NEAR EAST UNIVERSITY

Faculty of Engineering

Department of Electrical & Electronic Engineering

REMOTE SENSING

Graduation Project
EE – 400

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LIST OF ABREVATIONS

GIS:	Geographic Information System.
SLAR:	Side looking airborne Radar.
TOMS:	Total Ozone Mapping Spectrometer.
GOME:	Global Ozone Monitory Experiment.
AIRS:	Atmospheric Infrared Radiation Sounder.
ITS:	Infrared Temperature Sounder.
PAR:	Photosynthetically Active Radiation.
GEWEX:	Global Energy and Water Experiment.
EOS:	Earth Observing System.
ADEOS:	Advanced Earth Observing Satellite.
NASDA:	National Space Development Agency.
BSRN:	Baseline Surface Radiation Network.
SRB:	Short wave Radiation Budget.
TRMM:	Tropical Rainfall Measuring Mission.
DIM:	Digital Terrain Model.
ESMR:	Electrically Scanning Microwave Radiometer.

ABSTRACT

Remote sensing is the science of acquiring and analizing information about objects or phenomena from a distance. As humans, we are inimately familiar with remote sensing in that we rely on visiual perception to provide us with much of the information about our surroundings. As sensors, however, our eyes are greatly limited by :

- Sensitivity to only the visible range of electromagnetic energy.
- Viewing perspectives dictated by the location of our bodies.
- The inability to form a lasting record of what we view .

Because of these limitations, humans have continuously sought to develop the technological means to increase our ability to see and record the physical properties of our invironment.

Beginning with the early use of aerial photography remote sensing has been recognized as a valuable tool for viewing, analyzing, characterizing, and making decisions about our invironment.

In the past few decades, remote sensing technology has advanced on three fronts:

1. From predominantly military uses to a variety of invironmental analysis applications that relate to land, ocean, and atmosphere issues.
2. From photographic systems to sensors that convert energy from many parts of the electromagnetic spectrum to electric signals.
3. From aircraft to satellite platforms.

Today, we define satellite remote sensing as the use of satellite-borne sensors to observe, measure, and record the electromagnetic radiation reflected or emitted by the earth and its invironment for subsequent analysis and extraction of information.

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INTRODUCTION

Remote sensing is the field of study associated with extracting information about an object without coming into physical contact with it.

A difinition includes many disciplines such as medical imaging, astronomy, vision, sonar, and earth observations from above.

Spectral bands of the earth can appear quite different depending on which band it is being used to viewed it.

One of the most important parts of remote sensing is the sensor. The imaging system must have some type of sensing mechanism to capture the electromagnetic spectrum of an object. These mechanism can be analog or digital. Some images use film while others use other arrays. These instruments or sensors platforms can be devided into those with one to ten or more spectral channels (multispectral) and those with tens to hundreds of spectral chanels (hyperspectral). Imaging spectrometry has been under development since 1970's as a means of identifying and mapping earth resources.

Hyperspectral data increases the detection and classification of targets previously unresolved in multispectral images. In spectroscopy, reflectance variation as a function of wavelength provides a unique signature, or fingerprint, that can be used to identify materials. Imaging spectrometers create an image of a scene using high spectral resolution and many discrete wavelingth bands.

Remote sensing refers to methods that imploy electromagnetic energy, such as light, heat and radio waves, as the means of detecting and measuring target characteristics.

Remote sensing consists of creating images of the earth surface using several sensors each sensitive to a particular part of the electromagnetic spectrum , as every object on the earth's surface has a unique spectral signature and the whole spectrum is beyond the visible wavelingths it is then possible to produce images containing much more information that what the human eye visibe can.

CHAPTER 1

AERIAL PHOTOGRAPHY AND REMOTE SENSING

1.1 Introduction

This unit introduces basic concepts of remote sensing of the environment. It is intended to provide you with the background information necessary to successfully use remotely sensed imagery in conjunction with GIS technology to answer questions about the world in which we live.

In recent years, technological advances have changed the way geographic analyses are done. Increasingly, computers are used to automate aspects of cartography and remote sensing, producing data that are easily integrated into a GIS.

Many GIS systems have the capability of incorporating aerial photography, satellite data, and radar imagery into their data layers. The process is simple, as images may be scanned or read off a data tape. However, to use this technology effectively, it is important to know the strengths and limitation of remotely sensed data, and to understand which types of imagery are suited to particular projects. This unit was developed with these concerns in mind. The information and exercises contained within it are intended to familiarize you with the interface between remote sensing and GIS.

1.2 Foundations of Remote Sensing

1.2.1 The Electromagnetic Spectrum

The USGS defines the electromagnetic spectrum in the following manner, "Electromagnetic radiation is energy propagated through space between electric and magnetic fields. The electromagnetic spectrum is the extent of that energy ranging from cosmic rays, gamma rays, X-rays to ultraviolet, visible, and infrared radiation including microwave energy.

1.2.2 Some Frequencies and Wavelengths of Common E.M. Waves

Type	Frequency	Wavelength
Power lines	60Hz	5 x 10 m (about 3100 miles)
Television	1 MHz	300 m
Radar	1 GHz	0.3 m
Infrared	3 x 10 Hz	10 m
visidle light	5 x10 Hz	0.6 um (6000 A)
Ultraviolet	10 Hz	0.3 um (3000 A)
Gamma rays	3 x 10 Hz	0.01 A

1.2.3 Electromagnetic Waves

Electromagnetic waves may be classified by FREQUENCY or WAVELENGTH, and the velocity of ALL electromagnetic waves is equal to the speed of light, which we (along with Einstein).

Electromagnetic waves are radiated through space. When the energy encounters an object, even a very tiny one like a molecule of air, one of three reactions occurs. The radiation will either be reflected off the object, absorbed by the object, of transmitted through the object. The total amount of radiation that strikes an object is referred to as the incident radiation, and is equal to:

Reflected radiation + absorbed radiation + transmitted radiation

In remote sensing, we are largely concerned with REFLECTED RADIATION. This is the radiation that causes our eyes to see colors, causes infrared film to record vegetation, and allows radar images of the earth to be created.

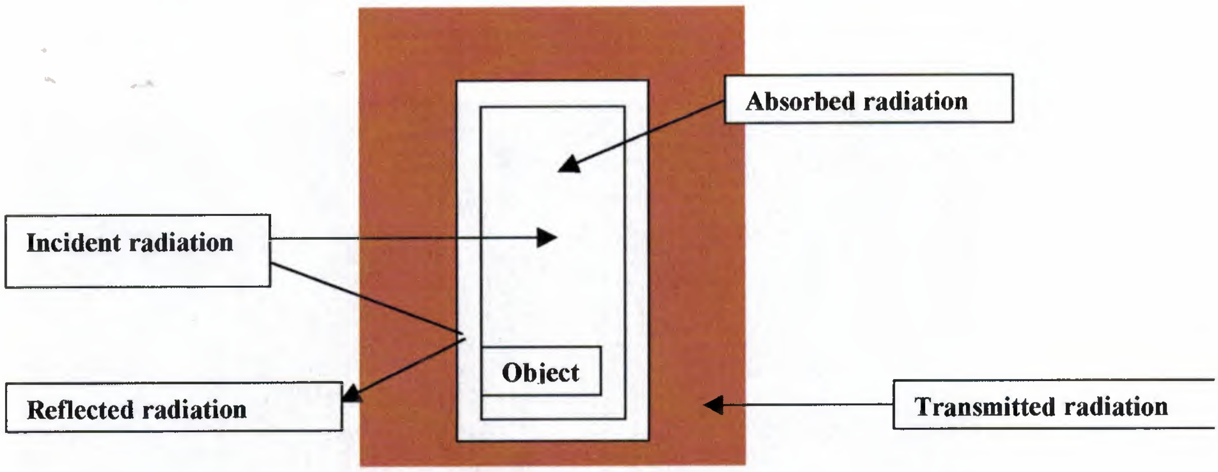

Figure 1.1 Reflected radiation

1.3 Radar Remote Sensing

Remote sensing image data in the microwave range of wavelengths is generally gathered using the technique of side-looking radar. When used with aircraft platforms it is more commonly called SLAR (Side- looking Airborne Radar). Airborne imaging radar systems in SLAR and SAR technologies are available. Airborne multispectral scanners offer a number of advantages over equivalent satellite based systems including flexibility in establishing mission parameters and proprietary rights to data. The cost of data acquisition is high. Hyper spectral airborne sensors can image ground materials in many bands of relatively high spectral resolution in a digital mode.

1.4 Electromagnetic Focusing and Remote Sensing

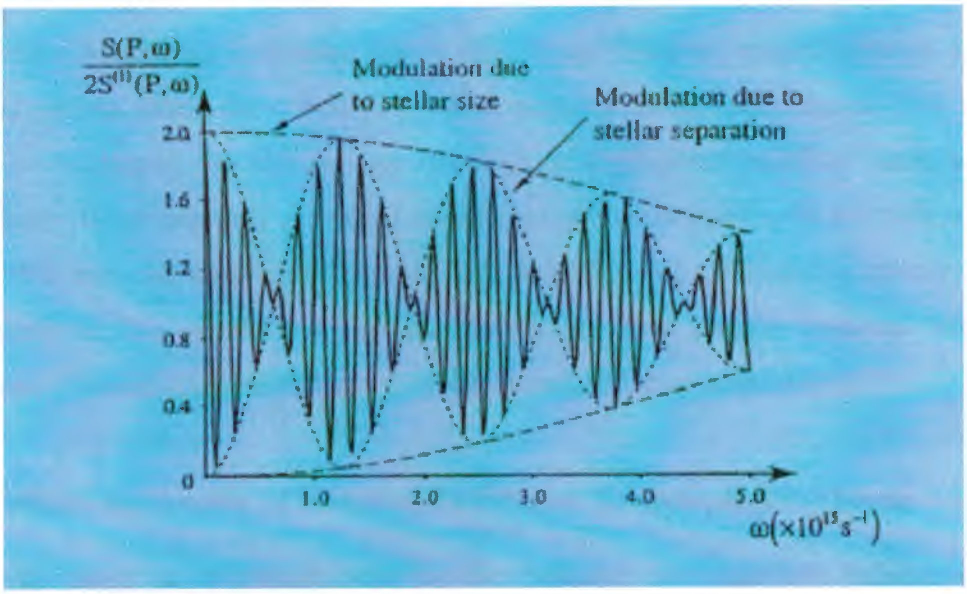

Figure 1.2 Electromagnetic Focusing

The spectrum formed when broadband lights originating in two incoherent sources (e.g. a double star) are made to interfere .

1.5 New Techniques for Remote Sensing

The main objective of this research is to develop novel techniques for remote sensing, based on coherence properties of sources and of radiation fields. We have accomplished our main goal, which was to demonstrate that changes in spectra produced by the state of coherence of a source or of a field provide information about distant objects.

Our future plans include extension of the method to detect objects of more complicated nature. We will study the possibility of using the technique at arbitrary distances from the sources, from scattering media and from other objects.

1.6 Structure of Focused Fields

Our chief aim in this area has been to extend the classical theory of focusing of radiation to novel types of systems, which are designed for use with laser light. We have largely accomplished this aim within the framework of deterministic scalar wave theory. We have also provided new theoretical methods for calculating the structure of focused fields not only in the focal region but also throughout the whole space. These calculations are based on a new representation of such fields that we have obtained and which greatly simplifies computations.

We are now developing a broader theory that would elucidate the behavior of light in the focal region when the converging wave acquires some randomness. This would occur, for example, by its passage through a fluctuating medium such as the atmosphere. There are only a limited number of previous studies of this subject. We believe that we can appreciably extend the understanding of focusing properties of random waves. We would combine the results we have already obtained with the techniques of optical coherence theory, which is one of our specialties.

1.7 Satellite Inference of Stratospheric and Tropospheric Ozone

Ozone plays an important role in the radiative and chemical balance in the atmosphere. Ozone in the stratosphere filters out harmful ultraviolet radiation from reaching the earth, and high levels of ozone near ground level cause respiratory problems for people. In addition, ozone near the tropopause exerts considerable radiative forcing. Dr. Robert D. Hudson is developing algorithms for the derivation of the global picture for total ozone in both the stratosphere and troposphere, from measurents of the ultraviolet albedo of the earth. Instruments which currently measure these albedos are the Total Ozone Mapping Spectrometer (TOMS), the Solar Backscatter Ultraviolet Spectrometer (SBUV), and the Global Ozone Monitoring Experiment (GOME). Algorithms have been developed which retrieve tropospheric column ozone in the tropics, and daily near real-time images of the results This technique is currently being extended to the Mid-Atlantic region to examine high ground-level ozone events (smog).

Two major interferences in the derivation of total ozone are sulfur dioxide and clouds of aerosol particles. An algorithm was developed to remove these interferences from albedos obtained during periods of major volcanic eruptions, and information was obtained about the nature of the emitted gas and the rate of formation of the resulting sulfate aerosols, which are another major source of climate forcing. A new algorithm is currently being developed to separate the effects of ozone and aerosols on the measured albedos during non-volcanic periods. This algorithm will determine the aerosol type and optical depth. In addition there is a continuing study of improvements to the algorithms used by NASA and NOAA for the retrieval of operational ozone and related data products.

1.8 Satellite Inference of Temperature and Moisture

Dr. Owen E. Thompson is pursuing several investigations dealing with the quality and fidelity of temperature and moisture soundings inferred from radiation measurements collected by advanced satellite instruments, such as the Atmospheric Infrared Radiation Sounder (AIRS) or Infrared Temperature Sounder (ITS).

1.9 Remote Inference of Surface and Atmospheric Radiation

Earth's climate depends on its radiative balance, controlled by solar input, surface properties, and distribution of radiatively active gases, clouds, and aerosols in the atmosphere. Radiative fluxes are the forcing functions of the climate system and are responsible for the maintenance of atmospheric motions. The exchange of energy from radiation fluxes to other forms of energy, such as sensible and latent heat fluxes, occurs at the surface of the earth. Therefore, it is of interest, to have information on surface radiative fluxes and thier variability. This can enable scientists to improve parametrization of surface-atmosphere interactions, to validate climate models, and to better understand the hydrological cycle. The use of climate models for simulating plausible climate change scenarios, requires improved capabilities in respect to hydrologic modeling and in assessing the effects of increased greenhouse gases. Of special interest is the solar radiation in the visible part of the spectrum, namely, in the interval of 400-700 nm, known as the Photosynthetically Active Radiation (PAR). Information on the spatial and temporal distribution of photosynthetically active radiation (PAR), by control of the evapotranspiration process, is required for modeling the hydrological cycle and for estimating global oceanic and terrestrial net primary productivity (NPP).

Earth orbiting satellites are well suited to provide a global view of our climate. Professor Pinker and her associates in the Department of Meteorology, Drs. I. Laszlo, G. Pandithurai, Xu Li, and graduate students, participate in several national and international projects, aimed at improving the understanding of the climate system. Examples of projects include the Global Energy and Water Experiment (GEWEX), the Earth Observing System (EOS) Program, the GEWEX Continental-scale International

Project (GCIP), the Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) Project, the NOAA/NASA PATHFINDER Project, and the Advanced Earth Observing Satellite (ADEOS)-II mission sponsored by the National Space Development Agency of Japan (NASDA). These activities are linked to efforts at other institutions.

In the EOS Validation framework, an activity in a desert ecroachment zone in sub-Sahel Africa was undertaken, in collaboration with African scientists from the University of Ilorin, Nigeria. This is a climatically important region due to its location in a desert transition zone and because of the influence of the dusty Harmattan wind which is persistent for prolonged periods of time, and characterized by steady dusty conditions with high aerosol loading. Observations are made of surface radiative fluxes, as well as aerosol optical depth. The radiation observations are linked to the World Climate Research (WCRP) Baseline Surface Radiation Network (BSRN) activity, and aerosol data from this station are part of the (AERONET) network.

Recently, a new CD-ROM was prepared which contains global scale information on the distribution of daily and monthly mean values of Surface and Top of the Atmosphere Shortwave Radiation Budget (SRB) Parameters, for the period July 1983 to August 1994. The derived values were produced at the University of Maryland, and are based on satellite observations and on ancillary data as available from the Global Energy and Water Cycle Experiment (GEWEX) ISCCP D1 product, at a nominal resolution of 2.5 degrees. Provided are: shortwave surface downward flux; shortwave surface upward flux; visible surface downward flux (Photosynthetically Active Radiation (PAR)); visible surface upward flux; shortwave top of the atmosphere net flux (down-up).

1.10 Remote Sensing of Rainfall

Accurate and detailed precipitation observations are crucial for the complete understanding of the surface hydrology, interaction of the surface with the overlying atmosphere, and prediction of changes in water resources on time scales ranging from hourly to seasonal and annual. At many locations within the continental United States, radar and raingauge coverage is inadequate, as evidenced by the experimental Stage IV analyzed data from the National Environmental Prediction Center (NCEP). Moreover, radar and gauge data do not exist over the Gulf of Mexico and Northern regions of Mexico. Satellite estimates of precipitation play an important role in the collection and the use of precipitation data. They have proven to be quite useful in large scale climate

applications, as produced for the Global Precipitation Climatology Project (GPCP), and have been applied to estimate rainfall for instantaneous and heavy precipitation events.
For high temporal and spatial resolution (about one hour and 10 km), estimates of rain from geostationary satellites represent the only plausible source of information. The most common techniques are based on infra-red observations, and they are most effective in tropical air masses which are dominated by deep convective rainfall. They tend to underestimate rainfall from warm top clouds, and overestimate precipitation from cold non-raining cirrus clouds, a problems that can prove to be serious for high spatial and temporal scales. A multi-spectral model was developed that seems to overcome many of these problems. It uses visible, near infrared and infrared observations from GOES satellites to identify both deep convective and "warm" precipitating clouds.

1.11 Remote Sensing of the Oceans

Observing the changing climate of the ocean presents a daunting observational challenge. One of the most exciting developments in climate research in recent years has been the introduction of satellite remote sensing observations to ocean studies. The ocean is a conducting medium and thus electromagnetic sensors are constrained to observe surface properties including: infrared and microwave emission (sea surface temperature), laser and microwave ranging (sea level), microwave reflectance (wave heights and surface wind stress), and brighness in the visible bands (phytoplankton concentration). Some of these surface observations allow us to infer subsurface properties of the ocean. For example, in the tropics, increases in sea level coincide with a deepening of the warm upper layer of the ocean (a 1cm rise roughly corresponds to a 2m deepening). In the very near future, satellite-based observations of time-dependent gravity will allow an additional direct measurement of the horizontal.
redistribution of mass. Scientists within the Department involved in research projects examining all of these data types include Drs. Carton, Wang, Subraminium, Murtugudde, Wajsowicz, and Chepurin.

Satellite Inference of Surface Chlorophyll, Primary Production and Carbon Fluxes:
The Wide Field of view Sensor (SeaWiFS) which was launched during August 1997 has been providing unprecedented high quality data of surface ocean color. Several ocean color missions are now operational or planned by the United States and other countries

such as India and Japan. Dr. Ragu Murtugudde is working on the simulation of surface distributions of chlorophyll to allow for the interpretation of remotely sensed ocean color in terms of subsurface ecosystem variability. Satellite data of ocean color have several applications such as its linkage to fisheries with a potential for forecasting fish locations. More importantly, global primary productions can be estimated for the first time from biomass inferred from SeaWiFS and other remotely sensed ocean color data. Research includes attempts to estimate surface CO_2 fluxes and their variability on seasonal-to-interannual time-scales. The overall goal is to determine the contribution of the marine ecosystem to the global carbon budget. Other satellite data such as precipitation from Tropical Rainfall Measuring Mission (TRMM) and winds from QuickScat are used extensively in this study.

1.12 Modeling Surface Energy Balances

The representation of surface processes in numerical models is critical in studies of climate change and variability; likewise, seasonal prediction relies on adequate characterization of land surface-atmosphere energy exchanges.

Dr. E. H. Berbery is examining the surface energy balances of operational models and evaluating them against ground and satellite information. His research is in close collaboration with respective Operational Centers, to help in their development of surface parameterizations.

The figure at left presents a comparison of downward shortwave radiation at the surface as estimated from satellites and the following two operational models: National Center for Environmental Prediction (NCEP) ETA model and the Canadian Meteorological Centre Global Multiscale Environmental (GEM) model. The Eta model seems to have an excess of downward shortwave radiation at the surface, which has to be compensated by other energy related processes.

CHAPTER 2

DEVELOPMENTS OF SENSORS

2.1 Developments and History of Sensors

2.1.1 Aerial Photography and Photography from Space

Around 1839, photography was developed by two Frenchmen Niepce and Daguerre. After the invention, cameras were taken on hot-air-balloon flights. These first aerial photographs were meant as a curiosity, but soon the military recognized the strategic importance. Due to this military interest, much effort was put into technical improvement of the equipment. Around 1850, the French officer Lausedat developed a special camera for topographic images. Besides air balloons also kites and rockets were used to carry cameras. Around 1858, the French balloonist Tournachon was the first to use aerial photographs for the production of maps. Only small areas were covered. With the invention of the Zeppelin large areas were systematically photographed because the Zeppelin was able to be steered. However, until the coming of the airplane, maps were still created by surveyors. It wasn't until 1930, before producers of maps started to use aerial photographs as the very basis for their maps. It became possible to map in a short time even areas were surveyors couldn't reach. In 1932, the Topographic Dienst, of the Netherlands, started using aerial photographs. Aerial Photographs for the production of maps can only be taken with precision instruments under very favorable circumstances. Only a few companies have the men and material at their disposal to take vertical aerial photographs. The basis of the equipment is a small powerful airplane (usually a twin-engine) that can fly a stable course at low altitudes. The camera is mounted in a hole of the hull with the lens pointing vertically downwards. The aerographical film must be of a very high quality and must not show any geometrical distortions during and after exposure. In the fine grain structure of the film even very small objects remain visible. During a photo flight there must be a good cooperation between the pilot and the navigator/photographer. At the preparation of the flight the altitude, type of camera, type of film and the route are determined according to the demands of the client. The flight must be done in a straight line. These lines are drawn on a map which includes information about the altitude and course. The navigator leads the flight. He supplies the pilot with course corrections and operates the camera.

The photographs must form straight strips and overlap about 60% for stereoscopic processing at a later stage. The camera must be kept horizontal and parallel to flying direction as much as possible. The pilot tries to keep a constant altitude and speed and takes care to keep the plane stable (no pitch, yaw or roll), even during course corrections. The weather is the most important factor for usable photographs. The best time of year is the period between middle of February and the end of May. Because the sun is higher fewer details are lost in the shadows. During this winter time frame, the sacristy of leaves on the trees allows little to remain hidden underneath. Flights can be flown only on days with sunny and clear weather. Only a few days per year are suited for making aerial photographs. An aerial photograph must be corrected and interpreted. Information not clear in the photograph is checked in the field. Next to the aerial photography, photogrammetry plays an important roll in the production of maps. This science developed techniques and equipment for doing very accurate measurements in aerial photographs. The photogrammetric processing needs very precise instruments. These are needed because measurements must be done at just a few hundredths of a millimeter. For example, a scale of 1:10,000 10 cm in the terrain is equivalent to 0.01 mm on the photograph. This 0.01 mm (10 micrometer) is also the approximate resolution of aerographic film. The film can show 256 shades of gray (= 8 bit or 1 byte). The data content of a 10x10" panchromatic film is 5 billion (5*10^9!) bits or about 600 Mb. Digital processing of photographs is necessary to convert the analogue photographic material to a digital form. Optical scanners can scan photographs at 12.5 μm resolution with geometric distortions (or positional placement) somewhere in the order of a magnitude of 5 μm. Modern laser scanners can scan photographs at 25 μm (1000 dpi) but geometric distortions may still be quite high. One undocumented source mentions 40 μm which is unacceptable for certain photogrammetric applications. The most important photogrammetric techniques are based on the possibility of stereoscopically viewing two overlapping photographs. This overlapping area can be viewed in three dimensions. The height of the terrain or buildings can be measured. Errors in altitude, course and orientation of the plane during the exposure of the film can be corrected using photogrammetric techniques. The field of remote sensing is about 30 years old. It began back to the late 40's and early 50's when some of the first satellite photographs were being recovered from V-2 launches.

Satellite imaging of the earth developed with the international space program. The satellite Sputnik 1, launched on October 4, 1957, were used to gather photographs and video images which were acquired by the U.S. Explorer and Mercury programs. The U.S. initiated its spaced-based reconnaissance program three years later; acquiring high-resolution photographic images from space.

Multispectral line scanners, similar in principle to the Landsat MSS and TM instruments, have been available for use in civil aircraft since the late 1960's. In satellite image acquisition, the forward motion of the aircraft, provides the "along" track scanning. A rotating mirror or linear detector array provides sensing in "across" track direction. There are several operational features that distinguish the data provided by aircraft scanners from that produced by satellite-borne devices. These are of significance to the image processing task. First, the data volume can be substantially higher. This is a result of having (1) a large number of spectral bands available and (2) a large number of pixels produced permission, due to the high spatial resolution available. Recording of the data during a mission usually requires the use of a high density digital tape recorder or a robust disc unit carried on board the aircraft. Use of airborne multispectral scanners offers a number of benefits. The user can select the wavebands of interest in a particular application, and small bandwidths can be used. Also, the mission can be flown to the specification of the user's requirements: concerning the time of day, bearing angle and spatial resolution (which can be established by the aircraft height above the ground). Data acquisition, from aircraft platforms, is expensive by comparison with satellite recording; since aircraft missions are generally flown for a single user and do not benefit from the volume market and synoptic view available to satellite data.

2.1.2 Multispectral remote sensing

When sunlight falls upon the Earth's surfaces, the solar energy maybe reflected by, absorbed by,or transmitted through the surface materials. Absorbed energy usually heats the material. .This heat may later be emitted as thermal radiation.

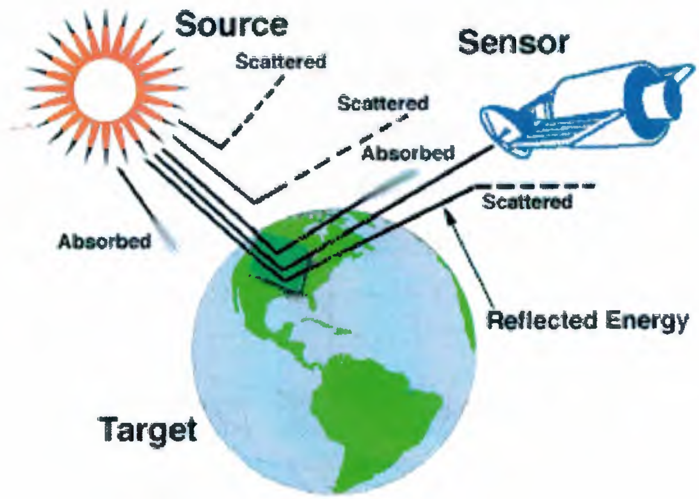

Figure 2.1 Multispectral remote sensing

Energy from the sun may be scattered, reflected, or absorbed by the Earth's surfaces. Remote sensing is the process of detecting and recording these interactions between matter and energy.

It is very useful for us to record these interactions in different portions, or bands, of the electromagnetic spectrum, because different objects on the Earth reflect sunlight differently in different parts of the spectrum.

Imagine looking at things through red lenses, or only blue or green glasses. When we record the energy in the red, green, blue, or infrared bands of the spectrum, we are doing multispectral remote sensing. Multispectral sensors are a basic remote sensing data source for quantitative thematic information, such as land cover. In addition, other thematic layers are often displayed against the backdrop of multispectral images. Resource managers use information from multispectral data to monitor fragile lands and other natural resources, including vegetation, wetlands, and forests. These data provide unique identification characteristics and a quantitative assessment of the Earth's features.

2.2 Archeological Remote Sensing

Now more than ever, archeological research is interdisciplinary: botany, forestry, soil science, hydrology - all of which contribute to a more complete understanding of the earth, climate shifts, and how people adapt to large regions.

As a species, we've been literally blind to the universe around us. If the known electromagnetic spectrum were scaled up to stretch around the Earth's circumference, the human eye would see a portion equal to the diameter of a pencil. Our ability to build detectors that see for us where we can't see, and computers that bring the invisible information back to our eyesight, will ultimately contribute to our survival on Earth and in space.

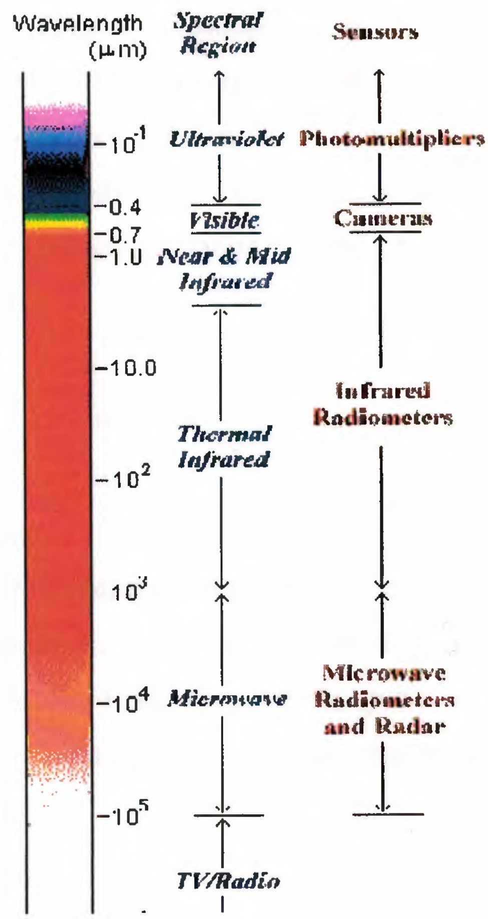

Figure 2.2 wavelength and spectral region of sensors

The spectrum of sunlight reflected by the Earth's surface contains information about the composition of the surface, and it may reveal traces of past human activities, such as agriculture. Since sand, cultivated soil, vegetation, and all kinds of rocks each have distinctive temperatures and emit heat at different rates, sensors can "see" things beyond ordinary vision or cameras. Differences in soil texture are revealed by fractional temperature variations. So it is possible to identify loose soil that had been prehistoric agricultural fields, or was covering buried remains. The Maya causeway was detected through emissions of infrared radiation at a different wavelength from surrounding vegetation. More advanced versions of such multi-spectral scanners (Visible & IR) can detect irrigation ditches filled with sediment because they hold more moisture and thus have a temperature different from other soil. The ground above a buried stone wall, for instance, may be a touch hotter than the surrounding terrain because the stone absorbs more heat. Radar can penetrate darkness, cloud cover, thick jungle canopies, and even the ground.

Remote sensing can be a discovery technique, since the computer can be programmed to look for distinctive "signatures" of energy emitted by a known site or feature in areas where surveys have not been conducted. Such "signatures" serve as recognition features or fingerprints. Such characteristics as elevation, distance from water, distance between sites or cities, corridors, and transportation routes can help to predict the location of potential archeological sites.

2.3 Remote Sensing Instruments

2.3.1 Aerial Photography

Many features which are difficult or impossible to see standing on the ground become very clear when seen from the air. But, black and white photography only records about twenty-two perceptible shades of gray in the visible spectrum. Also, optical sources have certain liabilities, they must operate in daylight, during clear weather, on days with minimal atmospheric haze.

2.3.2 Color Infrared Film (CIR)

Detects longer wavelengths somewhat beyond the red end of the light spectrum. CIR film was initially employed during World War II to differentiate objects that had been artificially camouflaged. Infrared photography has the same problems that conventional photography has, you need light and clear skies. Even so, CIR is sensitive to very slight differences in vegetation. Because buried archeological features can affect how plants grow above them, such features become visible in color infrared photography.

2.3.6 Microwave Radar

Beaming radar pulses into the ground and measuring the echo is a good way of finding buried artifacts in arid regions (water absorbs microwaves). Man-made objects tend to reflect the microwaves, giving one a "picture" of what is underground without disturbing the site.

2.4 Satellite Remote Sensing and its Role in Global Change Research

From a general perspective, remote sensing is the science of acquiring and analyzing information about objects or phenomena from a distance. As humans, we are intimately familiar with remote sensing in that we rely on visual perception to provide us with much of the information about our surroundings. As sensors, however, our eyes are greatly limited by

1) sensitivity to only the visible range of electromagnetic energy; 2) viewing perspectives dictated by the location of our bodies; and 3) the inability to form a lasting record of what we view. Because of these limitations, humans have continuously sought to develop the technological means to increase our ability to see and record the physical properties of our environment.

Beginning with the early use of aerial photography, remote sensing has been recognized as a valuable tool for viewing, analyzing, characterizing, and making decisions about our environment. In the past few decades, remote sensing technology has advanced on three fronts:

1) from predominantly military uses to a variety of environmental analysis applications that relate to land, ocean, and atmosphere issues; 2) from photographic systems to sensors that convert energy from many parts of the electromagnetic spectrum to electronic signals; and 3) from aircraft to satellite platforms. Today, we define satellite remote sensing as the use of satellite-borne sensors to observe, measure, and record the electromagnetic radiation reflected or emitted by the Earth and its environment for subsequent analysis and extraction of information.

Appreciating the role of satellite remote sensing in global change research requires an understanding of the following:

- The Technology of Satellite Remote Sensing
- The Importance of Satellite Remote Sensing
- The Potential of Satellite Remote Sensing for Human Dimensions Program Activities and Research

2.5 The Importance of Satellite Remote Sensing

Global change research poses significant challenges to the scientific community. Physical and biological scientists (together referred to as natural scientists) have grappled with the challenges of data requirements for a decade or more and have identified the utility of satellite remote sensors as major sources of consistent, continuous data for atmospheric, ocean, and land studies at a variety of spatial and temporal scales. An extensive body of literature within numerous natural science disciplines documents the development of, or potential for, satellite sensor data analysis techniques to identify environmental attributes and monitor physical and biological processes relevant to global change research.

Satellite sensor data have proven useful to the atmospheric and ocean sciences communities. While social scientists may have little involvement in the scientific study of the biological, physical, and chemical processes being addressed within these communities, human dimensions interests are associated with the causes of the perturbations to atmospheric and ocean systems being studied and in the resultant health and socioeconomic effects on humans. In "The Use of Satellites to Monitor Global Transmission of Microbes Simmer and Volz (1993) address the effects of atmospheric dispersion of disease on human health by discussing the use of satellite sensors for monitoring terrestrial and atmospheric parameters relevant to microbial spread and transmission. In "Health and Climate Change: Marine Ecosystems.Epstein, Ford, and Colwell (1993) discuss the human health implications associated with the degradation of marine ecosystems due to pollution and global warming. The CIESIN Thematic Guide on Human Health and Global Environmental Change provides information on use of remote sensing and geographic information systems (GIS) in Programs for Surveillance, Treatment, and Control of Vector-borne Diseases Clark (1993) reviews the applications of satellite sensor data to a wide range of marine pollution problems in "Satellite Remote Sensing of Marine Pollution."

The land sciences community has made extensive use of satellite image data for mapping land cover, estimating geophysical and biophysical characteristics of terrain features, and monitoring changes in land cover.Ehrlich, Estes, and Singh (1994) review many of the reported findings associated with defining the capabilities of NOAA Advanced Very High Resolution Radiometer 1-km data to provide global land-cover information. Goward (1989) discusses the current and future role of satellite image data for contributing to studies of bioclimatology. in "Satellite BioclimatologyTucker, Dregne, and Newcomb (1991) use coarse-resolution satellite image data for monitoring continental-scale climate-related phenomena in "Expansion and Contraction of the Sahara Desert from 1980 to 1990Colwell and Sadowski (1993) use high-resolution satellite data for monitoring regional patterns and rates of forest resource utilization in "Past Patterns as a Guide for Future Forest ManagementAnd Freeman and Fox (1994) discuss the semi-operational use of satellite image data by several forest assessment programs in "Satellite Mapping of Tropical Forest Cover and Deforestation

More recently, the scientific community has witnessed a growing emphasis placed on investigating the human dimensions of global change. In 1990, the International Social Science Council (ISSC) launched its Human Dimensions of Global Environmental Change Program to serve as the international social science research program on global change that would parallel and complement major natural science global change research efforts, namely, The World Climate Research Program (WCRP) and The International Geosphere-Biosphere Program (IGBP)

In the defining document of the HDP, A Framework for Research on the Human Dimensions of Global Environmental ChangeJacobson and Price (1990) identify seven topics of research central to understanding the interactions of human activities and the environment.

These topics include the following:

- social dimensions of resource use;
- perceptions and assessment of global environmental conditions and change;
- impacts of local, national, and international social, economic, and political structures and institutions;
- land use;

- energy production and consumption;
- industrial growth; and
- environmental security and sustainable development.

In identifying the research topics, Jacobson and Price state:
"Each of these topics must be investigated separately. In addition, they must be investigated in combination as they interact in specifically defined contexts where human activities have a direct impact on the physical, chemical, and biological processes that are involved in global environmental change. Such research must be conducted at all geographical scales and should include the past as well as the present and the future." Such commentary advises that to be most effective, human dimensions studies of global change must be "grounded" within the context of specific nature-society issues, geographic locations and scales, and time scales. Turner and Meyer (1991) further develop this precept by emphasizing the importance of particular space-time relationships in affecting human behavior in "Land Use and Land Cover in Global Environmental ChangeIn discussing the topic of land-use and land-cover change as a type of global environmental change, they maintain that macro-level driving forces of land use/cover change (such as population growth, technological change, economic development, socioeconomic organization, and attitudes/beliefs) are frequently modified by significant contextual variables and may therefore be inadequate for explaining types and rates of change. The authors advocate the regionalization of characteristic situations of society-land cover interactions on a global scale. A global set of regional situations that characterize deforestation, for example, would enable exploring relationships among macro-level driving forces and meso- and micro-level contextual variables.
Defining and locating various types of society-land cover interactions for study may pose new challenges for social scientists. Miller (1994) and Jacobson and Price (1990) note that social scientists studying global change should consider increasingly the spatial relationships associated with various physical land characteristics or anthropogenically induced land surface conditions for guiding the scale and extent of their data collection. Satellite remote sensors can serve as major sources of data on the effects of human behavior within the biosphere, enabling the establishment of the spatial scale and extent of the direct interaction of humans with the global land cover.

Ultimately, determining the integrated linkages between the human dimensions driving forces and the physical processes of global change will require collaboration among scientists from the human and natural science domains. Miller (1994) has called attention to the problems inherent to attempting collaboration and the new methodological paradigms needed to develop collaborative, interdisciplinary research in "Interactions and Collaboration in Global Change across the Social and Natural Sciences." Collaborative research will enable diverse disciplines to effectively hypothesize and study the linkages. Miller advises that in the initial stages of study, researchers should seek interdisciplinary agreement in defining global change research problems in their entirety, from anthropogenic forcing functions to their expression in physical or ecological processes to their subsequent impact on human society.

In "CIESIN's Experiences with Integrated Thomas and Roller (1993) discuss the results of the Consortium for International Earth Science Information Network's (CIESIN) 1991 Science Pilot Project Program, which demonstrate the value of satellite remote sensing in facilitating interdisciplinary global change research. Satellite image data record a variety of phenomena, some of which relate to the human sciences, some to the physical sciences, and many to both. The data provide a common spatial frame of reference for integrating interests within the scientific community to promote the interdisciplinary research essential for understanding and managing global change. In "Integrating Regional Studies of Deforestation Context," Thomas et al. (1993) provide an example of use of satellite image data to contribute to regional studies, and then integrate those results into a global change context.

2.6 The Technology of Satellite Remote Sensing

The fundamental principles of remote sensing derive from the characteristics and interactions of electromagnetic radiation (EMR) as it propagates from source to sensor. The principles relate to the following:

1) The source of energy and the type and amount of energy it provides
2) The absorption and scattering effects of the atmosphere on EMR
3) The mechanisms of EMR interaction with Earth surface features; and
4) The nature of sensor response as determined by the type of sensor. Lillesand and Kiefer (1987) provide an overview of these principles in the chapter "Concepts and Foundations of Remote Sensing in Remote Sensing and

Image Interpretation. Other reviews of the fundamental principles of remote sensing are available in most remote sensing textbooks, including those by Avery and Berlin (1992), Szekielda (1988), Elachi (1987), Sabins (1987), and Swain and Davis (1978). A thorough treatment is available in the Manual of Remote Sensing (Simonett, D.S., ed., 1983).

Most satellite sensors detect EMR electronically as a continuous stream of digital data. The data are transmitted to ground reception stations, processed to create defined data products, and made available for sale to users on a variety of digital data media. Once purchased, the digital image data are readily amenable to quantitative analysis using computer-implemented digital image processing techniques. Sabins (1987) describes these techniques in the chapter "Digital Imaging Processing in *Remote* Sensing: Principles and Interpretation. Some of these techniques (such as data error compensations, atmospheric corrections, calibration, and map registration) essentially involve pre-processing the data for subsequent interpretation and analysis. Another group of techniques is designed to selectively enhance the digital data and produce hard-copy image formats for interpreters to study. For these images, some of the principles and techniques of air photo interpretation can be applied to manual analysis of the image information content. Lillesand and Kiefer (1987) discuss such analyses in Remote Sensing and Image Interpretation. A third major group of digital processing techniques involves information extraction through the implementation of a wide range of simple to complex mathematical and statistical operations on the numerical data values in the image. The results of these operations provide output such as derived information variables (that might relate to terrain brightness or vegetation condition), categorized land and water features, or images showing changes over time.

A discussion of remote sensing technology would not be complete without mention of geographic information systems (GIS). Satellite remote sensing represents a technology for synoptic acquisition of spatial data and the extraction of scene-specific information. GIS provides a computer-implemented spatially oriented database for evaluating the information in conjunction with other spatially formatted data and information that may be acquired from remote sensor data, maps, surveys, and other sources of spatially referenced information. The concept of spatial data integration in a GIS. The Environmental Systems Research Institute (1992) describes this technology .

GIS technology should aid human dimensions studies of global change by enabling the integration and joint analysis of human science data and natural science data. In "The Potential Methodological Impact of Geographic Information Systems on the Social Sciences," Marble (1990) notes that GIS will be particularly instrumental for heightening social science researchers' awareness of the spatial complexity that surrounds all societal structures and conditions much of human behavior. In "Landscape: A Unifying Concept in Regional Analysis," Crumley and Marquardt (1990) propose the concept of "landscape" for unifying the study of human interactions with their environment and explain that GIS is the tool that allows for practical study of landscape elements. Madry and Crumley (1990) provide an informative discussion of the development and use of a GIS for evaluating the historical interaction of environment and culture in the Arroux River valley in "An Application of Remote Sensing and GIS in a Regional Archaeological Settlement Pattern Analysis

The emphasis on satellite-image data in this guide is not meant to diminish the roles of aerial photography and fieldwork for providing "ground truth" data. Any comprehensive program of mapping landscape features (meaning the spatial manifestation of the relationship between humans and their environment, as proposed by Crumley and Marquardt, 1990), evaluating and quantifying their characteristics, and monitoring change generally requires supporting ground truth data to develop and verify the use of satellite-image data. Developing the intended use of satellite sensor data refers to establishing the qualitative associations or quantitative relationships one wants to implement; in other words, determining the capability to accomplish an objective using a particular type of data. Verification refers to assessment of performance and refinement of the capability. These activities enable establishing the link between satellite image data and the desired landscape information (both natural and human dimensions attributes).

The type of supporting ground truth data employed in specific studies varies relative to the scale of the primary data being used. When working with coarse-resolution continental- and global-scale satellite image data (such as Advanced Very High Resolution Radiometer data of 1-km spatial resolution), high-resolution satellite data (such as Landsat or Systeme Probatoire d'Observation de la Terra (SPOT)) may serve as supporting ground-truth data. On the other hand, scientists studying the human dimensions of global change with high-resolution satellite images may need to incorporate interpretations of air photos and information acquired in the field to corroborate their intended use of the satellite data and validate their results.

The Potential of Satellite Remote Sensing for Human Dimensions of Global Environmental Change Program Activities and Research

The consistent, continuous land coverage provided by satellite image data has the potential to contribute land-cover and land-use change information to several Human Dimensions of Global Environmental Change Program (HDP) activities and developing research initiatives.

The HDP Working Group on Demographic Data identify and assess the manifold data about population in their report Population Data and Global Environmental (Clarke and Rhind 1992). The report recommends that, to be useful in global change research, georeferenced population data should be developed for at least three levels of application. The first two levels consist, respectively, of national level data, which generally exist but are not always available and not georeferenced in any consistent manner, and rectangular area data from the U.S. Bureau of Census Center for International Research, which have not been readily available to researchers. The Consortium for International Earth Science Information Network (CIESIN) is exploring ways to make both these levels of data available on a global basis. The third recommended level is for a high-resolution data set at the spatial resolution of 1 km or better to have population figures at the commune or even finer resolution level. The report recommends that satellite image data be investigated for creating such a high-resolution data set, using demographic data gathered by conventional means as a control.

The System for Analysis Research and Training (START) Program a joint activity for the International Geosphere-Biosphere Program (IGBP), the World Climate Research Program (WCRP), and the Human Dimensions of Global Environmental Change Programme (HDP), is devoted to assisting regional groups of developing countries in establishing global change regional research networks. The HDP has begun working within START to convene groups of social scientists from each of the regions to identify priority topics in the study of the human dimensions of global environmental change and to relate these to the emerging natural science research priorities. Although specific approaches and topics in each region differ, social scientists have begun to focus attention on land cover, its responses to the driving forces of land-use change, and its impacts on future land-use practices. Satellite remote sensors provide global image coverage that could offer comprehensive land-cover and land-use change information for all regional research networks.

The Global Omnibus Environmental Survey (GOES) initiative has evolved out of recommendations of two HDP Working Groups: the Perception and Assessment of Global Environmental Change group and the Survey Research Data group. Essentially, the purpose of GOES is to develop and administer a survey form for gathering baseline data worldwide on environmental knowledge, attitudes, and behaviours. Periodic re-surveys would provide for regular monitoring of peoples' understanding of global environmental change and activities related to it. A proposed research design for the GOES survey currently calls for a core survey, specialized modules focused on science and public policy issues, and contextual data. All three elements require stratification by geophysical location and type of land use. Satellite image data could be a valuable tool in assisting such stratification.

An IGBP-HDP Ad-Hoc Working Group has proposed a joint IGBP-HDP Core Project to investigate Land Use and Global Land Cover Change, as described by Turner, Moss, and Skole (1993) in "Relating Land Use and Global Land-Cover Change." Land-use change has been identified as a priority human dimensions issue because of the increased awareness of its role as a major driver of environmental change. Human dimensions research will have requirements for land-use information that includes the forms of land-cover change, the patterns of change, and the rates of change as influenced by the driving forces of human actions. Current global aggregations of land use/land cover change are subject to debate, because they are based on imprecise measurements or on estimates. Global aggregate relationships to driving forces often mask the increased complexities of human actions at the subglobal scale.

The joint IGBP-HDP project will address the dynamics of land-use and land-cover change by developing a typology for the relationships among human driving forces, land-use change processes, and resulting land cover. These "situational assessments" will be defined at subglobal levels to develop regionally sensitive relationships, and then tested through systematic case studies that use and collect common data to answer standard questions about the influence of socioeconomic context on land cover change. Regional models will be globally integrated to enable understanding and projection of global-scale land-cover change. Some of the data and information needs satellite image data could help provide include stratified land-cover characteristics in current time, stratified rates of change, and proximate sources of change.

2.7 Satellite Inference of Stratospheric and Tropospheric Ozone

Ozone plays an important role in the radiative and chemical balance in the atmosphere. Ozone in the stratosphere filters out harmful ultraviolet radiation from reaching the earth, and high levels of ozone near ground level cause respiratory problems for people. In addition, ozone near the tropopause exerts considerable radiative forcing. Dr. Robert D. Hudson is developing algorithms for the derivation of the global picture for total ozone in both the stratosphere and troposphere, from measurents of the ultraviolet albedo of the earth. Instruments which currently measure these albedos are the Total Ozone Mapping Spectrometer (TOMS), the Solar Backscatter Ultraviolet Spectrometer (SBUV), and the Global Ozone Monitoring Experiment (GOME). Algorithms have been developed which retrieve tropospheric column ozone in the tropics, and daily near real-time images of the results are given at the Tropical Troposheric Ozone Home Page. This technique is currently being extended to the Mid-Atlantic region to examine high ground-level ozone events (smog).

Two major interferences in the derivation of total ozone are sulfur dioxide and clouds of aerosol particles. An algorithm was developed to remove these interferences from albedos obtained during periods of major volcanic eruptions, and information was obtained about the nature of the emitted gas and the rate of formation of the resulting sulfate aerosols, which are another major source of climate forcing. A new algorithm is currently being developed to separate the effects of ozone and aerosols on the measured albedos during non-volcanic periods. This algorithm will determine the aerosol type and optical depth. In addition there is a continuing study of improvements to the algorithms used by NASA and NOAA for the retrieval of operational ozone and related data products.

2.8 Satellite Inference of Temperature and Moisture

Dr. Owen E. Thompson is pursuing several investigations dealing with the quality and fidelity of temperature and moisture soundings inferred from radiation measurements collected by advanced satellite instruments, such as the Atmospheric Infrared Radiation Sounder (AIRS) or Infrared Temperature Sounder (ITS).

Dr. Owen E. Thompson is pursuing several investigations dealing with the quality and fidelity of temperature and moisture soundings inferred from radiation measurements collected by advanced satellite instruments, such as the Atmospheric Infrared Radiation Sounder (AIRS) or Infrared Temperature Sounder (ITS). Remote Inference of Surface and Atmospheric Radiation Dr. Owen E. Thompson is pursuing several investigations dealing with the quality and fidelity of temperature and moisture soundings inferred from radiation measurements collected by advanced satellite instruments, such as the Atmospheric Infrared Radiation Sounder(AIRS)or Infrared Temperature Sounder (ITS).

2.9 Remote Inference of Surface and Atmospheric Radiation

Earth's climate depends on its radiative balance, controlled by solar input, surface properties, and distribution of radiatively active gases, clouds, and aerosols in the atmosphere. Radiative fluxes are the forcing functions of the climate system and are responsible for the maintenance of atmospheric motions. The exchange of energy from radiation fluxes to other forms of energy, such as sensible and latent heat fluxes, occurs at the surface of the earth. Therefore, it is of interest, to have information on surface radiative fluxes and thier variability. This can enable scientists to improve parametrization of surface-atmosphere interactions, to validate climate models, and to better understand the hydrological cycle. The use of climate models for simulating plausible climate change scenarios, requires improved capabilities in respect to hydrologic modeling and in assessing the effects of increased greenhouse gases. Of special interest is the solar radiation in the visible part of the spectrum, namely, in the interval of 400-700 nm, known as the Photosynthetically Active Radiation (PAR). Information on the spatial and temporal distribution of photosynthetically active radiation (PAR), by control of the evapotranspiration process, is required for modeling the hydrological cycle and for estimating global oceanic and terrestrial net primary productivity (NPP).

Earth orbiting satellites are well suited to provide a global view of our climate. Professor Pinker and her associates in the Department of Meteorology, Drs. I. Laszlo, G. Pandithurai, Xu Li, and graduate students, participate in several national and international projects, aimed at improving the understanding of the climate system.

Examples of projects include the Global Energy and Water Experiment (GEWEX), the Earth Observing System (EOS) Program, the GEWEX Continental-scale International

In the EOS Validation framework, an activity in a desert ecroachment zone in sub-Sahel Africa was undertaken, in collaboration with African scientists from the University of Ilorin, Nigeria. This is a climatically important region due to its location in a desert transition zone and because of the influence of the dusty Harmattan wind which is persistent for prolonged periods of time, and characterized by steady dusty conditions with high aerosol loading. Observations are made of surface radiative fluxes, as well as aerosol optical depth. The radiation observations are linked to the World Climate Research (WCRP) Baseline Surface Radiation Network (BSRN) activity, and aerosol data from this station are part of the (AERONET) network.

Recently, a new CD-ROM was prepared which contains global scale information on the distribution of daily and monthly mean values of Surface and Top of the Atmosphere Shortwave Radiation Budget (SRB) Parameters, for the period July 1983 to August 1994. The derived values were produced at the University of Maryland, and are based on satellite observations and on ancillary data as available from the Global Energy and Water Cycle Experiment (GEWEX) ISCCP D1 product, at a nominal resolution of 2.5 degrees. Provided are: shortwave surface downward flux; shortwave surface upward flux; visible surface downward flux (Photosynthetically Active Radiation (PAR)); visible surface upward flux; shortwave top of the atmosphere net flux (down-up).

2.10 Remote Sensing of Rainfall

Accurate and detailed precipitation observations are crucial for the complete understanding of the surface hydrology, interaction of the surface with the overlying atmosphere, and prediction of changes in water resources on time scales ranging from hourly to seasonal and annual. At many locations within the continental United States, radar and raingauge coverage is inadequate, as evidenced by the experimental Stage IV analyzed data from the National Environmental Prediction Center (NCEP). Moreover, radar and gauge data do not exist over the Gulf of Mexico and Northern regions of Mexico. Satellite estimates of precipitation play an important role in the collection and

Mexico. Satellite estimates of precipitation play an important role in the collection and the use of precipitation data. They have proven to be quite useful in large scale climate applications, as produced for the Global Precipitation Climatology Project (GPCP), and have been applied to estimate rainfall for instantaneous and heavy precipitation events.

For high temporal and spatial resolution (about one hour and 10 km), estimates of rain from geostationary satellites represent the only plausible source of information. The most common techniques are based on infra-red observations, and they are most effective in tropical air masses which are dominated by deep convective rainfall. They tend to underestimate rainfall from warm top clouds, and overestimate precipitation from cold non-raining cirrus clouds, a problems that can prove to be serious for high spatial and temporal scales. A multi-spectral model was developed that seems to overcome many of these problems. It uses visible, near infrared and infrared observations from GOES satellites to identify both deep convective and "warm" precipitating clouds.

2.11 Remote Sensing of the Oceans

Observing the changing climate of the ocean presents a daunting observational challenge. One of the most exciting developments in climate research in recent years has been the introduction of satellite remote sensing observations to ocean studies. The ocean is a conducting medium and thus electromagnetic sensors are constrained to observe surface properties including: infrared and microwave emission (sea surface temperature), laser and microwave ranging (sea level), microwave reflectance (wave heights and surface wind stress), and brighness in the visible bands (phytoplankton concentration). Some of these surface observations allow us to infer subsurface properties of the ocean. For example, in the tropics, increases in sea level coincide with a deepening of the warm upper layer of the ocean (a 1cm rise roughly corresponds to a 2m deepening). In the very near future, satellite-based observations of time-dependent gravity will allow an additional direct measurement of the horizontal

redistribution of mass. Scientists within the Department involved in research projects examining all of these data types include Drs. Carton, Wang, Subraminium, Murtugudde, Wajsowicz, and Chepurin

Satellite Inference of Surface Chlorophyll, Primary Production and Carbon Fluxes

The Wide Field of view Sensor (SeaWiFS) which was launched during August 1997 has been providing unprecedented high quality data of surface ocean color. Several ocean color missions are now operational or planned by the United States and other countries such as India and Japan. Dr. Ragu Murtugudde is working on the simulation of surface distributions of chlorophyll to allow for the interpretation of remotely sensed ocean color in terms of subsurface ecosystem variability. Satellite data of ocean color have several applications such as its linkage to fisheries with a potential for forecasting fish locations. More importantly, global primary productions can be estimated for the first time from biomass inferred from SeaWiFS and other remotely sensed ocean color data. Research includes attempts to estimate surface CO_2 fluxes and their variability on seasonal-to-interannual time-scales. The overall goal is to determine the contribution of the marine ecosystem to the global carbon budget. Other satellite data such as precipitation from Tropical Rainfall Measuring Mission (TRMM) and winds from QuickScat are used extensively in this study.

2.12 Modeling Surface Energy Balances

The representation of surface processes in numerical models is critical in studies of climate change and variability; likewise, seasonal prediction relies on adequate characterization of land surface-atmosphere energy exchanges.

Dr. E. H. Berbery is examining the surface energy balances of operational models and evaluating them against ground and satellite information. His research is in close collaboration with respective Operational Centres, to help in their development of surface parameterisations.

CHAPTER 3

BASIC PRINCIPLES OF ELECTROMAGNETIC ENERGY

3.1 The Electromagnetic Spectrum

Electromagnetic energy is the means by which information is transmitted from an object (target) to a sensor. While most of us are familiar with the visible form of electromagnetic energy, it exists in many forms besides visible light.

Among these are

- radio waves
- microwaves
- heat
- ultraviolet rays
- X-rays
- gamma rays

Each of these describes the energy in a specific region of the *electromagnetic spectrum.* The electromagnetic spectrum represents the continuum of electromagnetic energy from extremely short wavelengths (cosmic and gamma rays) to extremely long wavelengths (radio and television waves).

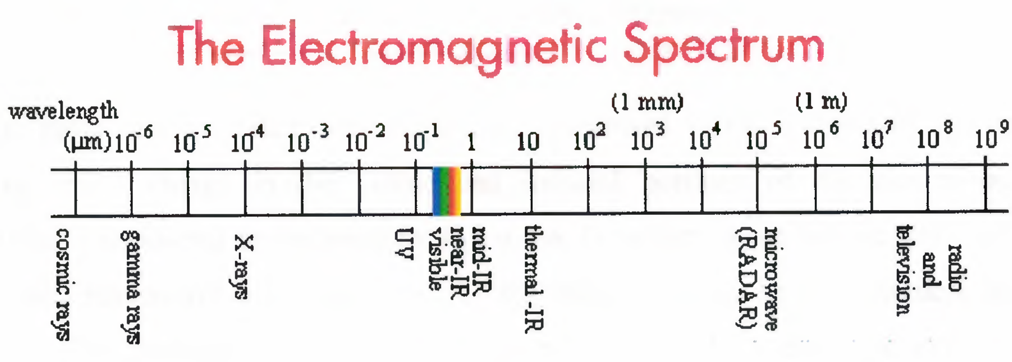

Figure 3.1 The electromagnetic spectrum

So that we can discuss sections of the electromagnetic spectrum conveniently, names have been assigned to regions of the spectrum in which adjacent wavelengths behave similarly (or are generated by similar mechanisms). However, the division between "ultraviolet" and "visible", or "microwave" and "thermal infrared" is not hard and fast. The regions blur into one another. The chart below outlines generally accepted regions of the electromagnetic spectrum and gives their spectral ranges.

Regions of the Electromagnetic Spectrum	*Regions of the Electromagnetic Spectrum*
gamma ray	<0.03 nanometers
X-ray	0.03 - 3 nanometers
Ultraviolet	0.3 nanometers - 0.4 micrometers
Visible	0.4 - 0.7 micrometers
near infrared	0.7 - 1.3 micrometers
mid-infrared	1.3 - 3.0 micrometers
thermal (far) infra	3.0 - 5.0 micrometers AND 8 – 14 micrometers
Microwave	0.3 - 300 centimeters
gamma ray	0.03 nanometers
X-ray	0.03 - 3 nanometers
Ultraviolet	3 nanometers - 0.4 micrometers
Visible	0.4 - 0.7 micrometers
near infrared	0.7 - 1.3 micrometers
mid-infrared	1.3 - 3.0 micrometers
thermal (far) infrared	3.0 - 5.0 micrometers AND 8 - 14 micrometers
Microwave	0.3 - 300 centimeters

The basic unit in which wavelengths are measured in the meter (m). In remote sensing, most energy in the visible and infrared portions of the electromagnetic spectrum is measured in micrometers (10-6 m). However, some wavelengths (such as radio and microwaves) are too long for the micrometer to be a convenient unit of measure. For example, while the wavelength of blue light is approximately 0.4-0.5 micrometers, a radio wave is in the neighborhood of 100,000,000 micrometers long (100 m)! You should be aware that visible wavelengths (including ultraviolet, visible, and near infrared) are frequently referred to in units other than the micrometer. Astronomers use a unit called *angstrom* (10-10 m) to measure these wavelengths. One micrometer equals 10,000 angstroms. Occasionally you may run across this unit when reading satellite documentation from NASA, although most of the information they have for remote sensing audiences uses micrometers. Also, some of the older literature in remote sensing refers to micrometers as microns, and many of the biological sciences still use "micron". One micron equals one micrometer.

Type of EM Wave	Typical Unit of Measure
radio	meter (m) centimeter (cm)=0.01 m
microwave (radar)	millimeter (mm)=0.001 m
infrared	micrometer (um)=10^{-6}m
visible	nanometer (nm)=10^{-9}m; 10^{-3}um
ultraviolet	angstrom (Å)=10^{-10}m

Figure 3.2 Unit of measure of electromagnetic waves

3.2 Digital Image Processing

3.2.1 Why Process Remotely Sensed Data Digitally?

Humans are adept at visually interpreting data. We can distinguish millions of colors, several shades of gray, and have a demonstrated ability to identify water, vegetation, and urban forms on several types of imagery. Why try to expand on this?

(1) There are limits to a person's ability to distinguish small differences in color. We are especially limited in our resolution of shades of gray. If data are collected using 256 shades of gray, but an analyst can only distinguish 8-10 (optimistically) of them, a great deal of information is potentially lost. The human interpreter is outpaced by the precision of the data. Computers, however, have no trouble distinguishing 256 shades of

gray. Each one is individually recognizable. And, the analyst has control over the conputer's presentation of the data. She can group it any way she pleases, extract a portion of it, or display it in false color. Data sets can also be combined, compared, and contrasted with more ease and precision (not to mention speed) than if the task were left to humans alone.

(2) Human interpretations are highly subjective, hence, not perfectly repeatable. Conversely, results generated by computer--even when erroneous--are usually repeatable.

(3) When very large amounts of data are involved (a series of photos of an orange grove taken at 5 day intervals over an entire growing season) the computer may be better suited to managing the large body of detailed (and tedious) data.
The processes of manual image interpretation and digital image interpretation are similar in many ways. The goals of analysis are often the same, though the routes may vary.

3.3 **Satellite Imaging**

LAND SAT refers to a series of satellites put into orbit around the earth to collect environmental data about the earth's surface. The LANDSAT program was initiated by the U.S. Department of Interior and NASA under the name ERTS, an acronym which stands for Earth Resources Technology Satellites. ERTS-1 was launched on July 23, 1972, and was the first unmanned satellite designed solely to acquire earth resources data on a systematic, repetitive, multispectral basis. Just before the launch of the second ERTS satellite, NASA announced it was changing the program designation to LANDSAT, and that the data acquired through the LANDSAT program would be complemented by the planned SEASAT oceanographic observation satellite program. ERTS-1 was retroactively named LANDSAT-1, and all subsequent satellites in the program have carried the LANDSAT designation. Over time, the sensors carried by the LANDSAT satellites have varied as technologies improved and certain types of data proved more useful than others. The table which follows outlines the sensors onboard each satellite, their launch dates, and the dates they were decommissioned

3.4 MSS, Thermal, and Hyper spectral Scanning

3.4.1 Thermal Radiation Principles

Thermal infrared radiation refers to electromagnetic waves with a wavelength of between 3.5 and 20 micrometers. Most remote sensing applications make use of the 8 to 13 micrometer range. The main difference between THERMAL infrared and the infrared discussed above is that thermal infrared is emitted energy, whereas the near infrared (photographic infrared) is reflected energy.

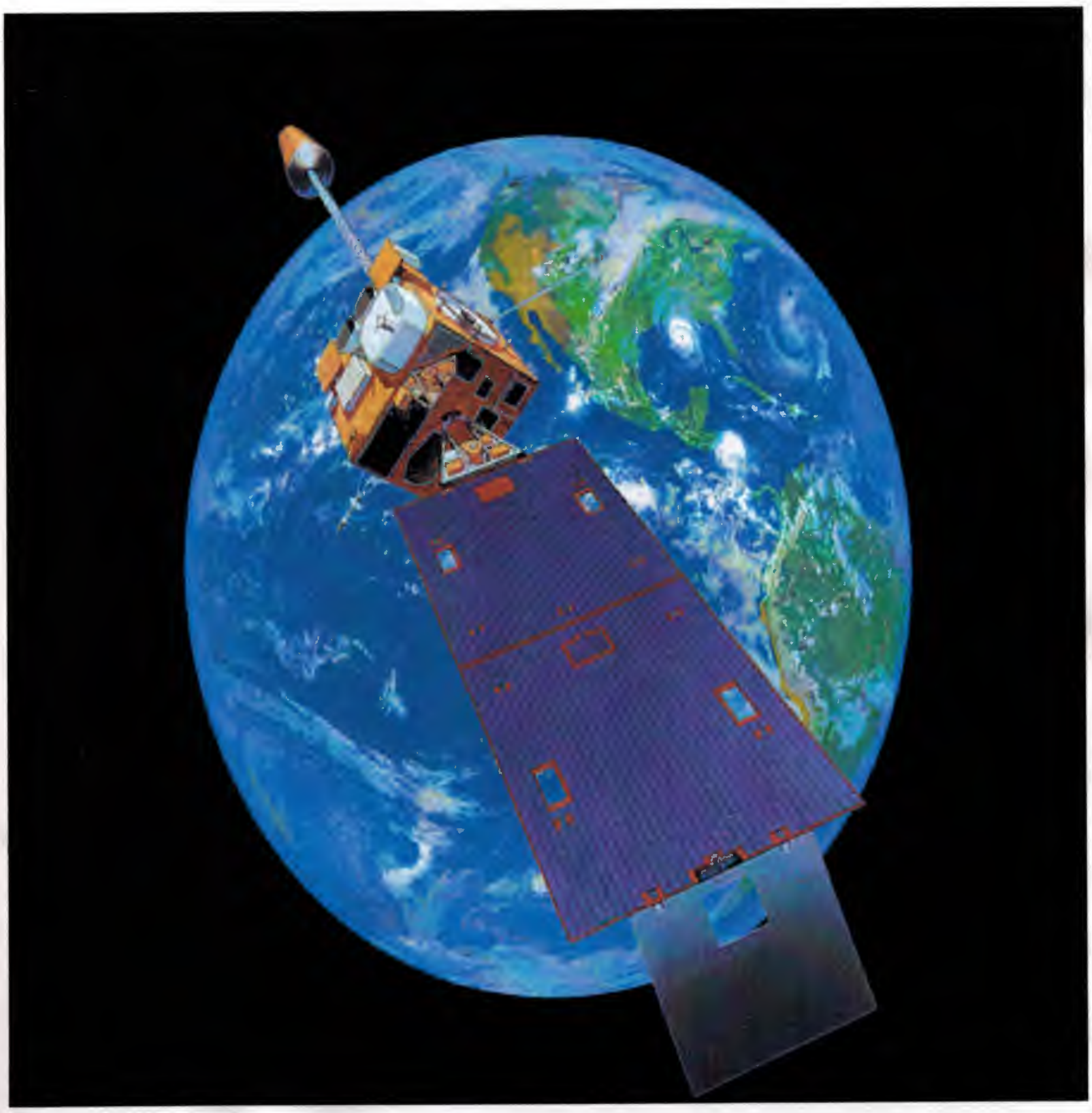

Figure 3.3 Interpreting Thermal Scanning Imagery

3.4.2 Limitations of Thermal Infrared Imaging

There are some limitations of thermal imagery you should be aware of if you plan to use it in your GIS:

1- It is very expensive.

2- Most thermal imaging systems have very strict operational parameters. For example, the detector must be kept extremely cold during use.

3- Thermal infrared imaging systems are notoriously difficult to calibrate.

4- The data collected has extensive processing requirements. A PC isn't going to cut it.

5- Thermal images can be quite difficult to interpret when compared with other types of imagery.

6- Thermal imagery is NOT geometrically correct.

7- Thermal images of water measure only the very top layer of the water. They tell you nothing of the water's characteristics below the top few micrometers.

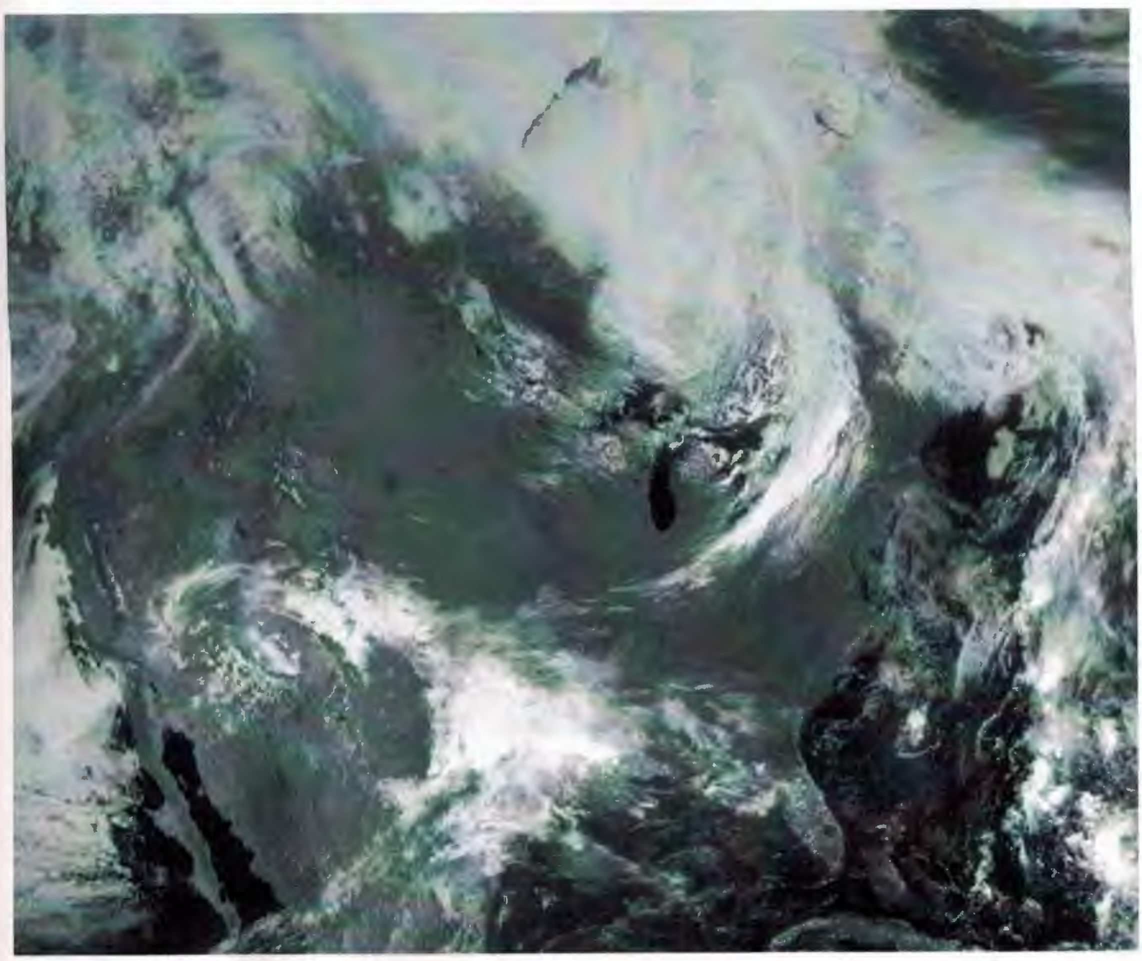

Figure 3.4 Imaging Spectrometry

3.5 Radar (Microwave) Scanning

3.5.1 Radar Images

The following radar images come from sites all over the world. The files at NASA's Jet Propulsion Laboratory have explanations accompanying the images.

_Spaceborne Synthetic Aperture Radar, Oetxal, Austria. This file was created by NASA's Jet Propulsion Laboratory in Pasadena, CA.

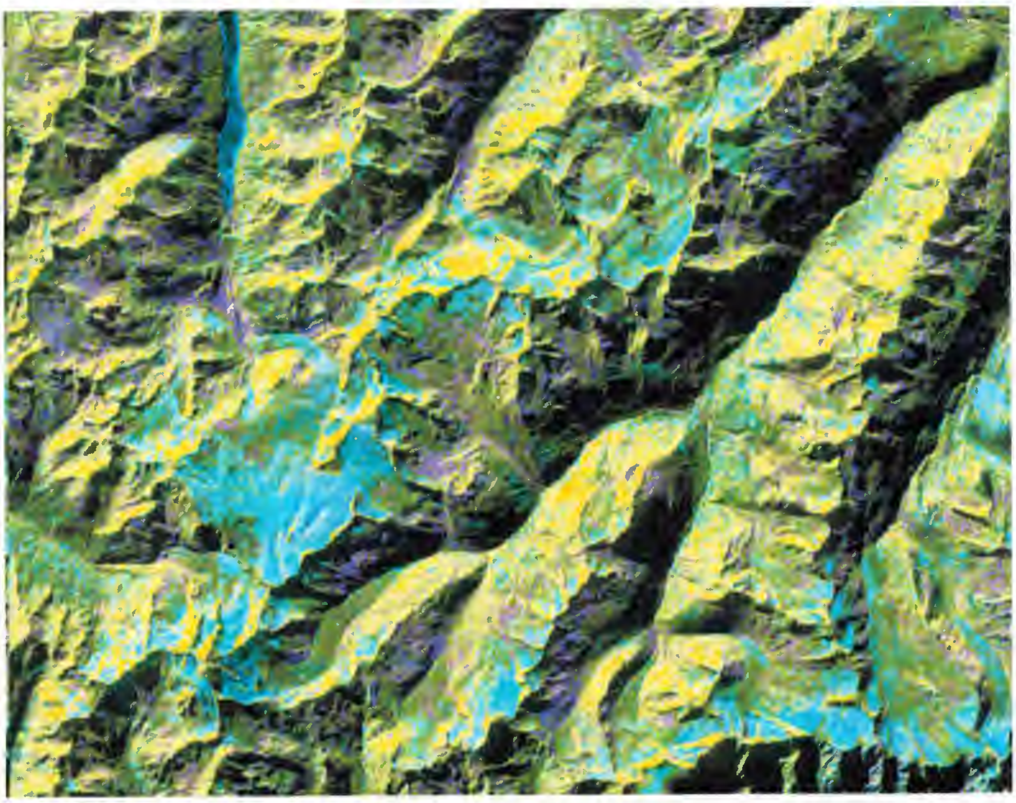

Figure 3.5 Image of radar

3.5.2 Oetztal, Austria

This is a digital elevation model that was geometrically coded directly onto an X-band seasonal change image of the Oetztal supersite in Austria. The image is centered at 46.82 degrees north latitude and 10.79 degrees east longitude. This image is located in the Central Alps at the border between Switzerland, Italy and Austria, 50 kilometers (31 miles) southwest of Innsbruck. It was acquired by the Spaceborne Imaging Radar-C/X-band Synthetic Aperture aboard the space shuttle Endeavour on April 14, 1994 and on October 5, 1994. It was produced by combining data from these two different data sets.

Data obtained in April is green; data obtained in October appears in red and blue, and was used as an enhancement based on the ratio of the two data sets. Areas with a decrease in backscatter from April to October appear in light blue (cyan), such as the large Gepatschferner glacier seen at the left of the image center, and most of the other glaciers in this view. A light blue hue is also visible at the east border of the dark blue Lake Reschensee at the upper left side. This shows a significant rise in the water level. Magenta represents areas with an increase of backscatter from April 10 to October 5. Yellow indicates areas with high radar signal response during both passes, such as the mountain slopes facing the radar. Low radar backscatter signals refer to smooth surface (lakes) or radar grazing areas to radar shadow areas, seen in the southeast slopes. The area is approximately 29 kilometers by 21 kilometers (18 miles by 13.5 miles). The summit of the main peaks reaches elevations of 3,500 to 3,768 meters (xx feet to xx feet) above sea level. The test site's core area is the glacier region of Venter Valley, which is one of the most intensively studied areas for glacier research in the world. Research in Venter Valley (below center) includes studies of glacier dynamics, glacier-climate regions, snowpack conditions and glacier hydrology. About 25 percent of the core test site is covered by glaciers. Corner reflectors are set up for calibration. Five corner reflectors can be seen on the Gepatschferner and two can be seen on the Vernagtferner.

Spaceborne Imaging Radar-C and X-band Synthetic Aperture Radar (SIR-C/X-SAR) is part of NASA's Mission to Planet Earth. The radars illuminate Earth with microwaves, allowing detailed observations at any time, regardless of weather or sunlight conditions. SIR-C/X-SAR uses three microwave wavelengths: L- band (24 cm), C-band (6 cm) and X-band (3 cm). The multi- frequency data will be used by the international scientific community to better understand the global environment and how it is changing. The SIR-C/X-SAR data, complemented by aircraft and ground studies, will give scientists clearer insights into those environmental changes which are caused by nature and those changes which are induced by human activity. SIR-C w as developed by NASA's Jet Propulsion Laboratory. X-SAR was developed by the Dornier and Alenia Spazio companies for the German space agency, Deutsche Agentur fuer Raumfahrtangelegenheiten (DARA), and the Italian space agency, Agenzia Spaziale Italiana (ASI), with the Deutsche Forschungsanstalt fuer Luft und Raumfahrt e.v.(DLR), the major partner in science, operations and data processing of X-SAR.

3.5.3 Remote Sensing

The objective of the project is to maximise the usefulness for archaeology of the images received. Such images may be used as a substitute for large-scale maps and can offer an invaluable visual aid for understanding of the site in relation to its surroundings, but there are other possible uses.

Firstly, the images may reveal features of archaeological interest which have not previously been identified. Secondly, they may assist in the planning and organisation of ground surveys and excavation. Thirdly, they may - especially if available in multispectral format - aid in analysing current land use and patterns of vegetation. Such analysis may also assist in selecting areas of likely occupation in ancient times and in studying the development of the landscape. Fourthly, they may be used as the basis of a GIS (Geographic Information System) which will serve as a record of the features of archaeological interest in relation to the landscape.

The first was initially received in photographic format. Enlargements allowed objects of 2 metres across to become visible and an interpretation was made on tracing paper, which was then verified by personal visits in May and October 1996.

The KVR photo was digitised and transferred to a CDROM which then permitted computer processing. A CDROM containing a digitised version was also received in October 1996. Initial work for rectification and enhancement of the images was carried out on a Pentium PC using the Idrisi for Windows programme. Subsequently, work began at the Institut Supérieur de Technologie using ERDAS on a Sun Workstation.

An example is provided here of enhancement of the SPOT image using ERDAS. The histogram of the area of Zeugma shows two initial peaks. The first of these corresponds to pixels showing water or damp areas and is shown in blue; the second to rich vegetation which is shown in green. The remainder - in red - corresponds to rock, earth, roads and and sparse vegetation.

The same procedure has here been applied to the whole image. The first peak for water is assigned to the blue colour gun and those parts of the histogram other than this peak are reduced to zero. The same is done for the second peak using the green colour gun and then the remainder is assigned to the red gun. Areas in green would be largely pistachio trees and other cultivated crops. The small reservoir of Hancagiz is visible at the lower right.

A detailed report in English or in French on work carried out in 1996 may be downloaded. Two illustrations are available in a separate file.

In 1997 and 1998 work concentrated on the KVR photos. A second and third photos were acquired by Dr Hartmann, a Swiss archaeologist also working at Zeugma on Roman military architecture. He kindly made available these photos, which cover a 40x40 km area to the North of Zeugma, including most of the future reservoir, and also a large area to the South in the direction of the Syrian border.

For reduced versions of these photos click here (from mid-January 1999!). In addition, a series of Corona photos from the late 1960s has been acquired. These are US reconnaissance photos, now in the public domain, but with a lower ground resolution than the KVR series. They are supplied in long strips covering approximately 200 by 20 kms. They are much less expensive than the KVR imagery, but show only objects of about 8 metres across and are thus less useful for archaeology. They are however extremely useful since they show how the landscape was at a moment which in this area just preceded an era of agricultural modernisation.

The text of the reports for 1997 and 1998 is now available for downloading either in Microsoft Word or as text only. Some tables may also be downloaded. Figures however are not generally be included, although some reduced images are available here. The full reports with illustrations may be ordered now from Anthony Comfort, but a small charge may be levied to defray the cost of reproduction and postage. A map of the places discussed in the reports may be consulted here.

Image 1 is a reduced version of the 40x40 km KVR photo from 1992 of the whole Euphrates valley North of Zeugma. All this valley will be drowned by the reservoir, but only in a rather narrow canyon (usually about 1 km across or less). Image 2 is a reduced version of a KVR photo, also from 1992, of the area including Zeugma and to the South. The map is included to provide the location of places mentioned in the text of the two reports. All these are too large to be included on the web-site as such and must be downloaded by ftp.

Finally, a Landsat image of the area from 1988 was acquired by the Institut Supérieur de Technologie and a variety of combinations of the difference bands has been used to show in particular variations in the vegetation coverage. Attempts to combine the Landsat image with SPOT and KVR data have however not succeeded, probably because of the difference in dates and the difficulty of rectifying and georeferencing a Landsat image using Ground Control Points obtained initially for the SPOT and KVR images. (Many of these GCPs are not visible on the Landsat image because of the lower ground resolution of 30 metres.)

3.6 GIS & Geomorphology

A database in which the information is related to geographical coordinates (or Geographic Information System - GIS) is now under construction, using the satellite images as a basis. The intention is to create on computer a three-dimensional model of the valley, especially of that part around Zeugma, on which will be placed the sites of archaeological and historical interest. For each such site, information will be available in the form of text, plans and photographs, in order to provide a visual record of the valley. Not all the information available will be available over the Internet, since this GIS is expected to be highly complex.

At a later stage such a GIS could be set up on a computer in the Museum of Gaziantep or at the Birecik dam in order to offer visitors an idea of the area and its cultural riches, even when those riches have been covered by the waters of the reservoir. One advantage of the GIS proposed would be the incorporation of results from geomorphological studies now under way, which should permit a representation of the valley on computer, as it appeared at various times in the past.

A study of the geomorphology of the section of the Euphrates valley which will be drowned by the Birecik dam is being conducted by Hervé Cubizolle of the CRENAM institute at the University of Saint-Etienne

A first step was taken in Spring 1997 with the creation of the attached map of the immediate area of the city of Zeugma, based on an extract from the KVR photo (please click on the map for a complete version with key). This map, created with symbols added via the programme Paint Shop Pro, will be replaced by more sophisticated versions using Idrisi and MapMaker Pro. However, only small extracts will be possible because of the file size of the resulting images.

The first stage in the production of such maps based on satellite images is the recording of Ground Control Points using a GPS machine (Garmin 40). Features such as crossroads which are easily identifiable on the images are selected and their position recorded. In this case at least three readings were taken on different occasions; obviously defective readings (more than 200 metres apart from the others) were discarded; and an average taken of the remainder. Some photocopies of 1:25 000 maps were available and where possible the readings were checked against these. In general, they provided positions which about 50 metres to the South-West of those indicated on the maps, but the reason for this is not known. Simple GPS machines such as the one used here will only provide readings accurate to within 100 metres, because of intentional distortions to the GPS satellite signals introduced by the US Department of Defense.

A correspondence file is then prepared using the column and row numbers of the selected points in the images and the UTM readings provided by the GPS. Using the Idrisi "Reformat" command a new "geo-referenced" image is produced oriented to the North, with grid refences and with the inevitable small distortions corrected. Either in Idrisi, or more easily via MapMaker Pro, a grid is superimposed and symbols added for ancient roads, sites, quarries, etc. The whole may then be printed out on special paper using a colour printer (in this case Epson Stylus 600), as a poster i.e. with several A4 sheets stuck together to provide a large-scale map. So far maps of the immediate area of Zeugma at a scale of approximately 1:25 000 and of a wider area to the South at a scale of approximately 1:40 000 have been produced. The degree of detail obtainable and the large file-size resulting precludes publishing these on the Internet in a complete form.

The next stage should involve the creation of a Digital Terrain Model (DTM - or else Digital Elevation Model).Unfortunately, the expense of creating such a DTM for the whole area (appprox. 50x50 sq kms) by interferometry using two contemporaneous ERS-1 radar images, was beyond the resources of this project. A cost of $17 000 was quoted. The hopes of obtaining a partial DTM based on the work of the dam surveyor have not been borne out either, except for the immediate area of Zeugma itself.

Nevertheless, a change of policy on the part of the Turkish national mapping authority may result in digitised 1:25 000 maps with contours becoming available shortly .

Zeugma lies on the Euphrates river, which served as a link between Anatolia and Mesopotamia from the earliest times. In particular, this route was used to bring timber from the Amanus and Taurus mountains to the first literate, urban civilisations of Southern Mesopotamia and probably by Assyrian traders in metals passing to and from their outpost at Kultepe in Central Anatolia.

Carchemish, an important state following the fall of the Hittite Empire to the "Peoples of the Sea" in the twelfth century BC, lies just 30 km downstream, on the present border between Turkey and Syria. This city played a dominant role in the area until it fell to the Assyrians, probably in the ninth century BC.

The city of Zeugma - or rather two cities on each side of the river, Seleuceia and Apamea - was founded in 300 BC by Seleucus I Nicator, one of Alexander´s generals who had been made satrap of Babylon. It was to guard what had become the principal crossing point of the river Euphrates for those passing from the Western Mediterranean world to the Eastern satrapies of the old Achaemenid empire, conquered by Alexander in 331 BC. Like many other such foundations, the role of Zeugma which means "link" in Greek, or "bridge", was to protect the communications of the Seleucid Empire which stretched from the Mediterranean Sea, near its Western capital of Antioch, to India. It lies close to the point at which the river emerges from its gorge in the foothills of the Taurus mountains.

In the second and first centuries BC, Rome gradually came to supplant the Seleucid Empire in the West, but the Parthian kingdom in the East also saw itself as a successor to Alexander´s Greek Empire. The river Euphrates became the frontier between Rome and Parthia, rivals for control of the East and the only two "Great Powers" in conflict during the first centuries of our era.

Zeugma became important both as a military base, home for one of only three legions on the Eastern frontier, but also as a trading city on the "Silk Route" from China to the West. As the Roman empire was extended to include Mesopotamia in the fourth century the city lost its importance as a frontier post, but its wealth increased and many fine mosaics from the third and fourth centuries have been found.

Early Parthian raids sacked the city on several occasions and the whole frontier was unstable throughout the Roman period, but Syria as a whole gained a remarkable prosperity. Even after the Sassanian Empire (successor to that of the Parthians) had pushed back the Byzantines into Anatolia, Zeugma remained important as the seat of a bishopric. Population and wealth of all Northern Syria and Mesopotamia however fell drastically following the Arab victories of the seventh century over both Byzantium and Sassanid Persia.

In succeeding centuries, Arabs, Turks, Armenians, Mamluks, Crusaders and Kurds all fought over this area. Certain cities - such as Aleppo and Edessa (now Urfa) retained their importance, but Zeugma was largely forgotten when the principal Euphrates crossing moved downstream to Birecik in the Middle Ages.

CHAPTER 4

REMOTE SENSING AND MICROWAVE RADIOMETRY

4.1 Basic Principles of Microwave Radiometry

In this introductory section we will consider blackbody microwaves, microwave radioactive transfer, and surface emissive and reflectivity.

4.2 Applications of Microwave Radiometry to Remote Sensing

Microwave radiometry is the detection of thermal radiation power at microwave frequencies. A wealth of information can be derived from radiometric observations. In addition to the intensity of the radiation its dependence on frequency, angle of incidence, and polarization can also provide additional information about the source.

The development of microwave radiometry for remote sensing (also called passive microwaves, as compared with active radars) derives its background from radio astronomy. Since the advent of satellites the use of passive microwaves.

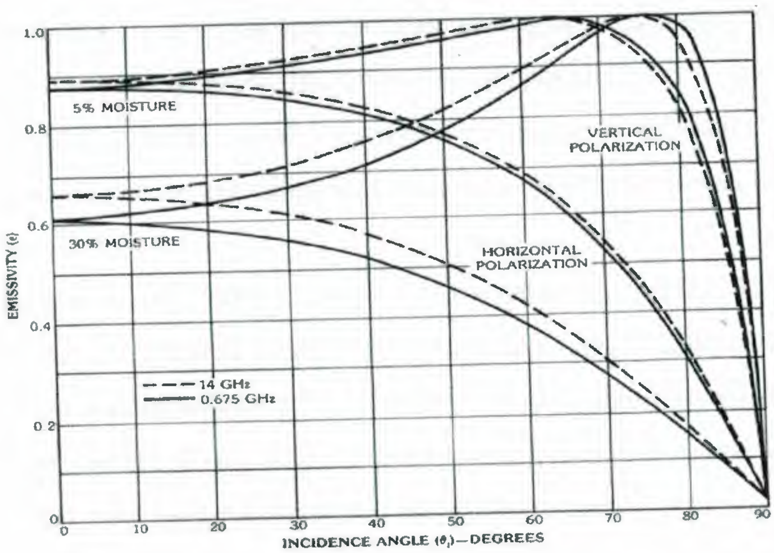

Figure4.1 Theoretical emissivity of bare soil .

remote sensing of the earth from space has gone through a rapid evolution in the last two decades, from a laboratory curiosity to daily operational systems.

As we enter the space shuttle era, which will allow one to transport larger and heavier satellites into space at cheaper costs, the use of passive microwaves for earth remote sensing will witness an even faster growth in the future. Is a picture of the microwave brightness temperature of the world obtained from a microwave radiometer [4] called the electrically scanning microwave radiometer (ESMR). it is evident that the microwave brightness temperature distribution is quite different from the physical temperature. Although the physical or thermodynamic temperature (based on the absolute scale, in Kelvin's) of the earth's surface is fairly uniform, in terms of the microwave brightness temperature scale the land masses stand out much hotter (250 to 280 K) compared with the cool oceans (200 K or less). This is because the land area, in general, has high emissivity, in the range of 0.7 to 0.9. Vegetation and forest covers increase the emissivity over bare soil surface moisture, on the other hand, reduces the emissivity. A calm ocean surface has a low emissivity.

Their longer wavelengths, as compared with visible and infrared, microwaves have an important advantage because they can penetrate through the clouds. Therefore they work in nearly all weather conditions. In addition, there are unique features in the microwave spectrum. For example, the presence of water in soil decreases its emissivity. This fact can be used to measure soil moisture. The longer wavelengths can better penetrate the vegetation coverage to sense the underlying soil moisture. Because of the long wavelengths, however, microwave radiometers need relatively large antennas for good angular resolution.

Furthermore, in order to cover large areas of earth from an orbiting satellite (in a typical low earth polar orbit) the antennas must be able to scan large angular limits (such as +5oo). Also, remote sensing radiometers usually need several frequencies that are widely separated from one another. To top off these demanding requirements, remote-sensing radiometer antennas must have extremely high beam efficiency and low side lobes. The radiometer must be well calibrated and maintain good stability. In addition, there are the usual space flight constraints. It must be lightweight, compact in size, and produce a minimum of heat and mechanical perturbation. In short, the overall performance and engineering requirements of a satellite microwave radiometer antenna for earth remote sensing can be very stringent.

A few of the more important applications of passive microwaves in earth remote sensing are discussed next. For more detailed information, the reader is referred to a recent review article.

4.2.1 The Atmosphere

Probably the most useful application of earth satellite remote sensing is the gathering of atmospheric data for meteorological purposes. Because the atomies in a continuous state of change, frequent samples (in both time and space intervals) are needed for weather forecasting. Measurements from orbiting satellites are the most economical methods used to meet this type of data requirement. Microwaves also have an advantage of being able to operate in cloudy regions, where most meteorological actions occur.

Oxygen and water vapor play dominant roles in shaping the absorption spectrum of the atmosphere. The lower curve is for dry air (US Standard, 1976) and the upper curve is for humid air with login surface water vapor content.

Temperature Sou!2ders~Microwave temperature sounders typically use the 60-GHz oxygen band to measure the atmospheric temperature profiles. This is based on the principle that the oxygen mixing ratio is fairly uniform in space and constant in time; hence the magnitude of the microwave brightness temperature is uniquely related to the atmospheric temperature. By having several frequencies (or channels) spreading down the wings of the 60-GHz oxygen band, each channel will sense a different layer of the atmosphere. The very opaque channels sense only the very top of the atmosphere, as the radiation from the lower layer of the atmosphere is highly attenuated and never arrives at the satellite. The more transparent a channel is, the deeper it will probe into the atmosphere. The complete temperature profile can be retrieved from the brightness temperatures and the associated weighting functions of all the channels.

Microwave temperature sounders are in routine use today [8]. For example, the microwave sounder units (MSUs) are aboard the National Aeronautics and Space

Administration's (NASA's) TIROS-N, and the US National Oceanic and Atmospheric Administration's (NOAA-series) weather satellites. A similar sounder called the special sensor microwave/temperature (SSM/T) is on the US Air Force's defense meteorological satellites (DMSs). The hardware aspects of these sounders will be discussed in more detail in Section 3. The oxygen line at 118.75 GHz can also be used for temperature sounding [9]. A major advantage of this frequency is that it needs smaller antennas (as compared with the 60-GHz band), which can be very important for geosynchronous satellites.

Humidity Sounders-The 22-GHz water vapor line has been used for sensing total water vapor content (humidity) over the ocean.

The very opaque water vapor line at 183 GHz can be used to ascertain humidity profiles. In addition to the temperature and humidity profiles, window frequencies can also be used to measure precipitation distributions. The measurement is based on brightness temperature contrast between the precipitation and the background. For example, at 18 GHz rain cells will appear as warm areas, in contrast to the rather cold ocean, because of their absorption. The rain cells will appear to be colder than the background at high frequencies and high intensities, when scattering is dominant [11]. In addition, satellite radiometers can be used to monitor other species in the atmosphere, such as 03, CO, and so on [12].

4.2.2 The Ocean Surface

Sea Surface Temperature-The microwave brightness temperature of the ocean is the product of the sea-water thermal temperature and its surface emissivity. The latter is also a function of thermal temperature. The sensitivity of emissivity to thermal temperature change is maximum at 4 to 5 GHz; therefore this is the region of frequency for sea surface temperature measurement [13]. One must also account for emissivity variations caused by other reasons, such as surface roughness (due to waves) and/or atmospheric water.

Sea Surface Wind Speed-When the wind disturbs a calm sea the surface emissivity increases from that of a smooth plane surface determined by the Fresnel equations. As the sea becomes very rough, patches of foam begin to form. This also increases the surface emissivity. These relationships can be applied in determining the sea surface wind speed from radiometric observations [14].

Sea Ice-Sea ice has a microwave emissivity value of 0.8 to 0.9 (at nadir), as compared with the value of about 0.3 to 0.6 for calm sea water. Hence, radio metrically, sea ice appears as a warm island against a cold sea-water background. Moreover, microwave radiometers can differentiate between new ice, which is warmer, and the old, multiyear ice, which is comparatively colder. Sea ice concentration maps, derived from orbital microwave radiometer measurements, are very useful in guiding ship routing near the polar regions. Repeated time-series images of the polar region allow one to study and monitor annual polar ice boundary evolution is an image of the microwave brightness temperature of Antarctica in the winter of 1974. The data were taken from the ESMR on the Nimbus-5 satellite at a wavelength of 1.55 cm.

4.2.3 Land Applications

There are two major applications of remote sensing with microwave radiometry over land: soil moisture and snow cover.

The need for regional or global data of soil moisture at frequent time intervals can be more efficiently met by remote sensing with microwave radiometry. The conventional point-by-point in site snow survey is inadequate and expensive.

The uses of soil moisture information are numerous. For example, in hydrology, area-wide soil moisture measurements are needed to assess regional drought conditions. Soil moisture information is also a basis for computing the watershed runoff coefficient, which is used for flood predictions. The evapotranspiration of soil moisture is a part of climate study. The soil moisture, at some critical period of the growth cycle of a plant, determines the yield of that crop at harvest. Timely soil moisture information can be used for irrigation control and yield forecasting.

Timely information on snow-covered areas and water equivalent (amount of water depth or water stored per unit area) in mountain watersheds, such as the western states of the

United States, is difficult and expensive to gather during the winter. This snow pack information, however, is important in forecasting the amount of water runoff, which is the basis for the management of this limited and precious natural resource. The passive microwave remote-sensing technique is capable of providing such snow pack information.

Soil Moisture-Water has a much larger dielectric constant than that of dry soil, particularly at lower microwave frequencies, below 5 6Hz. The presence of water in the soil increases the dielectric constant of the mixture and consequently lowers its surface emissivity.

A change in emissivity by 0.3 corresponds to a change in microwave brightness temperature of 80 to 90 K. An orbiting microwave radiometer can achieve measurement precision on the order of 1 K. Therefore a microwave radiometer can differentiate not only dry from wet areas, but it is also capable of resolving many levels of soil moisture content.

There are, however, factors that tend to complicate the quantitative determination of moisture content, and research is currently under way to resolve them. The soil dielectric constant is also dependent on the type of soil, because the bounding force between water and the host soil depends on the type of soil. Surface roughness also affects the emissivity. The presence of a vegetation canopy increases the emissivity. The net results are that both vegetation canopy and surface roughness tend to reduce the sensitivity of microwave radiometry techniques to measure soil moisture. (Sensitivity is defined as change in microwave brightness temperature per unit change in soil moisture.)

The lower microwave frequencies, from 1 to 5 6Hz. are better suited for soil moisture sensing. This is primarily because the difference between dielectric constants of water and dry soil is larger at lower frequencies Also. longer wavelengths in this range can penetrate deeper into soil and are less vulnerable to the masking effects of vegetation cover and surface roughness. However, a drawback of this low frequency range is that it requires a large antenna for use from satellites. The 1.4-6Hz (21-cm wavelength hydrogen line) protected radio astronomy band is a good compromise frequency for the previously mentioned factors.

Snow Hydrology When a land area is covered by a layer of dry snow its brightness temperature decreases. This is because snow particles scatter background land emission. The snow particles also absorb and reemit the background radiation but this is relatively unimportant; the scattering is the dominant loss for dry snow. The brightness temperature of a snow pack decreases as the snow depth increases. This relationship is used for remote sensing of snow depth by microwave radiometers decrease in brightness temperature of 60 K has been measured for a snow depth of 60 cm. When a snow pack begins to melt, the presence of liquid water drastically increases the absorption. As a result the snow pack brightness temperature increases substantially. This fact can be used to monitor the onset of snow pack melting.

As in the case of soil moisture, there are also complicating factors in quantitative determination of snow depth or its water equivalence. The dominant scattering loss implies that the snow pack brightness temperature also depends on snow grain size. Snow pack with smaller grain size scatters less and is, therefore, warmer as compared with larger-grain snow pack. Ice layers embedded in the snow also modify the brightness temperature. Because of these factors multiple frequencies are needed to resolve ambiguities.

4.3 Survey of Existing Space borne Microwave Radiometer Antennas

Characteristics of most existing satellite microwave radiometers. Unless mentioned otherwise the country of origin of the satellite is the United States. Most of the radiometers listed are for earth remote sensing, with the exception of Mariner-2. All radiometers are the Dicke switching type.

The atmospheric spectrum up to 240 GHz. Most of the present remote-sensing microwave radiometers use frequencies to the left of the 60-GHz oxygen band. This oxygen band has been used for atmospheric temperature sounders because of the well-behaved oxygen mixing ratio in the atmosphere, as mentioned previously in Section 2.

The 60-GHz oxygen band actually contains a complex hand of many individual lines which manifest themselves at higher altitudes. The fine structures of the dominant lines of this band and the frequencies used by many of the microwave temperature sounders. in a one-way zenith opacity in units of optical depth (OD, where 1 OD = 4.3 dB) versus frequency. These 60-6Hz band lines are the rotational lines of the oxygen molecules. Base numbers are the rotational angular momentum quantum numbers, and the superscript signs indicate the sign of the total angular momentum Changes in a transition. The up-pointing arrows indicate the center frequencies of microwave temperature sounders.

The numbers following each -acronym are the channel numbers of that sensor. Generally, the numerical designations of the channels are arranged in the order of ascending sensing height. This feature can also be seen from the opacity curve. The greater the opacity of a channel, the higher it senses above ground.

Note that most of the frequencies are situated at a ~valley'~ between two lines. This is because of two conflicting requirements of a microwave radiometer to be used as a temperature sounder. As we shall see later, the radiometric measurement precision AT (generally referred to as the temperature senility) is inversely proportional to the square root of the bandwidth. Hence the larger the bandwidth, the better the precision. However, a given point on the opacity curve is related to a particular height of the atmosphere. The (1 to 10 GHz, nadir). Humid air and rain show up as higher the opacity, the higher is 0.6 warm areas against the cool ocean background. This is particularly evident in the microwave atmospheric spectrum of the intertropical convergence zone (ITCZ) around 10^0N, S latitudes.

The particular frequencies used for a space borne microwave radiometer depend on the physics of the problem concerned, as well as the transmission characteristics of the atmosphere. The microwave spectrum of the atmosphere due to oxygen and water vapor. The major opaque lines are the oxygen lines at 60 and 118GHz, and the two water vapor lines are at 22 and 183 GHz. For radiometers whose primary purpose is sensing the earth's surface, one would use the so-called window regions between the opaque lines, such as 150, 90, and 30 GHz, or lower frequencies, below the 22-GHz line. Water vapor lines are used to sense atmospheric humidity and the oxygen lines to sense atmospheric temperature.

Like their infrared counterparts, microwave radiometers operate day or night since they rely on thermal emission rather than sunlight reflections.

In order to obtain good vertical resolution in temperature profile it is better for a channel to receive the energy from only a very narrow bandwidth (approaching a point on the spectrum) so that it senses only a very thin layer of the atmosphere (at a chosen height). A too-narrow bandwidth, however, can result in poor (large-value) temperature sensitivity. The valleys are locations where the opacity varies slowly with frequency; hence they allow the use of a maximum of bandwidth to improve the temperature sensitivity but pay little penalty in degrading the vertical resolution. There is also a single oxygen line, which can also be used for temperature-sounding purposes, but this line has not been fully explored yet. Because of its shorter wavelength (by a factor of 2), as compared with 60 GHz, this 118.75-GHz line has the advantage of affording a smaller antenna size. This feature will be a substantial factor in consideration of temperature sounding from a geosynchronous orbit. (See Section 6 for a discussion of a proposed geosynchronous satellite for severe weather monitoring from a geosynchronous orbit.) Other dominant atmospheric lines are the water vapor rotation lines at 22.2 and 183.3 GHz. Either of these lines can be used to sense the atmospheric humidity. The 22.2-GHz line is a weak line and can only yield the total (integrated) perceptible water. This line (or its vicinity) has been used by many remote sensing radiometers, e.g., Nimbus-7 and Seasat's scanning multichannel microwave radiometer (SMMR). The stronger 183.3-GHz water vapor line can be used to obtain humidity profiles. Because of the state of the art of millimeter-wave technology the use of this line is' still in the experimental stage. But it is anticipated that a satellite humidity sounder, based on the 183.3-GHz water vapor line, will be developed soon. (See Section 6.) There are the so-called window regions of lesser absorption around 30, 90, and 150 GHz, with varying degrees of opacity. The 30-GHz window has been a popular one (e.g., Nimbus-6 ESMR and Nimbus-7 SMMR) because the microwave components are readily available at this frequency and reasonably high spatial resolution can be obtained. The 90-GHz window is starting to be used for its high-resolution capability as the microwave components at this frequency become more available. The region around 5 to 6 GHz is an important one, because it is the optimum frequency for sea surface temperature measurement. The region between 1 and 2 GHz is sensitive to soil moisture because of the dispersion of water molecules.

4.4 Fundamentals of a Microwave Radiometer

A microwave radiometer is similar to a communication receiver except that its main signal is not a coherent carrier signal; its "signal" is the antenna (noise) temperature that a communication receiver is trying to minimize. A radiometer measures the magnitude of the noise power (brightness temperature) radiated by a target or scene. A microwave radiometer consists of an antenna for collecting the incoming radiation, whose intensity (in watts per square meter) is represented by the antenna noise temperature T, (to be called simply "antenna temperature" for short) and a receiver for detecting and determining magnitude of the noise power. The receiver may consist of a preamplifier followed by a detector, or just a detector. It could also be a heterodyne system. Which the incoming noise power is mixed with a local oscillator and down-shifted to an intermediate frequency before it is detected by a detector.

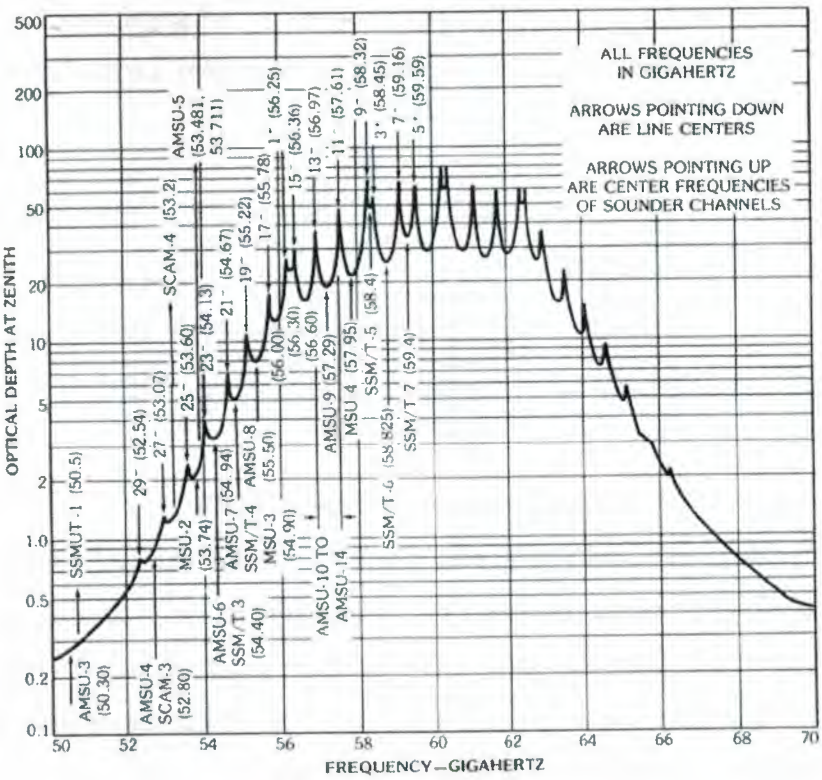

Figure4.2 Total power radiometer.

The output of the receiver (in voltage or digital count) is linearly related as in any instrument there are errors in a measurement. The errors in a radiometer measurement can be divided into two categories. One is the random, short-term (fast) fluctuations of the output, mainly associated with the noise of the front-end detector of the radiometer system (e.g., the mixer or first-stage amplifier). The other is the systematic errors (which may be slowly varying), resulting from calibration bias and component degradations. The former is commonly known as temperature sensitivity (or temperature resolution), and the latter is termed calibration accuracy.

Temperature sensitivity, commonly represented by the symbol AT, is the precision of the radiometer. It is defined as the ~minimum detectable change of antenna temperature at the collecting aperture. The mini-mum detectable change is taken to be the standard deviation of the radiometer output when its antenna is viewing a specified constant-brightness-temperature target.

Total Power and Modulating Radiometers The radiometers a "total power" radiometer. Its temperature sensitivity AT, referred to the radiometer input point *B,* is given by

,

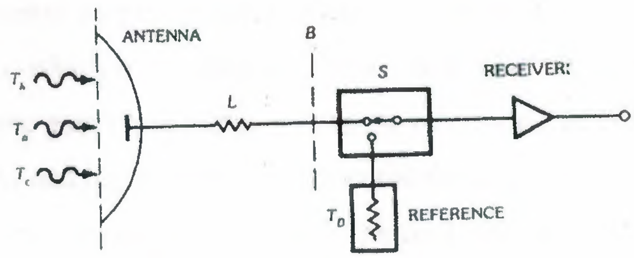

FIGURE4.3 Radiometer modulation

in order to remove the contribution to AT due to gain fluctuations, a 'modulating" method was introduced by R. M. Dicke and is now commonly crown as the Dicke radiometer. Fig. 9 is a block diagram of a simplified Dicke radiometer. The receiver is switching between the antenna ***Ta'*** and a reference load kept at a known temperature *TD.* Since in each half-period of a switching cycle the gain of the radiometer is measured by switching it to the known-temperature *TD* load, any gain fluctuation slower than the switching rate is removed. The spectrum of gain fluctuation normally has a 1/fdependence on the frequency, and as long as the switching rate is high enough, the AG noise can be removed or substantially reduced.

Most space borne microwave radiometers are the modulating type, and their modulating frequencies are in the 400- to 1000-Hz range. For example, the ESMR has a modulation frequency of 600 Hz; the SMMR and MSU have 1000 Hz.

4.5 Calibration

To remove systematic errors the complete radiometer system must be calibrated externally from time to time by introducing a known temperature at the antenna aperture This is needed because during either of the two half-cycles of a modulating period the radiometer output always includes a component which isthe receiver noise temperature Trn_1, which is usually much larger than either ***Ta*** or ***TD*** Therefore, if one were to rely on the gain determination from the reference half-cycle alone, the precise knowledge of ***Tr,i*** and its constancy are essential for accurate calibration In practice it is sometimes more convenient to devise frequent onboard calibrations which will eliminate the need to know the exact value

A commonly used calibration method is for the antenna to view two external targets at ***Tb*** and ***Th*** (for hoi and cold temperatures, respectively) so that the entire radiometer system, including the antenna, can be calibrated A second, often less satisfying, method is to use two "matched" loads maintained at ***Th,*** and ***Tc,*** respectively, and connected between the receiver and the antenna as shown in Fig 10 Switch S oscillates at a typical rate of about 1000 Hz Switch S1 is normally connected to the antenna. During calibration Si is first switched to ***Th,*** then to ***Tc*** The corresponding output voltages, ***Vh,*** and ***Vc,*** determine the calibration equations With the incorporation of ihe two-point calibrations one only needs to relate the amplitude of the demodulated voltage (which is proportional to the difference between ***Ta*** and ***TD)*** and ***Th*** and ***Tc,*** it is not necessary to know ***Tr,i*** and the gain values explicitly As long as the radiometer system transfer function is linear, any desired antenna temperature ***Ta*** can be interpolated from a calibration curve.

In principle the two-point calibration procedure is needed only once in a prelaunch laboratory test. In practice, however, because of the possibility of slow drift (component degradation) it is a better idea to provide periodic in-orbit calibrations with external calibration targets or matched loads, especially for total power types

The matched loads calibration method its less desirable because it does not include the antenna characteristics in the procedure, and it also introduces additional losses due to the switch S_1 In satellite operations, however, it is not always feasible to have onboard calibration targets due to their bulkiness. Hence, sometimes the more compact matched loads must be used For example, in the cases of the Microwave

Sounder Unit (MSU) and the scanning microwave spectrometer (SCAMS), onboard reference targets were used for through-the-antenna calibration. In these two cases the sizes of the antennas involved are relatively small, and the required calibration accuracy is high. However, because the antenna aperture sizes were too large (0.8 m in diameter) in the cases of scanning multichannel microwave radiometer (SMMR) and the Electrically Scanning Microwave Radiometer (ESMR), **it** was impractical to construct external targets, and matched loads were used as hot references. And space-viewing horns were used as cold references for both SMMR and ESMR

4.6 Special Requirements for Remote e Sensing Microwave Radiometers

There are several special features of antennas that are very important to remote-sensing radiometry, although they may not be important in other fields, such as communications These features are the following:

High beam efficiency

- Low ohmic loss
- Large scanning angle limits
- Provisions for accurate calibration
- High polarization purity

4.7 Beam Efficiency and Spatial Resolution

Power received by a radiometer antenna is the total sum of power from all directions Since the power is proportional to temperature we can relate the antenna temperature Ta(Ω) to the brightness temperature Tb(Ω) as follows

$$T_a(\Omega') = \frac{1}{4\pi} \int G(\Omega,\Omega')\, T_b(\Omega)\, d\Omega \qquad (4\text{-}1)$$

where Ω' = (θ',ϕ') is the direction the antenna main beam is pointing, $d\Omega$ = $\sin\theta\, \mathrm{d}\theta\, \mathrm{d}\phi$, with the integration being over 4π steradians, and the antenna directive gain /over isotropic media is such that

$$\oint G(\Omega)\, \mathrm{d}\Omega = 4\pi \qquad (4\text{-}2)$$

The main beam efficiency (or simply beam efficiency) ε_{MB} is the ratio of the power in the main beam to the total power received by the antenna. And the antenna is assumed to be in an isotropic environment (I e., the brightness temperature is not a function of angular direction). The extent of the main beam has been customarily defined as the null-to-null beamwidths (NNBWs). However, the "2.5 times half-power beamwidth" definition has also been used frequently in place of the null-to-null definition because in practical antennas, due to phase errors, there may not be distinct first nulls In the following the 2 5 (HPBW) is defined as the main beam width for beam-efficiency computation purposes The beam efficiency is

$$\varepsilon_{MB} = \frac{1}{4\pi} \int_{m} G(\Omega)\, \mathrm{d}\Omega \tag{4-3}$$

$$\varepsilon_{MB} = \frac{1}{4\pi} \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\theta_{MB}} G(\theta,\phi) \sin\theta \,\mathrm{d}\theta\, \mathrm{d}\phi \tag{4-4}$$

where θ_{MB} is 1.25 x half-power beam width.

The stray efficiency ε_{ST} is the fraction of power outside of the main beam [29]:

$$\varepsilon_{ST} = \frac{1}{4\pi} \int_{ST} G(\Omega)\, d\Omega \tag{4-5}$$

where the limit ST is 4π - MB (i.e., the angles outside the main beam), and

$$\varepsilon_{MB} + \varepsilon_{ST} = 1 \tag{4-6}$$

From (1), (2), and (3),

$$T_a(\Omega) = \overline{T}_{bMB}\varepsilon_{MB} + \overline{T}_{bSL}\varepsilon_{ST} \tag{4-7}$$

where

$$\overline{T}_{bMB} = \frac{\int_{MB} G(\Omega,\Omega')\,\mathrm{T}(\Omega)\, d\Omega}{\int_{MB} \mathrm{G}(\Omega,\Omega')\, \mathrm{d}\Omega} \tag{4-8}$$

So $\overline{T}_{bMB}$ is the "average" brightness temperature within the main beam Similarly, $\overline{T}_{bSL}$ is the average brightness temperature of the side lobes .

The desired quantity is $\overline{T}_{bMB}$ but the direct radiometer antenna measurement yields only Ta, which includes contributions from side lobes.

In designing the antennas for microwave radiometers, it is important to achieve high main-beam efficiency (frequently 90 to 97 percent is required) In an ideal case, $\varepsilon_{MB} = 1$ and $\varepsilon_{SL} = 0$; then, $T_a = \overline{T}_{bMB}$ the desired brightness temperature of the main-beam area, can be obtained directly from the radiometer measurement .

Usually this is not the case, and the term T_{bMB} must be solved from (7) in terms of T_{bSL} with the main beam and side lobe (stray) efficiencies, ε_{MB} and ε_{SL}, respectively, obtained from careful measurements of the antenna The side lobe temperature term in (7) must be provided by some other means For example, if the radiometer antenna scans the complete area cell by cell, then an interactive algorithm can be set up such that the side lobe term of one cell can be computed from the measurements of its immediate neighboring cells .

The beam efficiency as seen in (3) can be further defined for a single polarization For example, if a vertically polarized beam is desired, $G(\theta,\phi)$ in (3) can be changed into $G_v(\theta,\phi)$ to signify that only the directive gain of the vertically polarized wave in the main beam is to be counted .

The polarized beam efficiency is slightly lower than the nonpolarized beam efficiency, because there are always some mechanisms which tend to produce cross-polarized components of energy at the expense of the main polarization. For wave guide slotted array antennas the cross-polarized component could result from stray coupling and mechanical imperfections from the slot radiators For reflector-type antennas the curvature of the reflector will always give rise to some cross polarization even if everything else is perfect The curvature-related cross polarization decreases with the increase of the focal length to diameter ratio Imperfections in feed horns and orthomode transducers may also contribute to the cross polarization

The lowering of beam efficiency due to cross polarization is not a major source of concern in most reflector antenna designs for radiometry because the change caused by it Is small The more detrimental effect is the cross-polarization component of directive gain that will leak some of the orthogonally polarized emission from the earth's surface This mixing of the vrong polarization can deteriorate the accuracy for some applications For example, a radiometer antenna designed for the horizontally polarized brightness temperature of a calm sea surface, at an incident angle of 50^0 is expected to see a brightness temperature of about 80 kelvins The brightness temperature of the vertical polarization component at this same angle will be about 150 K. Hence a 2-percent contribution from cross polarization could cause a I 4-kelvin error, which is appreciable if not accounted for Of course, leakage in the orthomode transducers following the feed horn or the switches (if used) will result in the same effect.

Both accurate calibration and high beam efficiency are important features of a microwave radiometer to ensure accurate mapping of scene brightness variation However, each affects the radiometer performance differently The calibration accuracy affects the bias error of the brightness throughout an entire area containing many spatial resolution cells-all being affected equally.

The effect due to low beam efficiency, on the other hand, is to degrade the scene brightness contrast The effect of high beam efficiency is similar to a low integrated side lobe in a synthetic aperture radar (SAR), which prevents low-contrast targets from being "washed out " For the SAR, only the contrast is of importance in most cases, the absolute radar cross section is not always crucial In radiometry, however, one needs both the relative contrast and the correct absolute value of the brightness temperatures of individual resolution elements.

4.8 Spatial Resolution

Spatial resolution is the 'footprint" size, or the diameter of the antenna's main beam projected on the earth's surface The term instantaneous field of view (IFOV) is also commonly used in satellite remote sensing to mean the spatial resolutions If the antenna beam is a right circular cone of beam width θ_b . then the spatial resolution is the diameter the intersection of the cone and the earth's surface

In general, the intersection is a pear-shaped figure. and its size can be specified by a major and minor diameter, Q_M and Q_m respectively For a scanning antenna the IFOV may vary with scan angle And the minimum values of Q_M and Q_m are customarily taken as the spatial resolution values When the antenna is pointed at nadir, the footprint at nadir is a circle with a diameter $Q = h\theta_b$. where h is the satellite orbital height above the earth's surface .

The beam width θ_b is defined as the half-power beam width of the antenna main lobe It is related to the Raleigh criterion, which states that two point sources are beam broadens. Spatial resolution determines how small a scale the scene spatial variation can be resolved. But in order to faithfully reproduce scene brightness variation, a radiometer must have a high-beam-efficiency antenna High resolution (narrow beamwidth) can be achieved with a large-aperture antenna For a given antenna aperture size, high beam efficiency can be achieved by highly tapered aperture illumination (in addition to other design precautions, such as minimizing phase errors).

High taper, however, is an inefficient way to use the aperture and leads to low aperture efficiency and consequently broadened beamwidth In many microwave radiometer antennas, high beam efficiency is deemed to be of greater importance than narrow beamwidth, and it is often obtained at the expense of lowered aperture efficiency by using highly tapered aperture illuminations.

4.9 Losses

The losses may be categorized as (1) ohmic or (2) scattering. Ohmic loss results from reflector surface resistivity, waveguide feed losses, filter losses, and so on. The scattering losses result from redistribution of energy from the main lobe into other regions of the side lobes and back lobes The scattered energy may also occur because of undesired cross-polarized energy due to reflector curvature, feed horn cross polarization, reflector surface distortion, and the like.

The ohmic loss degrades the radiometer temperature sensitivity ΔT by increasing the effective system noise temperature as indicated in (28a) Ohmic loss also tends to deteriorate the calibration accuracy of a radiometer due to the self-emission term in (28d) because both the physical temperature of the loss element and the magnitude of the loss contain some uncertainties. Ohmic loss, however, does not affect the beam efficiency ε_{MB} [see (3)] as long as it can be considered\a lumped element so that the loss does not depend on direction. Even though ohmic loss diminishes the antenna gain, it does not affect the spatial resolution either, as long as it is not direction (angle) dependent .

Generally the nonohmic losses involve redistribution of energy and may affect any or all of the three radiometer performance parameters beamwidth, beam efficiency, and temperature sensitivity Any scattering loss that reduces the energy received by the antenna also degrades the radiometer temperature sensitivity by the same factor.

For example, any impedance mismatch causing reflection will lower the energy received, therefore increasing the ΔT value The mismatch loss L' affects the temperature sensitivity as does the ohmic loss in (28a), except that there is no self-emission term In other words, one can obtain ΔT from (28b) due to reflection by replacing L with L' and setting T_P =0

An example of the scattering loss is the antenna reflector surface roughness effect. The roughness produces a random scattering of energy into wide angles (as compared with the coherent main beam) and increases the side lobe envelope The end result is to reduce the main beam efficiency The reduction in beam efficiency can be calculated from Ruze's expression for gain reduction :

$$G = G_0 e^{-(4\pi\varepsilon_{rms}/\lambda)^2} \quad (4\text{-}9)$$

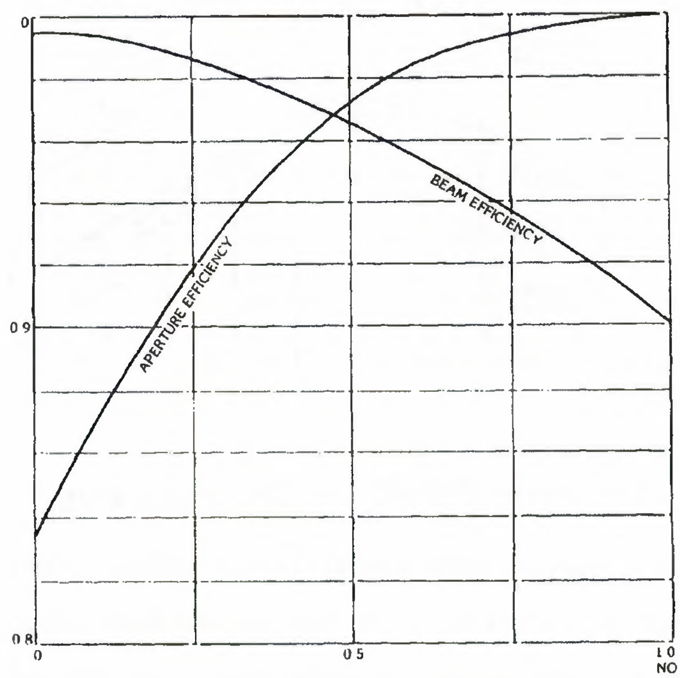

Figure 4.4 APERTURE TAPER *[K_1/(K_1 +K_2)l*

Aperture taper and aperture and beam efficiency (a) For a one-dimensional aperture as a function of taper *(b)* For a circular aperture as a function of taper and phase error.

- G = antenna gain of antenna with surface roughness

- G_0 =antenna gain of a perfect antenna with no surface roughness
- ε_{rms} =rms surface roughness
- λ = wavelength

4.10 Beam Scanning

Most of the remote-sensing microwave radiometer antennas are required to perform scanning of some kind The purpose of scanning is to produce a two-dimensional image of an area of the earth Different types of scanning are discussed in the following paragraphs.

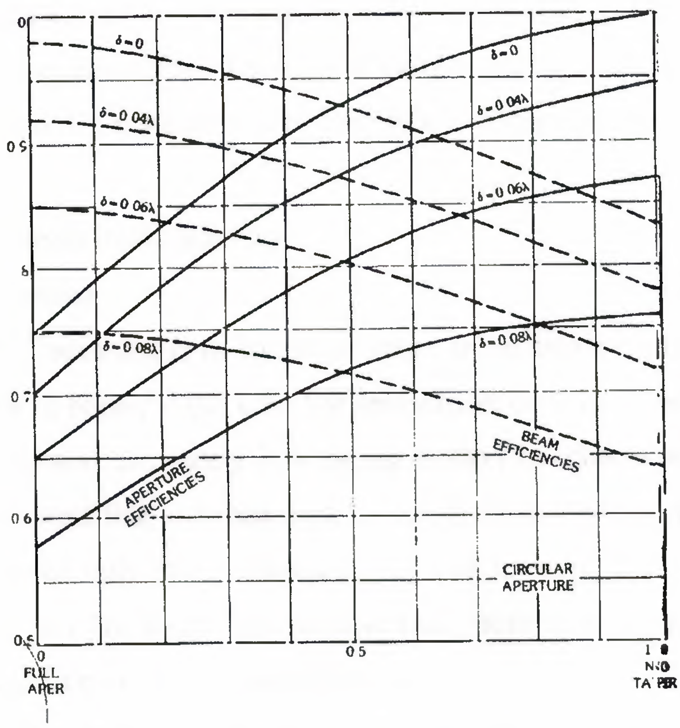

Figure 4.5 APERTURE TAPER $1K_1/(K_1.K_2)1$

For a spinning satellite, such as the Geostationary Operational Environmental Satellite (GOES), which spins about an axis parallel to the earth's polar axis. the spinning action provides an east-west scan motion and a radiometer on board only has to provide a north-south stepping motion at the end of each scan line .

But the spin-scan is an inefficient scan method in the sense that most of. Lie availabl time is not fully utilized for viewing the earth scene For example for each revolution the GOES satellite spins 3600 but only a maximum of about 17^0(Which is the angle the earth subtends from the geosynchronous orbit) can be used for observation. Therefore the "spin-scan" efficiency (which is the ratio of observation time to available time per spin period) can be 4.7 percent. At best If one only wishes to map a small portion of the earth disk, then the spins an efficiency e_{SP} is even less than 4.7 percent The future GOES satellites are most likely to be of the three-axes stabilized type and the radiometers on board must be able to scan their antenna beam in both E-W and N-S directions.

4.10.1 Scanning Requirement for Polar Orbiting Satellites

Radiometers flying on polar orbiting satellites (typical orbit height 700 to 1000 km above the earth's surface) known as low earth orbiting (LEO) satellites only have to scan in one dimension. The orbital motion provides the scan action in the north south or the down-track direction. Two types of scanning are commonly used in LEO satellites:

- planar, or cross-track, scanning
- conical scanning

The purpose of scanning is to create an image of an area by successive scan lines of a narrow beam In principle the scan line (movement or trace of beam) can move in both directions (senses) alternately in a zigzag motion In other words the beam can move from east to west first and then west to east in the second line, and so on Or, the beam can be scanned only in one direction, say east to west, during which time the radiometer takes data The beam then retraces back from west to east quickly for the beginning of a second scan line of data collection .

Since the LEO satellites continuously move in orbit, scanning in both directions (with a beam that moves only in the cross-track direction) will result in a zigzag footprint track on earth This problem can be rectified by providing a beam motion in the down-track direction to compensate for the satellite orbital motion. While this compensation can be realized with relative ease for optical imagers (e g , multispectral scanners [MSSs] on Landsats), it is much more complicated to provide the motion compensation in the case of a microwave antenna which usually has a much larger aperture As a result microwave radiometers usually scan in the cross-track direction only.

Along a scan line (i e in the cross-track direction) the adjacent resolution cells can be spaced in a variety of ways If the adjacent resolution cells are tangent to one another, it is called contiguous in the cross-track direction.

When the beam is scanned by mechanically slewing the antenna in a continuous motion the resolution cell also moves continuously, and it automatically results in a contiguous pattern in the cross-track direction But if the beam is scanned with a stepping motion (i.e. , it dwells" at a resolution cell position for a length of time and then moves quickly to the next resolution cell), the cell spacing in the cross-track direction can be arbitrarily chosen to be either contiguous, overlapping, or undercoverage (leaving gaps between cells).

As we shall see later, the choice of resolution cell spacing is not completely arbitrary Since the total available time per scan period is fixed, a smaller number of resolution cells per scan line (under sampling) will lead to more integration time per resolution cell, which yields better temperature sensitivity But spatial under-sampling will lose some details of scene spatial variation (aliasing) On the other hand. over sampling (overlap between cells) will result in less integration time per cell and poor temperature sensitivity The choice of spatial sampling frequency involves a trade-off between spatial resolution and temperature sensitivity of a mapping radiometer Within a given time t, a scanning radiometer (assuming a single beam for the moment) must cover an area of A = $sv_g t$.

As the sampling frequency increases, individual resolution cell integration time t_I decreases, resulting in poorer temperature sensitivity The choice of sampling frequency depends on the antenna beamwidth and the degree of cell overlapping .

Let p = d_L/e be the down-track contiguity coefficients; when p =1, there is (down-track) contiguity at nadir. When p >1, there is a gap in the down-track direction, i.e., under coverage at nadir. When p <1, there is some overlap in the down-track direction.

The scan time t_{scan} per line is

$$t_{scan} = d_L / v_g \tag{4-10}$$

Let q <1 be the scan efficiency, which is the fraction of t_{scan} actually used for taking scene data, and let n be the number of resolution cells per line Then

$$t_I = \frac{qt_{scan}}{n} = \frac{pqe}{v_g n} \tag{4-11}$$

For a given total nadir angle scan limit of $2\theta_{nM}$ the number of resolution cells per line is, assuming cross-track continuity,

$$n = \frac{2\theta_{nM}}{\theta_b}, \quad e = h\theta_b \tag{4-12}$$

and

$$t_I = \frac{pqh\theta_b^2}{2v_g\theta_{nM}} \tag{4-13}$$

For earth remote-sensing applications it is usually required that the sensor completely map the earth in a short time period The consequence is that the scan angle limit θ_{nM} must be as large as practical For example. in a LEO polar satellite. such as TIROS-N and the NOAA-series weather satellites, it is desired that the onboard sensors map the earth's atmosphere once every 6 to 12 hours in order to update the state of the atmosphere for weather forecasts. This requires two simultaneous satellites (in two polar orbits whose orbital planes are 90^0 apart), each having to scan to a limit of $\theta_{nM} \cong \pm 50^0$ For other earth resource applications, large swath width is also frequently needed in order to completely map the earth once in two to three days .

Equation 44 shows that the integration time t_I Increases with the square of the beamwidth θ_b or, equivalently, the square of the spatial resolution e Since the temperature sensitivity ΔT is inversely proportional to the square root of the integration time t_I, it is therefore inversely proportional to θ_b In other words, in a mapping radiometer the spatial resolution must be traded off against the temperature sensitivity (unless one can improve the radiometer system noise) Also the large magnitude of the scan angle limit θ_{nM} makes small-angle scan techniques for a reflector antenna (such as mechanical feed displacement in the trans-verse plane about the focal point) impractical

Planar scan has its advantages It is easier to implement. as compared with conical scan One can design an offset paraboloid reflector geometry .

4.10.11 Conical Scan

In conical scanning the beam moves on the surface of a cone Normally, the cone axis is pointed at the earth's center This results in constant incidence angle θ_i and constant footprint size, both features being advantageous in imaging and data interpretation.

For a given orbital height *h*, the ground spatial resolution of a conical scan is not as good as planar scan because the slant range *R* in the conical system is larger than *h* In the conical system, however, the slant range *R* is constant throughout a scan line The cross-track contiguity definition is the same as in a planar scan. except that the direction of cross track is really along the scan line (which is not necessarily perpendicular to the ground track). If the scan time t_{scan} is chosen for the nadir resolution cells to be contiguous in the down-track direction.

The individual cell integration time for conical scanning is also proportional to ~h^2, similar to the planar scan case

As in the case of planar scan the conical scan can also be realized either by mechanically rotating a reflector or by an electronically scanning phased array The scanning multichannel microwave radiometer (SMMR) is an example of conical scan by mechanical rotation of a reflector, and the Nimbus-6 ESMR is an example of conical scan by a phased array the planar array of the Nimbus-6 ESMR is mounted vertically on the Nimbus-6 satellite's sensory ring and its beam is pointed at 6~ from nadir The position of the beam is selected by controlling the phrasings of each vertical wave guide stick. Each beam is dual polarized an orthomode transducer separates vertical from horizontal polarization at the output of the array.

The Nimbus-6 ESMR has a spatial resolution on earth of 42 km (down-track) by 20 km (cross-track) from its 1100-km orbit. The scan time per line is t~, = 5 33 s, corresponding to dL 33 kin, hence p = dL/eM = 33/42 = 0 79, so that there is 21-percent cell overlap in the down-track direction at nadir The Nimbus-6 ESMR takes data while scanning in only one direction and, because it is electronically scanning, the retrace time needed to swing the beam 700 azimuthally is a very small fraction (a few milliseconds) of the 5.33-s scan time.

The SMMR (on both Nimbus-7 and Seasat) is an example of mechanical implementation of conical scanning. There were many reasons and trade-offs leading

to the choice of mechanical scanning of a reflector-type antenna for the SMMR Chief among them was the fact that the SMMR required five frequencies.
ranging from 6 GHz to 37 GHz. and each frequency had both linear polarizations To satisfy this requirement with multiple phase arrays would be impractical for the large earth-viewing areas they would need; heavy weight and high power consumption would also result from multiple-phased array designs.
For a large mechanically scanning antenna such as the SMMR, the "retrace time" can be an appreciable fraction of the scan time and the zigzag shape of the footprint trace on earth becomes a problem As can be seen in the following description of the SMMR. the overlapping zigzag traces were implemented only in its highest-frequency (37-GHz) channels For the four lower frequencies, only one

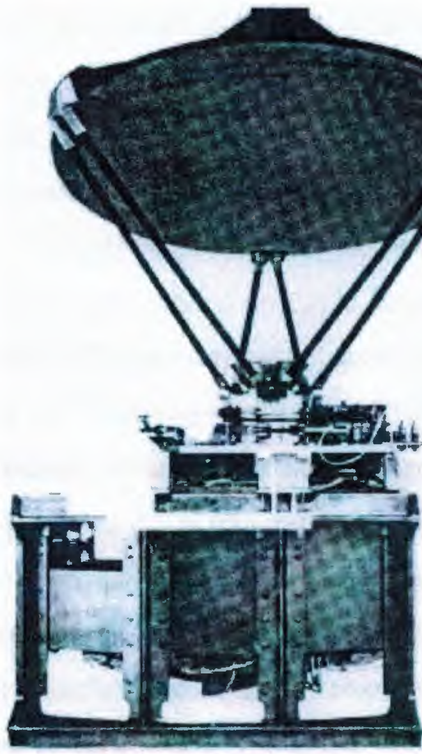

Figure 4.6 Photograph of an SMMR

A beam is formed in the direction of the symmetrical axis of the parent parabola, whose focal point is the phase center of the feed horn The reflector is rotated in a back-and-forth manner about the nadir axis by a drive motor which also drives a counter rotating mass to compensate the spacecraft for the angular momentum disturbance caused by the oscillating reflector
The azimuthally scan angle limit *PM* is ±250

As a result of this design (in which only the reflector moves) the total moving mass (consisting of the graphite epoxy reflector, with major diameter 108 cm by minor diameter 79 cm, ballast and thermal shield) is only 3.4 kg

The total weight of the instrument is 40 kg The reflector first rotates in a clockwise direction for 2 s and then counterclockwise, also for 2 s A total scan time period is *t*= *4* s (actually 4 096 s) This 4-s scan period is chosen so that the 37-GHz footprints (~A1 =27 kin, ~ = 16 kin) are contiguous in the down-track direction (at nadir). The sub satellite speed is ***Vg*** = 6.4 *kmls,* and ***dL*** = 6.4 x 4.096 = 26.2 kin, *orp* = *dLIeM* = .97 Hence it is almost (down-track) contiguous at 37 GHz.

4.10.12 Step Scan Versus Continuous Scan

In a step scan the beam dwells at a given position for a length of time t_I, then moves to the next position and repeats the dwell of t_I , seconds. For large antennas this step scan mode becomes impractical if an appreciable amount of time is required to accomplish the stepping motion, or it may consume too much power in order to move the antenna quickly to a new dwell position An alternative to step scan is to slew the antenna continuously across the total scan angle limit, namely the continuous scan Both the SCAMS and the MSU are step scan types, because their antennas are small and their scan periods are relatively long. The SMMR, on the other hand, is a continuous scan type because its antenna is much larger than that of the MSU or the SCAMS, and the scan period at 4 s is much shorter. In a continuous scan the antenna moves (ideally) at a constant angular velocity, and the resolution cell size along the scan direction is determined by the length of integration time. (Sometimes even a constant angular speed is difficult to obtain mechanically, and some kind of velocity variation with time must be accepted. For example, the SMMR antenna actually has a sinusoidal velocity variation with time.) If, in a continuous scan, the integration time is infinitesimally short, then the IFOV along the scan direction is the antenna beamwidth θ_b . For a continuous scan with a finite integration time the effective field of view (EFOV) along the scan direction is larger than the IFOV In other words the scan motion introduces some smearing effect along the cross-track direction The EFOV depends on the antenna directive gain pattern $G_D(\phi)$ and the length of time a given point of the scene is viewed by the antenna Normally the integration time is set so that the antenna moves one beam width during the integration rime (assuming constant scan velocity).

4.10.13 Scanning Requirements for Geosynchronous Orbiting Microwave Radiometers

Most of the previous discussions on scanning pertain to LEO microwave radiometers The same radiometer can certainly be used at the geosynchronous orbits. The advantage of this type of orbit is that the satellite appears stationary with respect to earth, it allows one to observe an area continually or repeatedly with high temporal frequency This could be important for some applications, such as observing severe storms From the radiometric viewpoint there are two types of geosynchronous earth orbiting (GEO) satellites the spinning and the three-axis stabilized type The present GOES satellites are of the spinning type The other type of GEO satellite is three-axis stabilized, in which the orientation of the satellite with respect to the earth remains unchanged In this case a sensor must scan in two orthogonal dimensions in order to obtain a map of a given area of the earth.

There is at present no microwave radiometer on a GEO satellite, because the required size of the antennas at a 36000-km orbit is relatively large, this makes it difficult and expensive for most launch vehicles to carry With the advent of the space shuttle, however, microwave radiometers for GEO satellites, such as GOES, will soon follow Because of the large orbital height, antennas used for GEO satellites will be much larger in order to achieve spatial resolution. Instead of being tens of centimeters in diameter, the antenna diameter will be in meters There appears to be a very limited utility in having a microwave radiometer on a spinning GEO satellite because of its inherently poor spin-scan efficiency In addition, large moving antennas may present difficult dynamic problems for the spacecraft attitude control system For these reasons, microwave radiometers will likely be used on future three-axis stabilized GEO satellites but not on spinning GEO satellites.

Scanning requirements for a microwave radiometer, from a three-axis stabilized geostationary satellite, are quite different from those of polar LEO satellites The angular scan limits from a GEO satellite are small, since the maximum extent of the full earth disk is only 17^0 but the pointing accuracy must be high The scan velocity can be much slower, although it depends on the size of a scene area to be covered and the temporal repeat frequency needed If a 2500-km x 2500-km area near nadir has to be covered in 15 min, with a resolution cell of 42 km, then each cell has about 0.25 s of dwell time The scan velocity is only 0.26^0/s, which is much slower than the 4.3^0/s MSU scan speed in low earth orbit.

4.11 Polarization

Most microwave radiometers require the reception of linearly polarized waves of either vertical or horizontal polarization, or both The reason for this is that surface emissivity characteristics of the two modes are distinctly different from each other Signals from vertical and horizontal channels can be used *t* delineate the surface from the atmospheric phenomena For example. The absorption due to the presence of moisture in the atmosphere attenuates both vertical and horizontal polarizations equally. While wind-driven sea surface waves affect vertical and horizontal polarizations differently. . The vertical polarization is defined as the mode in which the electric field vector E lies entirely in the plane of incidence (formed by the propagation unit vector $\hat{k}$ and the normal unit vector $\hat{n}$) In other words, the magnetic field H lies transverse to the incidence plane Hence the term transverse magnetic (TM) toned is also used The horizontal polarization is defined as the mode in which the electric field vector E is horizontal (i e transverse to the incidence plane. hence it is also called the TE mode) .

To state it more precisely let $\hat{h}$ and $\hat{v}$ be the unit vectors representing the directions of horizontal and vertical polarization, respectively Then

$$\hat{h} = \frac{\hat{n} \times \hat{k}}{\left|\hat{n} \times \hat{k}\right|} \tag{4-14}$$

And

$$\hat{v} = \frac{\hat{h} \times \hat{k}}{\left|\hat{h} \times \hat{k}\right|} \tag{4-15}$$

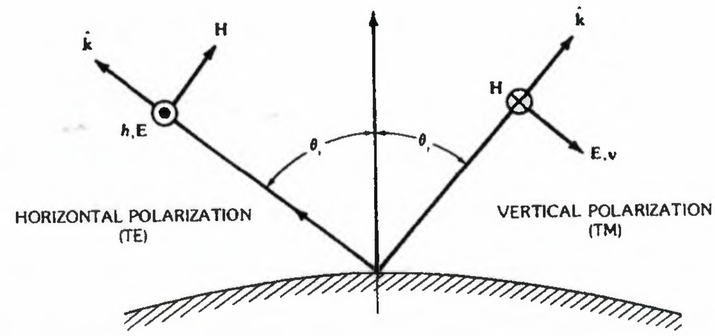

Figure 4.7 Horizontal and vertical polarizations

vertical In fact, as the incidence angle 0, approaches zero (approaching normal incidence) the electric field vector in vertical polarization approaches horizontal At normal incidence there is no distinction between the two polarizations.

For applications where separate vertical and horizontal polarizations are required, the radiometer antenna must be designed for high polarization purity. That is, the amount of orthogonal (cross) polarized component leaking into the main polarization must be kept small. In other words the isolation between the two modes must be good In general. Isolation on the order of 25 dB or better is needed This isolation is the total amount of energy leaked into vertical polarization from horizontal polarization or vice versa It includes reflector curvature induced cross polarization (if a reflector type antenna is used), switch and/or orthomode transducer imperfections, and other leakages.

In scanning antennas such as the SMMR, where only the reflector is rotating and the feed is stationary, each of the two orthogonal feeds receives a linear combination of the vertical and horizontal polarizations.

$$T_{bf_1} = T_{bv}\cos^2\phi + T_{bh}\sin^2\phi \tag{4-16}$$

and

$$T_{bf2} = T_{bv}\sin^2\phi + T_{bh}\cos^2\phi \tag{4-17}$$

where ϕ is the azimuthal scan angle, T_{bv}, and T_{bh}, are the vertical and horizontal polarization brightness temperatures, and T_{bf_1}, and T_{bf_2} are the output brightness temperatures of the two feeds, respectively Temperatures T_{bv},. and T_{bh}, can be computed from the measured T_{bf_1} and T_{bf_2} and scan angle ϕ. This is inconvenient and can also introduce additional errors in retrieving in T_{bv} , and T_{bh} , individually

The alternative is to scan the reflector and the feed as a unit, in which case T_{bv} and , T_{bh} will be decoupled from each other.

Since the front end of a radiometer is normally hardwired to the antenna by waveguides. in scanning with the whole antenna the masses of the radiometer front end must also be carried with the antenna. The penalty in scanning with the whole antenna is that the moving mass is increased and must be compensated for by the spacecraft altitude control system. An example of this type of scan is the SSM/I.

For atmospheric sounders most of the channels do not "see" the earth surface, therefore a pure linear polarization for these opaque channels is not essential Because of this, antenna configurations can used Orthomode transducers are often used as a convenient low-loss channel-depleting technique This is a particularly useful antenna design technique in the case of sounders where a single antenna must be shared by a large number of channels For example, the SCAMS, SSMIT, MSU, and AMSU all have this type of design in which only the reflectors are scanning. The feed horns are stationary, with orthomode transducers at the throat of the horn as diplexers to separate signals for different channels With this type of scan antenna design the output of each port of the orthomode transducer is, in effect, a linear combination of the pure vertical and horizontal polarizations

To put it in another way, the output of each port represents a rotating polarization However, this rotation affects only those channels which see the earth's surface (or see substantial effects of the surface) As it turns out in the case of the MSU, the variation in brightness temperature (due to this) for its window channel (at 50 3 GHz) is very small throughout the entire scan angle limit The smallness in variation is a result of the compensatory nature of the emissivity change and the change in cosine or sine functions For example.

the vertical polarization emissivity ε_v, increases with the scan angle for angles between zero degrees and the Brewster angle. In the same range of scan angles the cosine-squared function decreases monotonically Therefore the first term of (16). which is the product of the two, remains nearly constant Similarly, for the second term, the horizontal emissivity ε_h, decreases with the angle and is compensated by the increasing sine-squared function

4.12 Spacecraft Constraints

Any satellite instrument is subject to the usual constraints of weight, volume (shape), and power limitations as well as thermal and dynamical interactions with the host spacecraft These constraints vary, depending on the type of satellite and other sensors on board.

4.13 Dynamical Interactions

Any momenta produced by scanning motion of an antenna on board a satellite must be compensated Otherwise, the antenna motion will cause a reaction by the host spacecraft, resulting in a change of its attitude For small motion disturbances the excess momenta can usually be absorbed by the attitude control system (ACS) gyros of the host spacecraft For larger antennas, however, the motion may be beyond the capacity of ACS gyros, and momentum compensation devices must be included in the antenna scan system Both the SMMR and the SSM/I contain momentum compensation devices in the form of counter rotating masses driven by the same scan motor.

4.13.1 Thermal Considerations

The thermal environment affects satellite microwave radiometers in several ways:

1. Temperature gradients across a spacecraft antenna can cause shape distortion, which can lead to antenna performance degradation (reduced gain and beam efficiency); this is an important consideration for larger antennas and higher frequencies .
2. Ambient temperature fluctuation can affect the electronic gain stability of a radiometer (especially important for a total-power type radiometer), it can also introduce errors in the calibration by changing the self-emission part of an ohmic loss element
3. For a radiometer mounted externally to a satellite, the instrument frequently has to be almost thermally isolated from the host spacecraft. Frequently the

radiometer must dissipate its heat with its own radiators into the cold space to maintain a suitable temperature.

Weight, thermal, and mechanical considerations have led to the popular choice of graphite epoxy composite material for many spaceboine microwave radiometer antennas, especially for those with larger apertures (1 m in diameter or larger) and shorter wavelengths (1 cm or smaller) For example, both SMMR and SSM/I radiometers have graphite epoxy antennas.

4.13.2 Future Needs and Trends

As remote-sensing microwave radiometry evolves from the research and development stage and becomes mature, we are likely to see some new developments in the following areas of microwave radiometers and their antennas:

1. Low-frequency large antennas (aperture diameters 10 m or larger. L-band) for soil moisture measurements from low earth polar orbiting satellites
2. High-frequency radiometers (100 to 300 GHz) for atmospheric temperature, humidity, and precipitation monitoring from both low earth orbiting and geostationarv orbiting satellites .
3. Multibeam, multifrequency microwave radiometers (with frequencies similar to those of the SMMR and SMM/I) for low earth orbit applications
4. Synthetic aperture antenna radiometry .

4.13.3 Future Space borne Systems

There are several satellite microwave radiometer systems which already exist in various stages of development The SSM/I, currently under development, is scheduled to be launched on a defense meteorological satellite in 1988 The advanced microwave sounding unit (AMSU) [33], proposed for the NOAA-series weather satellites beginning in the early 1990s, is also being developed The microwave scanning radiometer (MSR) [34], proposed for the Japanese marine observation satellite (MOS)-1 [351. and the radiometer for the European Space Agency's (ESA's) remote-sensing satellite (ERS)-1 are both in the planning stage.

The SSM/I is a four-frequency, dual-polarized microwave radiometer system It contains seven individual radiometers. Table 3 is a summary of the 54-kg, 33-W SSM/I's characteristics All four frequencies share a common 66-cm x 61-cm offset parabolic reflector and a multifrequency feed horn The SSM/I scans by rotating the complete antenna-and-radiometer (the antenna, feed horn, and electronics) about a nadir axis in such a manner that the antenna beams scan conically The half-cone angle is 45^0 and the rotation rate is 31 rpm By scanning the reflector and its feed horn as one unit, the vertical and horizontal polarizations of each frequency are decoupled This is one advantage of the SSM/I over the SMMR The penalty for this advantage is that the moving mass of the SSM/I is much larger than that of the SMMR. Consequently a continuous rotating type scan motion has to be adapted The zigzag, oscillating type of scan motion, such as that of the SMMR, !5 impractical for the SSM/I because it would cause too much mechanical disturbance and cannot be compensated easily by the spacecraft attitude control system.

Only 1000 of the 3600 of each scan (rotation) cycle, however, are utilized for data gathering, resulting in very inefficient use of the available scan time This mates the integration time per resolution cell, t_I, extremely short To obtain the required temperature sensitivities, a total-power type radiometer is used for the SS~A/I. Since the scan period is only 2 s, calibrations at the end of each scan cycle are used to remove the gain fluctuations.

The advanced microwave sounding unit (AMSU) is a 20-channel microwave radiometer designed for measuring global atmospheric temperature and humidity profiles from the National Oceanic and Atmospheric Administration's series polar orbiting weather satellites beginning in the earls 1990s

The AMSU is the next-generation instrument of the current microwave temperature sounder MSU It, together with an infrared sounder such as the high-resolution infrared sounder (HRIS-2). will form a combined microwave/ infrared vertical sounding system for the future NOAA weather satellites.

The AMSU system is still in its design stage at the time of this writing; the following is a brief description of the system.

Summarizes the essential channel characteristics as specified for the radiometer.

The functions of each channel are as follows

Channels 2, 15, and 16 are the "window" channels They' are relatively trans Special Sensor Microwave/Imager Characteristics

Frequency (GHz)	Polarization	Beamwidth (0)	Bandwidth (MHz)	Temperature Sensitivity AT (K)	Integration Time (ins)
1935	v&h	18	10to250	04	795
22235	v	16	10 to 25()	07	795
370	v& h	10	100 to 100()	04	795
85 5	v & h	U 4	lot) to 1500	0 7	389

The lower seven channels are for the troposphere, the remaining channels are for the stratosphere. Channel 3 is a quasi-surface channel. It provides a direct surface emissivity measurement at a frequency close to the oxygen band. The weighting-functions' peak heights of the 4 through 14 channels are nearly uniformly distributed from surface to about 40 km Channels 5 through 9 are the "valley" frequencies, i.e., they are at the valley between two oxygen line peaks. The valley channels have the favorable characteristics that permit the use of wider bandwidth and still have narrower weighting-function widths (or sharper vertical resolution) than the normally type Channels 10 through 14 are for the troposphere temperature Because narrower bandwidths are required from a given part of a line at these channels in order to avoid too broad functions, energies from two or four similar portions of a line (or two lines) are combined to form a channel.

This increases the signal-to-noise ratio by increasing the total bandwidth but not broadening the weighting function Channels 10 through 14 exploit the symmetry between lines 13 and 11 Channel 10 combines two portions in the valley between the two lines Each of the channels 11 through 14 combines energies from four pass bands. two each from both sides of lines 13 and 11 Channels 17 through 20 use the strongly opaque water vapor absorption line at 183.3 GHz for obtaining the humidity profile Channels 18, 19, and 20 also combine two portions of energy from both sides of the line to enhance the signal-to-noise ratio. Channels 18, 19, and 20 are 1. 3. and 7GHz. respectively. from the 118 3-GHz line center. Because of its increasing distance from the line center, each succeeding channel has decreasing opacity to the atmospheric water vapor and consequently each ~s sensing primarily d laser of the water vapor closer to the earth surface. Channel 17 contains a single pass band and is located far away from the 183-GHz line It senses water vapor down to the earth surface Both channels 15 and 16 serve essentially the same function except that the latter has a 3 1 surface spatial resolution advantage, and hence will he better suited to delineate fine scene features, such as a weather front.

The AMSU is a total-power microwave radiometer system The high spatial resolution required by the AMSU results in relatively short integration-times for each IFOV; they are about 180 ms for channels 1 through 15 and about 18ms for channels 16 to 20.

Onboard calibration targets are provided for periodic calibrations at the end of each antenna scan period of 8 and 2.67 s.

The AMSU is divided into two subsystems Channels I through 15 are called AMSU-A and are primarily used for temperature sounding Channels 16 to 20 are called AMSU-B, whose primary function is for humidity\ profibng

The antenna designs of the AMSU are similar Because of the large spread in the AMSU's frequency range (23 to 183GHz), four separate reflector type antennas are used. Two with 11-in (28-cm)Apertures, and two with 6-in (15-cm) apertures

Channels 1 and 2 share a reflector with about a II-in (28-cm) aperture diameter Channels 3. 4, 5, and 8 share another reflector with about a 6-in (15-cm) aperture Channels 6, 7, and 9 through 15 use a third reflector also with about a 6-in aperture All of the three reflectors are scanning in s\nchroilous at one revolution per 8 s.

The AMSU-B uses one single reflector of 11-in aperture for channels 16 through 20, which are scanned at three revolutions per 8 5.

The AMSU-A is estimated to weigh 140 lb (63 5 kg) and consumes 115 W of power, while the AMSU-B is estimated to require about 60 lb (27.2 kg) and 60 W of power.

4.14 Large Antennas for Low-Frequency Soil Moisture Mapping

As mentioned in Section 1, the soil moisture content can be determined from measurements by a low-frequency microwave radiometer The frequency range suitable for soil moisture detection is between 1 and 2 GHz, and the most widely used frequency is the 1.41-GHz hydrogen line, which is protected for radio astronomy. At this frequency, a 10 m aperture diameter antenna would produce a 0 60 beam, which corresponds to a 10-km IFOV from a 400-km orbit To provide a wide swath width suitable for global soil moisture mapping, the antenna must be able to scan through at least ± 400 from nadir A likely configuration for such an antenna is a phased array similar to that of the ESMR For antenna apertures larger than 10 m, deployable mesh type reflector antennas with multiple feeds [361 are likely approaches.

4.15 Millimeter-Wave Radiometers

As pointed out in Section 4, there is an oxygen line at 118 GHz that can be used for atmospheric temperature sounding, much like the use of 60 GHz in the SSM/T and MSU. There is also a 183-GHz strong water vapor line that is being used by the AMSU for humidity profiling In addition, there are a host of other absorption lines, at frequencies between 100 and 300 GHz. that can be used to measure other atmospheric parameters and to monitor the abundance of atmospheric constituents One advantage of the 1 18-GHz oxygen line and the 183-GHz water vapor line is that their short wavelengths reduce the antenna size needed This is an important advantage when the radiometer is used from a satellite in a geostatlonary orbit.

CONCLUSION

Remote sensing is the determination of characteristics of physical objects through the analysis of measurement taken at adistancefrom these objects.One important problem in remote sensing is classification of (spectral)measurements taken from different situations on the earth surface.Data can be collected in afew (multispectral)to as many as 200 (hyperspectral)spectral bands.

The aim of using using remote sensing:

- Remote sensing provides a regional view.
- Remote sensing provides repetitive looks at the same area.
- Remote sensing see over a broader portion of the spectrum than the human eye.
- Sensors can focus in on a very specific bandwidth in an image.
- They can also look at a number of bandwidths simultaneously
- Remote sensors often record signals electronically and provide geo-referenced, digital, data.
- Some remote sensors operate in all seasons, at night, and in bad weather.

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