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Utilization of the Radiofrequency Spectrum above 1 GHz by Passive Services

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Abstract. Microwave atmospheric radiometry and radio, mm and sub-mm astronomy are "passive" services, i.e. not involved in any man-made transmission but only concerned with the reception of naturally occurring radio waves. The intensity of the radiation received is not subject to human control, unlike the situation for active services. All active services operate in bands occupied by natural signals of atmospheric and cosmic origin and the active service tranmissions may be powerful enough to noticeably interfere with reception of those signals by scientific services. A conflict exists for the coexistence of active and passive services in many frequency bands, which leads to a need for regulating how to share the electromagnetic spectrum. This document gives an overview of the problems of frequency sharing in the longwave region of the electromagnetic spectrum (radio to submillimetre waves).

1. Introduction: General Capabilities of Passive Microwave Atmospheric Radiometry and Radio Astronomy

Passive microwave radiometry is a tool of fundamental importance for the Earth Exploration-Satellite Service (EESS). The EESS operates passive sensors that are designed to receive and to measure natural emissions produced by the Earth's surface and its atmosphere. The frequency and the strength of these natural emissions characterize the type and the status of a number of important geophysical, atmospheric and surface parameters (land, sea, and ice-caps), which describe the status of the Earth/Atmosphere/Oceans System, and its mechanisms :

1. Earth surface parameters such as soil moisture, sea surface temperature, ocean wind stress, ice extension and age, snow cover, rainfall over land, etc.;

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2. Three-dimensional atmospheric parameters (low, medium and upper atmosphere) such as temperature profiles, water vapour content and concentration profiles of radiatively and chemically important trace gases (for instance O_3, SO_2 and ClO).

Microwave observation techniques below 100 GHz allow us to study the Earth's surface and its atmosphere from space-borne instruments even in the presence of clouds, because the clouds are almost transparent at these frequencies. This "all-weather" capability has considerable interest for the EESS, because more than 60% of the surface of our planet is overcast with clouds. Passive microwave sensing is an important tool widely used for meteorological, climatological and environmental monitoring and survey (operational and scientific applications), for which reliable repetitive global coverage is mandatory.

Observation of the longwave electromagnetic spectrum is also extremely important for the understanding of our universe. Whereas "optical astronomy" detects the radiation from hot objects such as stars, radio waves in the universe often come from cooler objects, such as interstellar gas or electrons in ordered motion in a magnetic field. Radio waves thus open our knowledge of the Universe to a series of physical phenomena that optical waves alone would never reveal.

The spectrum of cosmic radio waves consists of a broad continuum covering the whole range of frequencies that can penetrate the Earth's atmosphere and a large number of spectral lines (atomic and molecular resonances), each of which is confined to a more or less narrow frequency range. The fact that some of these lines are keys for studying our universe (21-cm neutral hydrogen line, carbon monoxide rotational resonances, the lines of the OH radical) makes the protection of their frequencies highly important.

2. Spectrum Requirements

2.1. EESS Requirements

Several parameters may generally contribute, at varying levels, to the natural emission which can be observed at a given frequency. Therefore, measurements at several frequencies in the longwave spectrum must be (quasi)simultaneously implemented, in order to isolate and to retrieve each individual contribution. This is true for both geophysical and astrophysical measurements, although the required degree of simultaneity in recording the information can be very different.

The absorption characteristics of the atmosphere, shown in Figure 1 (Pardo et al, 2001), are characterized by absorption peaks due to rotational resonances of atmospheric molecules (of which H_2O and O_2 are the most important), "dry"continuum-like absorption (collision-induced absorption involving O_2 and N_2) and water vapour continuum-like absorption (far wings of IR lines most probably).

The selection of the frequencies best suited for passive microwave sensing depends closely on the characteristics of the absorption:

- Frequencies for observation of surface parameters are selected below 100 GHz, where atmospheric absorption is the weakest. One frequency band per octave, on average, is necessary.

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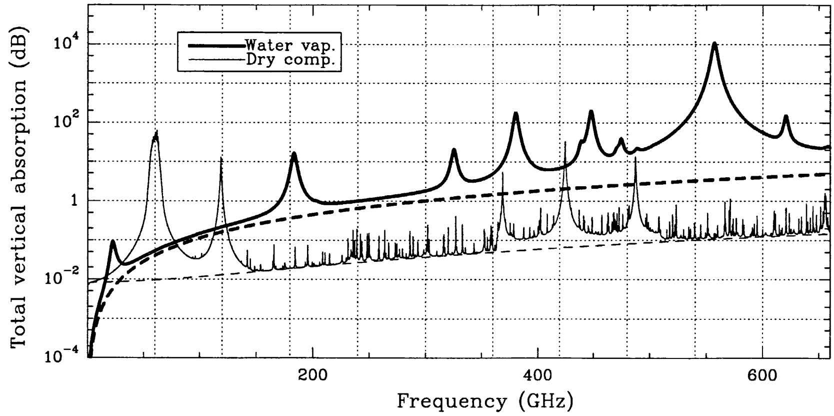

Figure 1. Spectrum of the atmospheric absorption. The dashed lines represent the contributions of the collision-induced "dry" absorption and the water vapour pseudocontinuum (water opacity not related to lines below 10 THz).

- Frequencies for observation of atmospheric parameters are very carefully selected mostly above 50 GHz within, and in the vicinity of, the absorption peaks of atmospheric gases.

The frequencies and bandwidths required for Earth remote sensing up to 200 GHz are listed in the Table 1. Most frequency allocations above 200 GHz contain absorption lines of important atmospheric trace species but have been in general much less used to date.

2.2. Radio Astronomy Requirements

The electromagnetic radiation detected in radio astronomy is either emission from atoms or molecules at very specific frequencies (line emission), or very broadband thermal or non-thermal radiation (continuum emission). In both cases the polarization characteristics of the signal are also important as an indicator of the physical conditions of the emitting object. Thus, the following requirements are essential for radio astronomical research:

- Good frequency coverage.
- High spectral resolution.
- High spatial resolution.
- High time resolution.

Table 2 provides information on some of the main targets of radio astronomy at frequencies between 1 and 200 GHz. We stress in bold the extremely important bands.

Table 1. Frequency bands and bandwidths used for satellite passive sensing of the atmosphere below 200 GHz

Frequency (GHz)	Necessary BW (MHz)	Main measurements
Near 1.4	100	Soil moisture, salinity, sea temperature, vegetation index
Near 2.7	60	Salinity, soil moisture
4.2-4.4	200	Ocean surface temperature (back-up for 6.9 GHz, with reduced performance)
6.7-7.1	400	Ocean surface temperature
10.6-10.7	100	Rain, snow, ice, sea state, ocean wind
15.35-15.4	200	Water vapour, rain
18.6-18.8	200	Rain, sea state, ocean ice, water vapour
23.6-24	400	Water vapour, liquid water
31.3-31.8	500	Window channel associated with temp. measurements
36.5-37	500	Rain, snow, ocean ice, water vapour
50.2-50.4	200	O_2 (Temperature profiling, magnetic field)
52.6-59.3	6700 (1)	O_2 (Temperature profiling, magnetic field)
86-92	6000	Clouds, oil spills, ice, snow
100-102	2000	N_2O
109.8-111.8	2000	O_3
115.25-122.25	7000 (1)	O_2 (Temperature profiling, magnetic field), CO
174.8-191.8	17000 (1)	H_2O (Mcisture profiling), N_2O, O_3

Table 2. Current and requested radio astronomy frequency allocations which are shared with active services.

Frequency Band	Main measurements
1330-1400 MHz	Doppler-shifted radiation from hydrogen
1400-1427 MHz	**21-cm line of neutral atomic hydrogen**
1610.6-1613.8 MHz	**Important OH line**
1660-1670	OH lines and continuum
1718.8-1722.2 MHz	Study of the OH radical
2655.0-2690.0	Continuum emission of radio sources
3100.0-3400.0 MHz	Lines of CH
4800.0-4990.0 MHz	Interstellar ionized H clouds and supernova remnants
10-15 GHz	Non-thermal synchrotron sources
22.01-22.21 GHz	Red-shifted H_2O
22.21-22.5 GHz	**H_2O line (accessible from the ground)**
22.81-22.86 GHz	Studies of non-metastable ammonia and methyl formate
23.07-24.0 GHz	Ammonia lines
31.5-31.8 GHz	Continuum band
36.43-36.5 GHz	HC_3N and OH lines
42.5-50.2 GHz	Two important diatomic molecules: SiO and CS
86.0-95.0 GHz	Continuum and various lines
95.0-100.0 GHz	J=2-1 CS line
105.0-116.0 GHz	**Carbon monoxide and its isotopes**
121.0-182.0 GHz	Continuum and various lines
182.0-185.0 GHz	**Important water vapour line**
185.0-200.0 GHz	Various lines

3. Performance Parameters and Constraints

Passive sensors are characterized by their radiometric sensitivity and their spectral and geometric resolutions.

3.1. Radiometer Sensitivity

This parameter is generally expressed as the smallest temperature differential, ΔT_e, that the sensor is able to detect (σ level). ΔT_e is is given by:

$$\Delta T_e = \frac{\alpha T_s}{\sqrt{B\tau}} \quad \text{(K)} \tag{1}$$

where:

- B = receiver bandwidth (Hz);
- τ = integration time (s);
- α = receiver system constant (depends on the configuration);
- T_s = receiver system noise temperature (K).

The radiometer threshold ΔP is the smallest power change that the passive sensor is able to detect. ΔP is given by :

$$\Delta P = \Delta T_e B \quad \text{(W)} \tag{2}$$

where $k = 1.38\times10^{-23}$ (J/K) is Boltzmann's constant.

3.2. Geometrical Resolution

In case of two-dimensional measurements of surface parameters (see Section 4), it is generally considered that the transverse resolution is determined by the -3 dB point of the antenna pattern projected onto the ground. In case of three-dimensional measurements of atmospheric parameters (see Section 5), the longitudinal resolution along the antenna axis is also to be considered. This longitudinal resolution is a complex function (generally known as a weighting function) of the frequency-dependent characteristics of the atmosphere and the receiver performance characteristics (noise and bandwidth).

3.3. Integration Time

The integration time is also an important parameter which results from a complex trade-off taking into account in particular the desired geometrical resolution, the scanning configuration of the sensor and its velocity with respect to the scene observed.

3.4. Frequency Coverage and Spectral Resolution

Some sensors carry out a contiguous spectroscopic coverage along the line profile. Their total coverage $\Delta\nu$ and frequency resolution $\delta\nu$ determine the range of pressures that is covered.

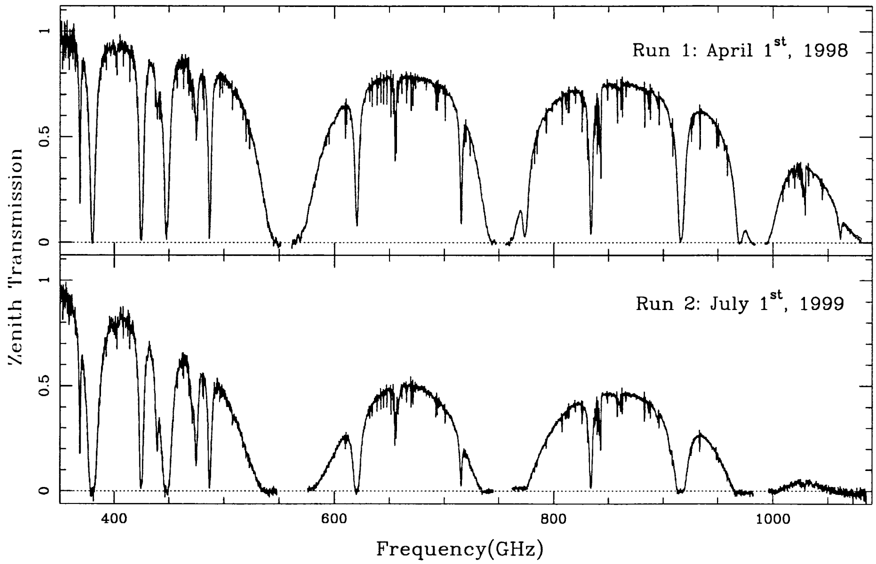

Figure 2. Fourier Transform Spectroscopy measurements of the atmospheric transmission at Mauna Kea (Hawaii), 4100 m above sea level, showing outstanding conditions for submillimetre-wave astronomy. Data from Pardo et al. (2001).

4. Typical Operating Conditions of Passive Sensors

Passive sensors can be ground-based or space-borne, the first type being dominant nowadays for radio astronomy and the second for the EESS.

The evolution of radio astronomy towards the submillimetre domain has required high and dry sites in order to allow for an at least partially transparent at such wavelengths. Figure 2 shows the measured atmospheric spectrum at one such submillimetre site.

Satellite-borne facilities are deployed essentially on two complementary types of satellite system:

- Low altitude (polar) orbiting satellites.

  Passive radiometers operating at frequencies below 100 GHz are currently flown only on low-orbiting satellites. This is essentially due to the difficulty of obtaining adequate geometric resolution at relatively low frequencies, which may change in the future. Those systems, based on satellites in low sun-synchronous polar orbits, are used to acquire high resolution environmental data on a global scale. The repeat rate of measurements is limited by the orbital characteristics and only a maximum of two global coverages can be obtained daily, with a single satellite.

- Geostationary satellites.

Systems involving satellites in geostationary orbits are used to gather low- to medium-resolution data on a regional scale. The repeat rate of measurements is limited only by hardware technology and is typically one regional coverage every 30 minutes or less.

5. Interference Criteria and Recommendations

Passive sensors integrate all natural (wanted) and man-made (unwanted) emissions. They cannot, in general, differentiate between these two kinds of signals because the atmosphere is a highly unstable medium with fast changing characteristics, spatially and temporally. The sensors are therefore extremely vulnerable to interference which may have extremely detrimental consequences:

- It was demonstrated that as few as 0.1 % of contaminated satellite data could be sufficient to generate unacceptable errors in Numerical Weather Prediction forecasts, thus destroying confidence in these unique all-weather passive measurements.
- The systematic deletion of data where interference is likely to occur may prevent recognition of new developing weather systems and vital indications of rapidly developing potentially dangerous storms or other phenomena may be missed.
- For climatological studies and particularly "global climate change" monitoring, interference may lead to mis-interpretation of climate signals.
- If the exclusive use for the Radio Astronomy Service of key bands of the electromagnetic spectrum is not guaranteed, our studies of the Universe will suffer to the extent of preventing understanding of some of its basic physical processes.

In those frequency bands shared by active services and passive EESS, it is necessary to establish recommendations on the maximum accepted interference level. The International Telecommunication Union has given the following such recommendations:

1. For EESS performing surface measurements, the typical accepted interference level is around -163 dBW for a reference bandwidth of 100 MHz (spectral region from 1.4 to 90 GHz). The limits can be exceeded by less than 5% of all measurement cells within a sensor's service area in the case of a random loss and by less than 1% of measurement cells in the case of a systematic loss.
2. In the 50 - 66 GHz frequency band, the required radiometric resolutions are 0.3 K and 0.1 K for scanning sensors and for push-broom sensors respectively. The resulting interference thresholds are -161 dBW for a scanning sensor and -166 dBW for a push-broom sensor, in a reference bandwidth of 100 MHz. These levels are equivalent to brightness temperature increases of 0.06 K and 0.02 K respectively and can be considered as a normal contribution to the error budget of the instrument.

3. Above 100 GHz the required radiometric resolution is currently 0.2 K at all frequencies, leading to an interference threshold of -160 dBW in a reference bandwidth of 200 MHz. However, these figures need to be revised in light of the most recent achievements in atmospheric sciences.

The interference criterion applicable to all three-dimensional measurements in the atmosphere is the following (from an ITU recommendation): "The interference levels given above can be exceeded for less than 0.01% of the pixels in the sensor's service area for three-dimensional measurements of atmospheric temperature or gas concentration in the absorption bands including those in the range 50.2-59.3 GHz and bands near 118 GHz and 183 GHz."

In addition to these quantitative recommendations established by the ITU for the EESS, the Committee on Radio Astronomy Frequencies has given other general recommendations:

- To define in the ITU Radio Regulations the term "level of harmful interference to radio astronomy".
- To adopt a definition of a passive service in the ITU Radio Regulations.
- Improve current definitions to make passive frequency use better understood.
- To improve communication/contact between the radio astronomical bodies and administrations on the one hand and "industry" on the other hand.
- To pay attention in frequency allocation procedures that existing passive bands should not be touched.
- To avoid that "passive" bands should be shared with "active" services.
- To create more "Primary exclusive Passive" bands.

6. Future Developments that will need Protection

Technical advances during the past years have opened the doors for the access of passive services to the submillimetre domain of the electromagnetic spectrum. In fact, the technical improvements to allow access to this frequency region (ν >300 GHz) have been the results of efforts by the passive services. As a result, practically no active service operates today in those bands, but their protection should now be secured to ensure the quality of future research.

Here we provide a list of the most significant passive submillimetre projects that will operate in the coming years.

6.1. EESS Submillimetre-Wave Projects

- **Microwave Limb Sounder** (EOS - MLS) NASA/JPL, with various channels from 118 GHz to 640 GHz, with possibly other channels at 1.23 and 2.5 THz.

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- **ODIN** (Swedish Space Corporation), with various channels from 118 GHz to 576 GHz. This satellite will also perform passive astronomical observations in the same bands.

- **Sub-mm Observation of Processes in the Atmosphere Noteworthy for Ozone** (SOPRANO) - ESA. The submm bands of this instrument will range from 497 to 955 GHz.

- **Millimetre-wave Acquisitions for Stratosphere-Troposphere Exchanges Research** (MASTER) - ESA, with mm and submm bands from 199 to 505 GHz.

6.2. Submillimetre-Wave Astronomy Projects

- **Far InfraRed and Submillimetre Telescope** (FIRST), will perform photometry and spectroscopy in the 60-670 μm range. It will have a radiatively-cooled telescope and carry a science payload complement of three instruments housed inside a superfluid helium cryostat. It is hoped that FIRST will be operated as an observatory for a minimum of three years following launch and transit into an orbit around the Lagrangian point L2 in the year 2007.

- **Atacama Large Millimetre Array** (ALMA), will be a 64-element interferometer (12-m antennas) located at an elevation of 5300 m in Llano de Chajnantor (Chile) that will image the Universe at frequencies in all atmospheric windows between 10 mm and 350 μm.

- **Stratospheric Observatory for Infrared Astronomy** (SOFIA), will be a Boeing 747SP aircraft modified to accommodate a 2.5-m reflecting telescope. It will be the largest airborne telescope in the world. It is expected to carry submillimetre receivers as well as infrared instruments.

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