10. PASSIVE MICROWAVE SENSING

10.1 Concepts of Microwave Radiometry

A microwave radiometer is a passive sensor that simply measures electromagnetic energy radiated towards it from some target or area. As a passive sensor, it is related more to the classical optical and IR sensors than to radar, its companion active microwave sensor. The energy detected by a radiometer at microwave frequencies is the thermal emission from the target itself as well as thermal emission from the sky that arrives at the radiometer after reflection from the target. The thermal emission depends on the product of the target's absolute temperature and its emissivity, but at microwave frequencies (in contrast to the thermal infrared) it is the change in emissivity rather than the change in temperature that produces most of the significant differences between the various targets. The intervening atmosphere between the target and the radiometer can have an adverse effect on the measurement by attenuating the desired target signal and contributing unwanted thermal radiated energy due to its own temperature and emissivity.

The microwave portion of the electromagnetic spectrum includes wavelengths from 0.1 mm to more than 1 m. It is more common to refer to microwave radiation in terms of frequency, f, rather than wavelength, λ. Recall that $c = \lambda f$ where c is the speed of light. In frequency then, the microwave range is from 300 GHz to 0.3 GHz. Most radiometers operate in the range from 0.4-35 GHz (0.8-75 cm). Atmospheric attenuation of microwave radiation is primarily through absorption by H_20 and O_2 and absorption is strongest at the shortest wavelength. Attenuation is very low for $\lambda > 3$ cm ($f < 10$ GHz). In general μwave radiation is not greatly influenced by cloud or fog, especially for $\lambda > 3$ cm.

Microwave sensing can be done day or night, in essentially any weather, particularly when operated at frequencies less than 10 to 15 GHz. Note also that the atmosphere is essentially opaque for $f > 300$ GHz ($\lambda < 1$ mm).

10.2 Brightness temperature

The main parameter of interest being measured in microwave radiometry is the radiometric temperature or <u>brightness temperature</u> of the source. The brightness temperature of an object is the temperature of a blackbody with the same brightness (i.e., the same radiance.) The most widely accepted terminology converts radiation received to an equivalent radiometric (brightness) temperature in degrees Kelvin.

The maximum possible radiation that a body can emit at any given temperature, T, and wavelength, λ, is described by Planck's Equation (see Chap. 3 of the monograph):

$$M_\lambda = \frac{2\pi hc^2}{\lambda^5\left[\exp\left(\frac{hc}{\lambda kT}\right)-1\right]} \tag{10.1}$$

Using the Taylor series expansion we have:

$$\exp\left(\frac{c}{\lambda T}\right) = 1 + \frac{hc}{\lambda kT} + \frac{1}{2!}\left[\frac{hc}{\lambda kT}\right]^2 + \frac{1}{3!}\left[\frac{hc}{\lambda kT}\right]^3 + \cdots \tag{10.2}$$

In the microwave region, since $\lambda T >> hc/k$, then $\exp(hc/\lambda kT) - 1 \approx hc/\lambda kT$. With this approximation (the Rayleigh-Jeans approximation), the emittance of the body is given by:

$$M_\lambda = \left(\frac{2\pi ck}{\lambda^4}\right)T \tag{10.3}$$

where k is Boltzmann's constant. Thus, in the microwave region the radiation received from an object is <u>directly proportional to T</u>. For real sources, then:

$$M_\lambda = \varepsilon M_{bb\lambda} = (2\pi ck/\lambda^4)\varepsilon T \tag{10.4}$$

There is then a relatively small linear temperature dependence compared with the fourth power of temperature dependence found in IR regions. Clearly, microwave radiation is much more sensitive to emissivity variations than is thermal infrared, and most of the observed variability will be due to differences in emissivity. The radiometric temperature of objects at the earth's surface is called the <u>brightness temperature</u>, and is related to the true or thermometric temperature as:

$$T_B = \varepsilon T \tag{10.5}$$

In the microwave region materials have large variations in emissivity, ε, i. e., their ability to emit radiation. These may vary form 0.41 for liquid water to almost 1.0 for ice; thus for a water surface with ice floating in it, the water appears very cold and the ice very warm. Other materials have different emissivities, generally between these two figures.

One of the major limitations of a microwave radiometer is its relatively crude resolution. The resolution is partially a consequence of the antenna characteristics which will be dealt with in a later section. The instrument resolution is also limited by its sensitivity. The thermal radiation from a body of temperature T is not as great in the microwave as in the IR region. The microwave radiometer itself is also less sensitive.

10.3 Influence of the atmosphere and active sources

10.3.1 Observed brightness temperature from a reflecting surface.

A μ-wave radiometric sensor (radiometer or scanning radiometer) is a temperature measuring device; its output is calibrated in °K. For a microwave sensor near a target, the observed brightness temperature, T_B, is the sum of radiation received directly from the target source, plus the sky radiation reflected by the source (Figure 10.1).

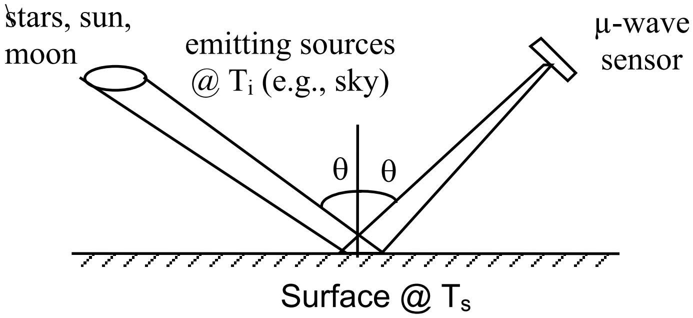


Figure 10.1: A microwave sensor sees emission from the target as well as from reflected skylight.

If the surface of an object is very smooth it can also reflect radiation from the sky and from space. Thus smooth water will reflect the sky temperature and the remotely observed temperature will depend on the reflected energy of the surface and on the polarization of the radiation as well as on the temperature and emissivity. Water, if it is smooth, will reflect the very low sky temperature. However, if it is choppy the reflectivity and emissivity are changed and the apparent temperature can increase considerably. That is, for an opaque surface,

$$T_B = \varepsilon T_s + \rho T_i(\theta_i) = \varepsilon T_s + (1-\varepsilon)T_i(\theta_i) \qquad (10.6)$$

- The observed brightness of objects with high ε ($\varepsilon \approx 1$) is little influenced by other sources of moderate brightness temperature.
- The observed brightness of objects with high reflectivity (low ε) is much affected by the background radiation.
- Natural materials may have relatively low emissivities in the μ-wave region.

  (c.f.) in the infrared, $\varepsilon = 0.8$ to $0.9+$; in the μ-wave, $\varepsilon = 0.6$ to 0.9

$\varepsilon_{\mu w}$ for water	$\varepsilon < 0.5$;	ice	$\varepsilon \approx 1$;
ocean	$\varepsilon \approx 0.4$;	earth	$\varepsilon > 0.85$

- Emissivity is a function of angle of incidence (θ) and azimuth (φ), as well as polarization: $\varepsilon_v(\theta,\varphi)$ or $\varepsilon_H(\theta,\varphi)$. It is generally found that as the angle increase a drop in apparent temperature is due principally to the non-Lambertian quality of the emitter. In some cases, however, a rise in apparent temperature is found as the angle is increased. Another effect is the polarization of the radiation detected. It has been found that significant differences exist in emission when observed in vertical and horizontal polarization. Note: Blackbody radiation is randomly polarized -- radiation from real bodies may not be.
- Emissivities are determined by surface properties (roughness) and, to some extent, by subsurface properties (dielectric coefficient or, more properly, "complex dielectric coefficient").
- Note that dielectric properties vary with θ, water content, salinity, etc.
- If the reflecting surface is rough compared to λ – i.e., a partially diffuse surface – then interference (external) sources at other incidence angles may contribute to brightness observed; ρ will also vary.
- T_B varies with observation angle, wavelength (λ) and polarization.

10.3.2 Brightness observed through an absorbing medium (atmosphere)

One remaining factor in microwave radiometry, as in all airborne or satellite sensors, is atmospheric absorption, re-emission, and scattering. For wavelengths longer than 3 cm the air is quite clear; however, shorter than this there is significant absorption by H_2O and O_2 components. Such gases also re-emit radiation at similar frequencies thus making interpretation even more difficult. This fact can, however, be used to advantage if it is the component of the atmosphere that the observer wishes to see. As in the case of radar, the spatial resolution of the microwave radiometer depends on the wavelength of the radiation and the size of the antenna. Thus, for fine spatial resolution a large antenna and a high frequency are desirable; however, if the frequency is too high, atmospheric absorption becomes excessive, The antenna also must be sufficiently small to be carried in an aircraft. Matters are further complicated since in order to obtain sufficient signals for processing there is a lower limit to how small the beamwidth can be made.

- Atmospheric transmittance = τ
  $\alpha + \rho + \tau = 1$
- atmospheric absorptance:
  $\alpha = (1 - \tau) = \varepsilon$ if $\rho = 0$
  [in μ-wave, $\rho \approx 0$]
- for thermal equilibrium, $\alpha T_a = \varepsilon T_a$

$$T_B = \underbrace{\tau(\varepsilon T_s)}_{\substack{\text{attenuated}\\ \text{brightness}\\ \text{temperature}\\ \text{of the surface}}} + \underbrace{(1-\tau)T_a}_{\substack{\text{energy absorbed}\\ \text{and reradiated}\\ \text{by the medium}\\ \text{in theoptical path}}}$$

Figure 10.2: Brightness observed through an absorbing medium.

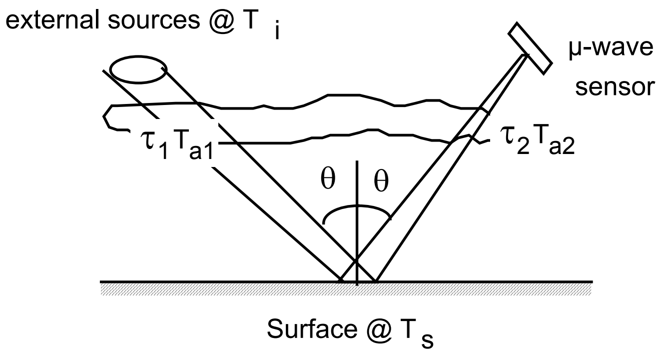


Figure 10.3: Combined influence of active (external) sources and atmosphere

T_i = brightness temperature from external sources.
τ_1 = transmittance of the whole atmosphere in direction θ.
τ_2 = transmittance of atmosphere between surface and sensor.
T_{a1} = mean temperature of whole atmosphere.
T_{a2} = mean temperature of atmosphere between surface and sensor.

Observed brightness temperature:

$$T_B = \{ [\underbrace{T_i \tau_i}_{\substack{\text{External energy}\\ \text{which is not absorbed,}\\ \text{i.e., it reaches the}\\ \text{earth's surface}\\ \text{at temperature } T_i}} + \underbrace{(1 - \tau_i)T_{a1}}_{\substack{\text{External energy}\\ \text{which is absorbed}\\ \text{and re-emitted by}\\ \text{the atmosphere}\\ \text{at temperature } T_{a1}}}] \rho + \underbrace{\varepsilon T_s}_{\substack{\text{Energy}\\ \text{emitted}\\ \text{by the}\\ \text{surface at}\\ \text{temp. } T_s}} \} \tau_s + \underbrace{(1+\tau_i)}_{\substack{\text{Energy absorbed}\\ \text{and re-radiated by}\\ \text{the atmosphere}\\ \text{at temperature } T_{a2}}} T_{a2} \quad \mathbf{(10.7)}$$

10.3.3 Summary

The radiation collected appears as a noise level at the detector and for recording purposes is generally read out as equivalent temperature, that is the temperature of a blackbody source which would produce the same amount of noise in the bandwidth of the system. The equivalent temperature is determined by comparing the level at the antenna with that of a reference resistance held at a constant temperature. Comparison is carried out by rapidly switching from one to the other and measuring signal difference; thus the change in antenna equivalent temperature is recorded.

This equivalent temperature which is recorded is not equal to the temperature of the area observed. Since it is a passive system a large number of factors contribute to the radiation levels thus complicating interpretation. Some of these factors are:

1. actual temperature of sources.
2. emissivities (function of surface, subsurface, dielectric properties, etc.)
3. observation angle and direction (also angle of incident radiation.
4. wavelength, λ (or frequency, f)
5. polarization (blackbody radiation is randomly polarized; consider object & reflected)
6. external sources, atmospheric interactions, sky reflections, etc.
7. noise from the radiometer itself.

10.4 Sensors/radiometric measurement

The detector for microwave radiation is an antenna. The apparent temperature observed at the antenna -- the antenna temperature -- is related to the brightness temperature, T_B, by:

$$T_A = \int_{\Delta\lambda}\int_{\Omega} T_B \, G \, d\Omega \, d\lambda \qquad (10.8)$$

where Ω is the IFOV of the system and G is the antenna gain. This equation basically states that the apparent temperature at the antenna is a function of the viewing angle (**beamwidth**) and wavelength range (**bandwidth**) of the antenna.

The beamwidth is defined as the angular interval over which the antenna's power pattern exceeds one-half of its maximum value ("half-power" beamwidth). A typical microwave radiometer has a pencil-beam antenna with high sensitivity within a small solid angle. The sensitivity of the antenna is highly directional and provides the angular (or spatial) resolution of the system.

Antennas, like lenses, are diffraction limited. As such, the angular resolution of the antenna will be on the order of λ/d, where d is the antenna's diameter. However, where the λ/d ratio is on the order of 10^{-5}, the ratio in the microwave is on the order of 10^{-1} and the diffraction effects are much more significant. In the optical domain, diffraction effects can be seen if a plane wave is incident on a narrow slit (Figure 10.4). The resulting intensity (diffraction) pattern on a screen parallel to the slit plate is a diffraction pattern – evidence of the wave nature of light. As the slit width increases the side lobes decrease in amplitude and occur closer to the center lobe. In an optical system this corresponds to an increase in the angular resolution as the diameter of the lense (or aperture) increases.

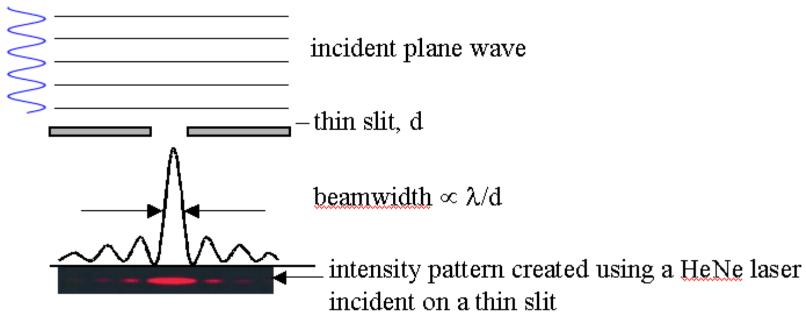


Figure 10.4: Single thin slit diffraction pattern.

In microwave systems, where the aperture size is on the same order as the wavelength being sensed, the magnitude of the side lobes is frequently significant and troublesome (Figure 10.5). Part of the design criterion for antennae is the minimization of the side lobes, particularly when a highly directional beam is needed.

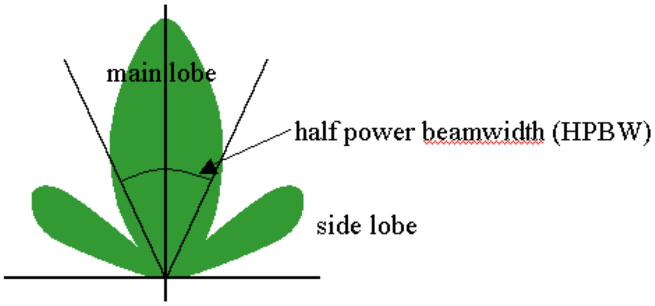


Figure 10.5: Typical antenna power pattern in polar coordinates.

Temperature sensitivity can be increased merely by integrating the signal over the long periods of time. This is a great advantage for ground-based systems; however, for aircraft systems the dwell time cannot be long. As a result, integration times in aircraft radiometers are generally kept below one second. Nevertheless, very good temperature sensitivity can be obtained with these systems and the problem remains one of interpretation of results.

Although the passive system has many difficulties in interpretation that can be eliminated in the active systems, it does have an advantage over them in its size and power requirements since it does not require transmitting equipment. It also promises to produce a good deal of information which is not available to active systems since it does measure emissions from the targets rather than scattered radiation.

10.5 Antennas

10.5.1 Simple dipole antennas

Since the antenna is the critical detection device for both passive and active (radar) systems, it is worth spending some effort learning a few basics of antenna design. To begin, consider a simple dipole antenna. Although this is probably the simplest of all antennas, it forms the core of many more sophisticated antennas. This is the type of antenna commonly used for a car radio and for FM radio. The dipole is so named because it has two electrical poles, not two physical poles (it also has two zeros and could have been called a di-zero antenna). When the length is such that the poles are at ends of the conductor and the zeros are at the center, the antenna will be exactly 1/2 wavelength long and will be an efficient radiator

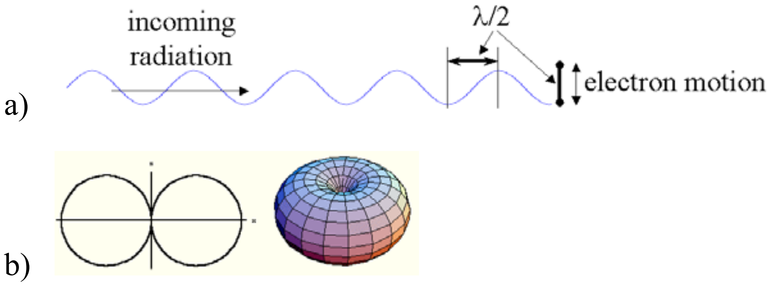
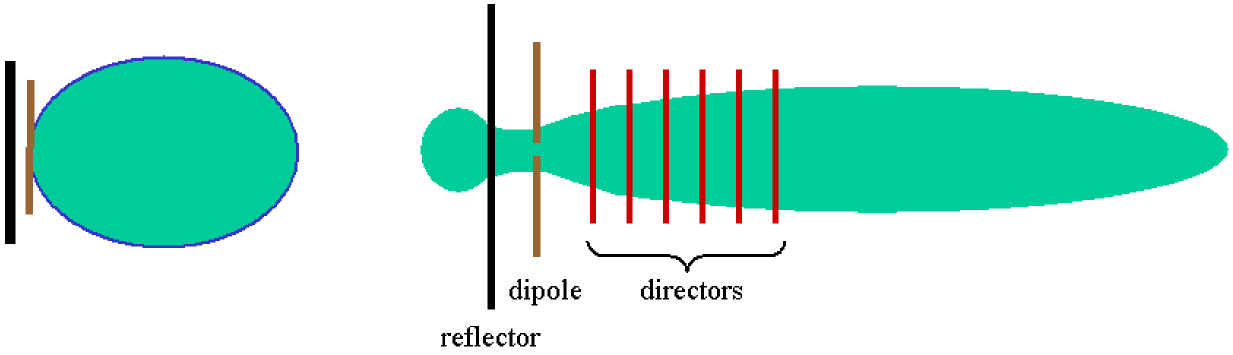


Figure 10.6: Simple dipole antenna. The optimal size of the antenna is λ/2.

A dipole can be fed anywhere along its length, however center fed (your FM radio antenna) and end fed (your car antenna) are the most common. When fed at the center, it presents a pure resistive, balanced resistance to the feed line. If the antenna is oriented vertically, then vertically polarized radiation from all (2π) directions in the horizontal plane will induce a current in the antenna (Figure 10.6a). The corresponding directional sensitivity of the dipole antenna is shown in Figure 10.6b. The antenna's directionality is related to its polarization. It will not respond to radiation arriving along the axis of the antenna and will respond most effectively to vertically polarized radiation incident at 90° from the antenna axis. This polarization sensitivity is characteristic of all microwave system since polarization is an inherent property of the microwave detector.

A simple dipole antenna has many uses, but remote sensing is not one of them. For remote sensing from aircraft and satellite (as well as for many other purposes) it is essential to be able to select the direction from which the radiation is coming. The simplest way to improve the directionality of the antenna is to place a reflector behind the primary antenna (Figure 10.7a). A reflector is often a flat, perforated plate. It will essentially limit the sensitivity of the detector to one hemisphere. A similar idea is to add passive elements in front of the antenna (directors). Directors alter the directivity of the antenna so that the gain is improved in front of the dipole. Most antannas have more than one director, and the more directors the antenna has the smaller the beamwidth.



a. b.

Figure 10.7: Directional response of dipole antennas with passive focusing elements.

a. Dipole antenna with a reflector.
b. Dipole antenna with a directors and a reflector.

10.5.2 Parabolic dish antennas

Taking the idea of the reflector one step farther, one may put the dipole antenna at the focus of a parabolic dish (Figure 10.8a). In this case, the larger the antenna, the more narrow the major lobe will be, and the beamwidth will be ~ λ/d where d is the diameter of the dish. Note that the antenna is still only sensitive to radiation polarized along the axis of the dipole antenna at the focus.

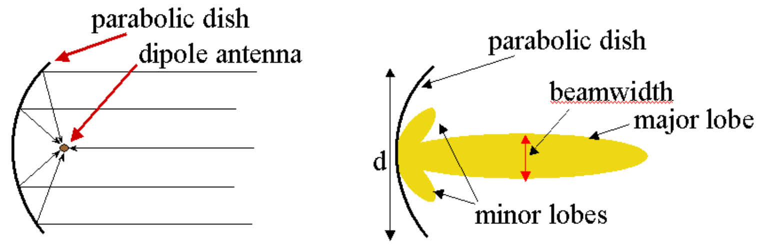


Figure 10.8: Dish antenna with a dipole receiver.
a. Receiving geometry of the dish antenna.
b. Directional response of the dish antenna.

10.5.3 Phased array antennas

Whenever two or more simple antenna elements (e.g. dipoles) are brought together and driven from a source of power at the same frequency, the resulting antenna pattern becomes more complex due to interference between the signals detected separately from each of the individual elements. At some points, this interference may be **constructive** causing the transmitted signal to be increased. At other points, the interference may be **destructive** causing a decrease or even a cancellation of transmitted energy in that direction.

Focusing improves with the addition of more antenna elements. For example, four dipole antennas placed near each other and monitored by a receiver set to receive in-phase signals results in a narrower pattern than that for the 2-dipole case (Figure 10.9a). Of course, **sidelobes** also appear in the total antenna pattern. These are a characteristic, undesirable feature of most complex antenna arrays. It is theoretically possible to suppress sidelobes completely in an array of antenna elements if the excitation of each element is controllable. The process of shaping the antenna pattern so as to eliminate sidelobes is called ***tapering***. Eliminating sidelobes results in less total gain at the pattern maximum, however, and it yields a broader main lobe.

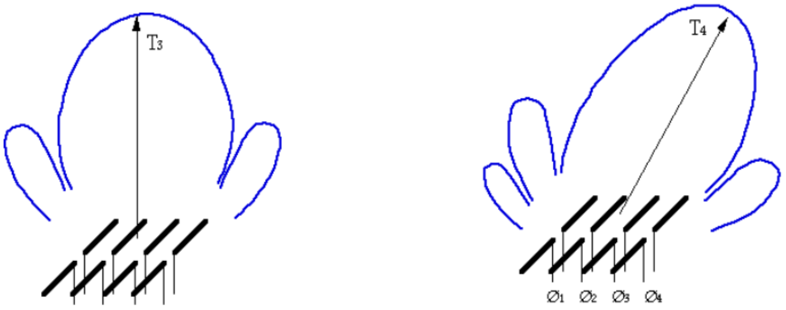


Figure 10.9: Phased array antennas are used for focusing and pointing the antenna. [Adapted from: http://www.haarp.alaska.edu/haarp/ant3.html]
a. 4-element phased array with all antenna elements in phase.
b. 4-element phased array with a phase shift between the antenna elements.

The angle at which the pattern maximum occurs can be changed by adjusting the ***phase*** of the signals received from each of the antenna elements. With all elements in-phase, the pattern maximum will occur perpendicular to the front of the array. By adjusting the relative phase, the peak of the main lobe can be shifted (or steered) to a new angle relative to the array face (T4 in Figure 10.9b). In general, the maximum signal strength at the new pointing angle is close to but less than the perpendicular case.

When the pattern is steered to a new direction, the shape and direction of any sidelobes that may have originally been present changes. If the pattern is steered too far relative to the element spacing, a new lobe (called a *grating lobe*) will appear with a peak in its pattern nearly equal to the main lobe. The point where this occurs is the maximum useful steering angle.

10.5.4 The RA-2 Microwave Radiometer (MWR)

The RA-2 Microwave Radiometer (MWR) is one of the instruments being flown on Envisat (Launched March, 2002). The main objective of the MWR is the measurement of the integrated atmospheric water vapour column and cloud liquid water content to provide correction terms for the radar altimeter also flying on Envisat. In addition, MWR measurement data are useful for the determination of surface emissivity and soil moisture over land, for surface energy budget investigations to support atmospheric studies, and for ice characterization.

Operating Frequencies	23.8 GHz, 36.5 GHz
Bandwidth	650 MHz
Dynamic Range	3 - 300 K
Abs. Radiom. Accuracy	< 3 K
Radiometric Sensitivity	< 0.5 K
Operation	Continuous
Data Rate	16.7 kbps
Mass	25 kg
Power	23 W

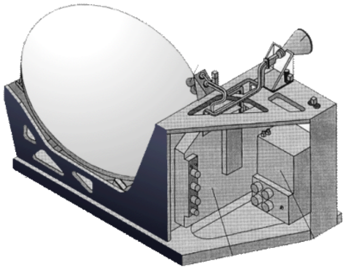
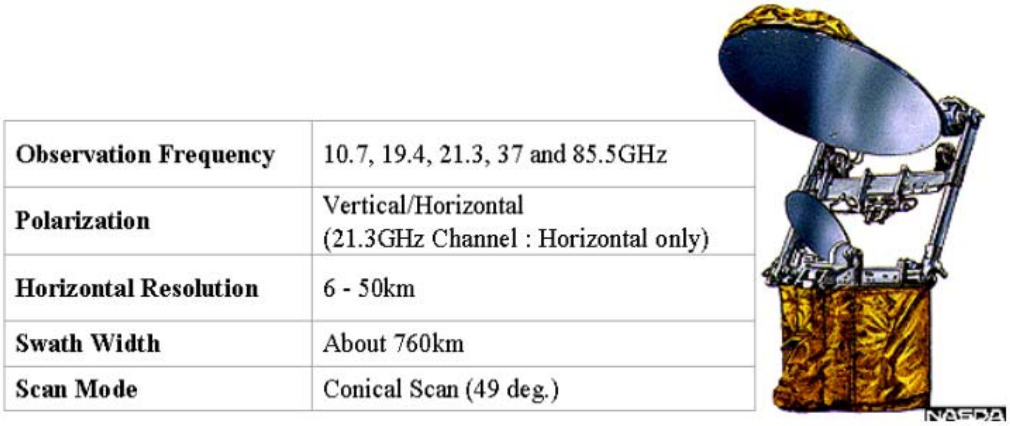


Figure 10.10:

10.5.5 Tropical Rainfall Measurement Mission (TRMM)Microwave Imager(TMI)

The TMI is a multi-channel/dual-polarized microwave radiometer which provides data related to rainfall rates over the oceans. The TMI data are intended to be used together with the Precipitation Radar (also flown on TRMM).



Observation Frequency	10.7, 19.4, 21.3, 37 and 85.5GHz
Polarization	Vertical/Horizontal (21.3GHz Channel : Horizontal only)
Horizontal Resolution	6 - 50km
Swath Width	About 760km
Scan Mode	Conical Scan (49 deg.)

Figure 10.11:

10.5.6 NASA's Passive Microwave Imaging System (PMIS)

(Description from NASA's Earth Observations Aircraft Remote Sensing Handbook,

1972, p 5 -54 to 5-56 and p. 6-60).

The 10.69-GHz passive microwave imaging system (PMIS) gathers low dimensional quantitative antenna brightness temperature data over a variety of targets. The system is composed of two airborne subsystem (described below) and a ground data system.

The PMIS consists two major subsystems. The first subsystem, the imaging radiometer, includes the radiometer, antenna, and the radiometers mounted aboard the aircraft. The primary data outputs are interfaced with an encoder which generates digital data for tape recordings. The second subsystem, the airborne control and display, controls and monitors the imaging radiometer subsystem and includes a switchable real-time readout for monitoring the instrument and engineering outputs. A near real-time black-and-white image display provides a quick-look capability. A camera records data from a second display.

<u>Options</u>: Airborne options are available only to control the operational modes of the antenna: automatic scan, single beam, or manually inserted scan rates. Any further options require programming prior to flight.

<u>Coverage</u>: The antenna is a two-dimensional phrased array, electrically stepped to achieve scanning transverse to the flight-path. the antenna scans along a cone which makes a 50° incidence angle with the ground. A single antenna scan traces an arc on the ground forward of aircraft nadir (Figure 5-21). the antenna is dual polarized with two output ports. One for vertical polarization and the other for horizontal polarization.

<u>Operational capabilities</u>: Predelivery specifications for the antenna are listed below; actual operating values may differ.

<u>System specifications</u>: The specification below apply to total system accuracy, including the radome and antenna:

Frequency:	10.69-GHz (±5 MHz)
Bandwidth:	150 MHz (3 dB points)
Sensitivity:	ΔT rms for a V/h of 0.02 is less than 0.5° K
	ΔT rms for a V/h of 0.134 is less than 2.0° K
Absolute Accuracy:	Less than 1.5° K

<u>Antenna specifications</u>:

Voltage standing wave ratio (VSWR): the input VSWR of the antenna system is less than 1.15 over the RF bandwidth.
Loss: dissipative loss of the antenna up to the antenna attachment reference flange is 2 dB or less for all beam positions.

Coupling: the two output ports have minimum 20-dB isolation.

Polarization: linear for both vertical and horizonal axes.

Beamwidth: less than or equal to 1.8 ° (= ±0.25°) increasing the 2.7° at the scan limits; constant 3° or less beam in the alongtrack direction (all nominal between 3-dB points) measured to ±0.25°.

Beam efficiency: 90% or greater measured to ±1 percent.
Side lobes: less than -21 dB for any beam position throughout the scan.

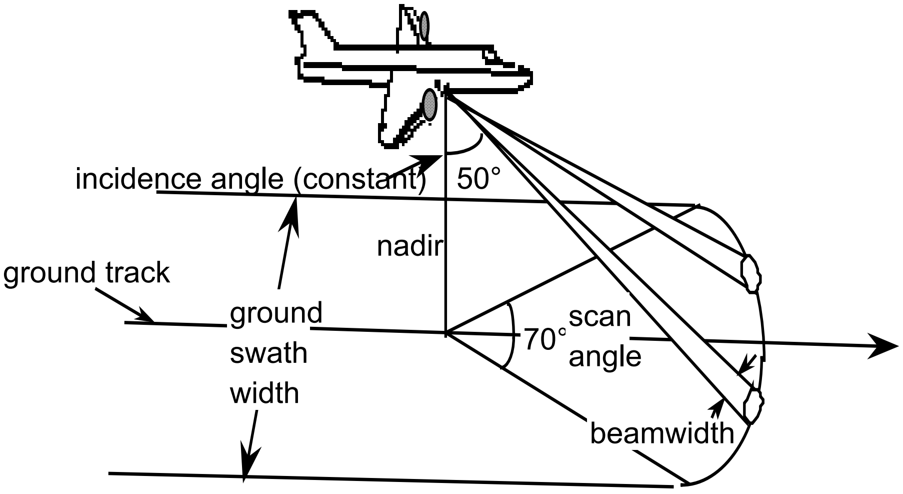
Scan specification:

Scan angle:±35° transverse to the flight line; results in 44 scan positions.

Scan steps:produces a 20- to 30- percent overlap of adjacent beams (at their 3-dB points); controls available to stop the beam scan on any beam position and to manually step through all positions.

Scan rate:step controlled with 95 discrete rates; inputs for the stepped control are from the Airborne Control and Display Sub-system. A manual override permits the operator to independently insert ground speed in knots and altitude vales in hundreds of feet.

Data Analysis The PMIS data preprocessing is performed on the ground data station [Passive Microwave Imaging System (PMIS) Microwave/Multispectral Data analysis Station (M/MDAS)]. The PMIS M/MDAS is a high-resolution color imaging and recording system. It is used for the processing imaging, and recording (digital and film) of the 10.69 GHz passive microwave radiometric data acquired by the PMIS imaging radiometer system.



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