper atmosphere. |
| | | 115.25-116<br>116-122.25 | Better horizontal resolution and worse vertical resolution than 50-60 GHz band; effected more by cloud precipitation. |
| | | 148.5-151.5* | Reference window for 118 GHz band<br>(see Rec. ITU-R RS.515). |
| | | 416-434 | Proposed for cirrus cloud measurements; poor penetration and therefore poor lower atmosphere measurement capability; sensitive to clouds<br>Oxygen line at 424-425 GHz. |

The asterisk (*) next to the frequency band indicates that this particular band has an “exclusive passive allocation”.

TABLE 4

## Ocean data products and associated sensing bands

| **Product area name** | **Product area function** | **Passive sensing bands (GHz)** | **Band evaluation** |
|---|---|---|---|
| Ocean Surface Wind Speed OSWS (m/s) | Sea surface parameter | 10.65 | Best for horizontal resolution. |
| | | 31 | Best in correlating the “roughening” of the ocean surface with surface wind speed. |
| | | 37 | Same as above. |
| Sea Ice Concentration SIce (%) | Window can scattering | 19 | Sea surface and sea ice emissivity. |
| | | 23 | Sea surface and sea ice emissivity. Improved resolution over the 19 GHz channel. |
| | | 31 | Sea surface and sea ice emissivity. This measurement is needed for comparison to the 23 GHz to distinguish new ice form multiyear ice. Improvement over 37 GHz channel because it is an exclusively allocated band. |
| | | 37 | Sea surface and sea ice emissivity. |
| | | 50.3* | Sea surface and sea ice emissivity. Reduces impact of non-precipitation clouds. |
| | | 85 | TBD. |
| Sea Surface Temperature SST (°C) | Sounding for sea surface temperature | 6.925 | Best band for SST because nearest to 5.5 GHz peak sensitivity. Provides good horizontal spatial resolution. Only source in cloudy regions. |
| Ocean Salinity | | 1.4* | Ocean circulation patterns<br>The sensitivity of the brightness temperature to ocean salinity (ocean) increases as the observation frequency decreases. L-band (1 400-1 427 MHz) is optimum because the frequency is sufficiently low and the Faraday rotation is still negligible. |

TABLE 4 (*end*)

| Product area name | Product area function | Passive sensing bands (GHz) | Band evaluation |
|---|---|---|---|
| Oceanic Precipitation in mm/hr | Window | 10.7 | Provides more direct rainfall estimates than the 50 GHz bands. Only direct satellite measurements of precipitation. |
| | | 18 | Better frequency for rainfall than 50 GHz band. |
| | | 19.35 | Better frequency for rainfall than 50 GHz band. |
| | Scattering | 37 | Detects liquid hydrometers. |
| | Window | 50.3* | Window for sensing surface, provides large cloud eater vapour and surface radiance contribution, minimizes the effect of water vapour variation on rainfall estimates. |
| | Spectral absorption and emissions from oxygen | 53.74 | Temperature in Troposphere. |
| | | 54.96 | Temperature in upper stratosphere. |
| | | 57.94 | Temperature in lower stratosphere. |
| Water vapour | Water vapour | 23.8 | Primary water vapour channel over oceans. |
| | Window | 31 | |
| | Window | 89 | |

The asterisk (*) next to the frequency band indicates that this particular band has an “exclusive passive allocation”.

TABLE 5

## Land data products and associated sensing bands

| Product area name | Product area function | Passive sensing bands (GHz) | Band evaluation |
|---|---|---|---|
| Snow Cover SNOWC (%) | Sounding | 23.8* | Principal background channel for use with 22 GHz vapour line. |
| | Window | 31.4* | Background reference channel for 23.8 GHz water vapour line, exclusively passive allocation. |
| | | 37.0 | Window channel. |
| | | 85.0 | Window channel at high frequency end. |
| | | 89* | Window channel at high frequency end. |
| Land Surface Temperature STEMP (°C) | Window | 19 | 33% lower emissivity.<br>Perturbation due to surface wetness on brightness temperature. |
| | | 22.3 | Primary band for integrated water vapour content in high content areas. |

TABLE 5 (*end*)

| **Product area name** | **Product area function** | **Passive sensing bands (GHz)** | **Band evaluation** |
|---|---|---|---|
| Land Surface Temperature STEMP (°C) (*end*) | Sounding | 23.8* | Primary/best use for integrated water vapour content in low content areas. |
| | Window | 31.4* | Reference band for 23.8 GHz water vapour measurement. |
| | | 37 | |
| | | 50.3* | |
| | | 85 | |
| Snow Water Equivalent SWE (m) (or inch) | Sounding | 23.8* | Primary/best use for integrated water vapour content in low content areas. |
| | Window | 31.4* | Background reference channel, exclusively passive allocation. |
| Soil moisture SM (%) | Window | 1.4* | The sensitivity of the brightness temperature to soil moisture (ground) increases as the observation frequency decreases. L-band (1 400-1 427 MHz) is optimum because the frequency is sufficiently low and the Faraday rotation is still negligible. |
| | | 18.7 | |
| | | 19 | |
| | | 85 | |
| Land surface emissivity | Window | 23.8* | This band is primarily a window channel over land. |
| | | 31.4* | |
| | | 50.3* | |

The asterisk (*) next to the frequency band indicates that this particular band has an “exclusive passive allocation”.

# Annex C

# Acronyms

| | |
|---|---|
| A/D | Analogue to digital |
| ADD | Agile digital detector |
| AMSR-E | Advanced microwave scanning radiometer-E |
| AMSU | Advanced microwave sounding unit |
| ANC | Ancillary |
| ATMS | Advanced technology microwave sounder |
| CAL | Calibration |

| | |
|---|---|
| CLW | Cloud liquid water |
| CMIS | Conical-scanning microwave imager/sounder |
| DMSP | Defence Meteorological Satellite Program |
| EDR | Environmental data records |
| EESS | Earth exploration-satellite service |
| Envisat | Environmental Satellite is an Earth-observing satellite built by the European Space Agency |
| EOS | Earth observation system |
| FFT | Fast Fourier transforms |
| GOES | Geostationary operational environmental satellite |
| GRACE | Gravity Recovery and Climate Experiment |
| HIRS | High Resolution Infra-red Sounder |
| IASI | Infrared atmospheric sounding instrument |
| IF | Intermediate frequency |
| IFOV | Instantaneous field of view |
| IWP | Ice water path |
| ITU-R | International Telecommunications Union – Radiocommunication Sector |
| Meteosat | Series of geostationary meteorological satellites operated by EUMETSAT |
| METOP | Series of polar orbiting meteorological satellites operated by the European Organisation for the Exploitation of Meteorological Satellites |
| MHS | microwave humidity sounder |
| MIRS | Microwave integrated retrieval system |
| MIS | Microwave imager/sounder |
| NASA | National Aeronautics and Space Administration |
| NCEP | National Centres for Environmental Prediction |
| NOAA | National Oceanic and Atmospheric Administration |
| NPOESS | National polar-orbiting operational environmental satellite system |
| NRL | Naval Research Laboratory |
| OSWS | Ocean surface wind speed |
| PDF | Probability density function |
| POES | Polar-orbiting operational environmental satellite |
| RDR | Raw data records |
| RFI | Radio-frequency interference |
| RI | RFI Index |
| RR | Radio Regulations or Rain Rate |
| SDR | Sensor data records |

| | |
|---|---|
| SIce | Sea Ice concentration |
| SM | Soil Moisture |
| SMOS | Soil moisture and ocean salinity |
| SNOWC | Snow cover |
| SST | Sea surface temperature |
| STEMP | Land surface temperature |
| SWE | Snow water equivalent |
| TDR | Temperature data records |
| TIROS | Television and InfraRed Observation Satellite |
| TOVS | TIROS Operational Vertical Sounder |
| TPW | Total precipitable water |
| TRMM | Tropical Rainfall Measuring Mission is a joint space mission between NASA and the Japan Aerospace Exploration Agency |
| 3D-VAR | Three Dimensional Variational |