CHAPTER - 1
Introduction

1.1 Preface to the study
1.2 Objective and area of study
1.3 Significance of the study
1.4 Precipitation
   1.4.1 Precipitation Process
   1.4.2 Types of Precipitation
1.5 Basis of Remote Sensing
   1.5.1 Nature of light & electromagnetic radiation
   1.5.2 Black body radiation and laws
   1.5.3 Grey body radiation
   1.5.4 Source of Electromagnetic Radiation for remote sensing
   1.5.5 Propagation of Electromagnetic Radiations through Atmosphere
1.6 Signatures of precipitation and clouds in remote sensing data
1.7 Physical basis of precipitation monitoring using satellites
   1.7.1 Visible and Infra Red techniques
   1.7.2 Microwave band
1.8 Conclusions
Chapter 1 – Introduction

1.1. Preface to the study

Water is one of the most prevalent substances in the Earth-atmosphere system and it is one of the most fundamental to the existence of life. Shortages of fresh water for domestic consumption, as well as suitable water for agriculture and industry have been a critical problem in most parts of the world. Water supply problems already restrict significantly the life of men and the economics of the entire globe. The source of all water in its most desirable state is precipitation. Precipitation is very indispensable in determining the nature of our globe at the very fundamental level. Most of earthly forms of life would not exist without precipitation and, in turn the geology and chemistry of the globe would be quite different. Precipitation is vital for sustaining life by providing pure water over the land. It is the key contribution for oceanic hydrological cycle and as a regulator of salinity, which plays a significant role in determining ocean dynamics and thermodynamics. Precipitation both influences and is influenced by the dynamics of the earth’s atmosphere. On many temporal and spatial scales, the latent heat released by the precipitation is dominant energy source to the atmosphere thereby determines the subsequent evolution of meteorological system. Importance of precipitation is well known in agriculture, hydrology, flood/drought prediction, runoff model and water resource management. Ideally it is substance of life on the earth. Precipitation is any form of water (liquid or solid) that falls from a cloud and reaches the ground.

It is unfortunate, especially in view of man’s need for accurate observations of precipitation amounts and distributions, that rainfall is one of the most variable elements of weather. Precipitation varies notably with respect to its frequency, duration, intensity and spatial pattern, not to mention its propensity to fall as rain, hail, sleet or snow. As the physical state of snow is so different from rain, it results in very different problems of monitoring and possible solutions involving satellites as aids to ground data collection systems. This thesis will focus upon the rainfall to the exclusion of hail, sleet and snow.

Ordinarily rainfall events last up to a few hours. They tend to be shorter where rainfall is influenced by the diurnal cycle of heating and cooling, and longer in topographic situations exposed to moist airstreams and in regions affected by large cyclonic disturbances, e.g. mid-latitudes lows and tropical cyclones when these are slow-moving.
Chapter 1 - Introduction

There is wide range of intensities of rain rate, ranging from practically zero; to above 100 mm/h. Intensity is an inverse function of the duration: the highest intensities are recorded over the smallest intervals. Rainfall is most intense in the tropical region, where 50% of rainfall occurs during 10% of rain interval (Riechl, 1954; Garstang, 1972; Woodley et al., 1974). The gross features of the global distribution of rainfall are closely related to the general circulation. Rainfall is relatively abundant where thermal uplift is encouraged and enhanced in the great convergence zones of the equatorial trough of low pressure and polar frontal zones of middle latitudes; it scarce in areas of surface divergence, such as trade wind anticyclones and the anticyclones which dominate cool and cold land surface in middle latitudes in winter and high latitudes throughout the year. Precipitation is a very difficult parameter to estimate, because it is one of the most discontinuous atmospheric phenomena due to its high spatial and temporal variability. The accurate estimation of its distribution and variability, spatially and temporally, remains one of the most unsolved problems of meteorology till date. The fraction of Earth actually receiving rain at an instant in time could not be much more than one half of 1% (Barrett and Martin, 1981). The importance of precipitation monitoring is growing, too, within the context of current trends in environmental research. Usually, rainfall estimation has been a straightforward matter of setting out rain gauges. Around 350 B.C, the Indian author Chanakya described the first known rain gauge in his manuscript "Arthasastra". Conventional measurement from rain gauge is as accurate up to 1/100th of an inch, but it gives point measurement and to measure rainfall over an entire area a very dense network of rain gauges has to be set up which is very costly and is nearly impossible. Further, measurement of rainfall by gauges is affected in particular by the interrelated factors of topography, site, wind, and gauge design. The gauge catch may be representative of a small or large area depending on slope, aspect, elevation, and location in relation to hills and ridges. Taking an extreme example, raingauges located on volcanic islands in the tropics are not likely to give readings representative of rainfall over the ocean in their vicinity. On a very small scale, the gauge catch is influenced by the nature of local surface and presence of nearby objects and structures: these may act as shields, decreasing the catch from what would have been measured in their absence (Weiss and Wilson, 1958). Exposure becomes acute for measurement of forest rainfall (Miller, 1977): it is especially complicated on ships,
which provide an unstable platform. Wind is the single factor contributing most significantly to errors in gauge measurements. Even if a rain gauge is well sited and exposed, owing to deflection of raindrops in the disturbed airstreams around the orifice of the gauge, monthly average winds as light as 5 m/s may result in errors of underestimation as large as 12% in regimes where half the monthly rainfall comes at rates less than 1.8 mm/h (Struzer et al. 1965). Rain gauge designs are intended to reduce wind effects: for example, rain gauges may be mounted flush with the ground, or provided with shields. However, flush mounting increases the possibility of error from splash, makes the gauge more vulnerable to shielding by natural objects, and is relatively expensive; and, according to a study of Weiss and Wilson (1958), shields attached to gauges are not entirely effective. Apart from these problems there are some practical and/or organizational difficulties, some of which are more significant in certain types of regions than others. These problems generally includes: (1) accessibility of desired rain gauge locations; (2) the availability of suitable personnel for reading and servicing the gauges; (3) a suitable power supply for some types of continuous-recording rain-gauges; (4) preserving the rainfall catch in accumulating rain gauges especially when read infrequently; (5) security of the rain gauge station from vandalism and other damage; (6) access to a suitable communication link so that the data can be sent quickly to a central facility for processing and archiving; and (7) transcription and transmission errors, which tend to introduce positive errors in reported rainfall (R. W. Burpee, 1979). The advent of weather radar tried to alleviate this challenge of measuring rainfall considerably. In case of weather radar for the measurements of rainfall there are comparable ranges of problems which restrict the use of such a system. There are difficult problems which are not completely solved relating to the proper relationship of backscattered microwave energy to drop size distribution, beam filling problems, attenuation of the radar beam by intervening drops, absorption and reflection by the ground (anomalous propagation), and signal calibration. Further it is less likely to find Weather radars in less developed countries or in sparsely populated area of the world due to its procurement and maintenance expenses. Moreover it is also not capable of measuring rainfall over oceans, although some radar do exist in the ship and island but their coverage is not adequate. The real solution of rainfall measurement then was achieved somewhat by the method of
remote sensing. Remote sensing is the small or large-scale acquisition of information of an object or phenomenon, by the use of either recording or real-time sensing device(s) that are wireless, or not in physical or intimate contact with the object (such as by way of aircraft, spacecraft, satellite, buoy, or ship). In practice, remote sensing is the stand-off collection through the use of a variety of devices for gathering information on a given object or area. Thus, Earth observation or weather satellite collection platforms, ocean and atmospheric observing weather buoy platforms, the monitoring of a parolee via an ultrasound identification system, Magnetic Resonance Imaging (MRI), Positron Emission Tomography (PET), X-radiation (X-RAY) and space probes are all examples of remote sensing. In modern usage, the term generally refers to the use of imaging sensor technologies including: instruments found in aircraft and spacecraft as well as those used in electrophysiology, and is distinct from other imaging-related fields such as medical imaging. As a scientific approach remote sensing was effectively born in the mid-nineteenth century with the invention of photography. As a tool in rainfall monitoring it began with the development of meteorological radar after World War 2. As a recognized discipline its rise has been both recent and meteoric: the term “remote sensing” was coined as recently as 1960. It was the birth of space exploration by satellites which prompted the new discipline to take off in the late 1960s as one of the most rapidly expanding fields of scientific technological endeavors. Today the variety and flexibility of satellites both as communication links and platform for Earth observation systems rivals that of their conventional predecessors. Over last few decades, the satellite precipitation estimation techniques have grown enormously with a parallel growth of the satellite sensors technology. Modern day’s operational precipitation measurements are made with satellite observations of clouds and rain at Visible (VIS), Infrared (IR) and Microwave (MW) frequencies.

Visible methods observe radiation with wavelengths generally between about 0.5 and 0.7 \( \mu \text{m} \). In visible method it is assumed that cloud brightness is the indicator of cloud thickness and hence rainfall, but this relationship is neither simple nor constant. In IR method cloud top temperature is a function of cloud top height; higher and colder clouds means thicker clouds and are more likely to rain. For this purpose 10 – 12.5 \( \mu \text{m} \) thermal band is used which is an atmospheric window and all earthly objects radiate maximum
spectral power in this band and the absorption of gases are very low. Rainfall is also measured by the combination of both VIS and IR observations simultaneously. Taken together, these often successfully resolve ambiguities in cloud type recognition based either type of data alone. In VIS and IR techniques rainfall is inferred from the observations at the cloud top and thus indirectly estimate rain and also they are not portable from one region to other, moreover VIS method works only during day time, but these measurements have the advantage too, as they are continuously available with larger viewing area and with high space time resolution. Further use of water vapor (WV) at 5.7 - 7.1 μm channel along with IR and WV also helps in identifying the clouds and hence helps in rainfall monitoring. Wexler (1954) and Widger and Touart (1957) suggested that surface temperatures could be inferred from satellite measurements of Infra red radiation. Comparisons of Infra red temperatures maps and radar echo maps were made by Hawkins in 1964. The coldest temperatures corresponded with a wide band of echoes; otherwise, temperatures and echoes were not well matched. Radok (1966) and Rainbird (1969) also explored the relation of cloud top temperature to rainfall, using window radiation measurements of TIROS-3 and gauge measurements of rainfall from Indochina.

Satellite-borne microwave radiometers recording target radiation in the 0.81 cm and 1.55 cm bands have been shown to reveal not clouds, as in the case of IR, VIS, or both IR and VIS, but rain areas embedded in the clouds, with the qualification that these are most obvious over sea area, being often obscured over land by the stronger “background” radiances from such surfaces. It is in the microwave region, therefore, that rain has been most directly evidenced from satellite data available now; all rainfall monitoring schemes involving visible and/or infrared data depends on some indirect relationships between clouds and rain. Problem with the microwave measurements is that they suffer from poor resolution. The microwave measurements of rainfall started way back in 1969 by the launch of Soviet Cosmos -243, but the real boost was obtained by the launch of Defense Meteorological Satellite Project’s (DMSP) satellite series starting from F-8 which was launched in 1987 and still continuing with the recent one F-18. All of these satellites carried microwave radiometer named Special Sensor Microwave Imager (SSM/I). The success of SSM/I leads to a dedicated satellite mission for precipitation, called Tropical
Chapter 1 – Introduction

Rainfall Measuring Mission (TRMM) in Nov 1997 which carried microwave radiometer christened TRMM Microwave Imager (TMI) and an active space-borne Precipitation Radar.

Indian space effort had its beginning in 1962 with the establishment of a rocket launching station in the southern part of India through which the geomagnetic equator passes. Subsequently, the Department of Space (DOS) was established by the Government of India, in 1972, to promote development and application of space science and technology for identified national socio-economic objectives. The Indian venture in satellite remote sensing started with launch of Aryabhatta in 1975 by Soviet Intercosmos Rocket. The objective of the satellite was to indigenously design and fabricates a space-worthy satellite system and evaluates its performance in orbit. The real venture started with the launch of the two series of satellites. The Indian Remote Sensing (IRS) series at low earth sun synchronous orbit primarily for providing earth observation data to Indian and global users and the Indian National Satellite (INSAT) at geosynchronous orbit primarily for communication service, broadcasting, and meteorological applications. The revolutionary attempt began with the launch of the first earth Observation Satellite, Bhaskara–1, in 1979 followed by Bhaskara–2 in 1981, both launched by Soviet Intercosmos Rocket. These satellites carried a two band TV payload for land applications and a SAteellite MIcrowave Radiometer (SAMIR) for oceanographic and atmospheric applications. The SAMIR instrument carried a 2-frequency passive microwave radiometer operating at 19 and 21 GHz (Bhaskara–2 had an additional channel at 31 GHz), with footprints of about 125 km. Television Cameras operating in visible (0.6 micron) and near-infrared (0.8 micron) are used to collect data related to hydrology, forestry and geology. SAMIR data have been widely used for studying ocean-state, water vapor, liquid water content in the atmosphere besides to some extent ocean surface winds (Pandey and Hariharan 1983). Studies related to rainfall retrieval were also been carried out using SAMIR data (Gohil et. al., 1981). Bhaskara programme provided valuable experience and insight into a number of technological aspects – such as sensor system definition and development, conceptualization and implementation of a space platform, ground-based data reception and processing, data interpretation and utilization as well as the issues relating to the integration of the remotely sensed data with the conventional data systems for resource
management. The two Bhaskara satellites were launched with Soviet collaboration and provided an excellent training ground for conceiving future operational missions in remote sensing. Several experiments in practical applications involving users were undertaken to evaluate the efficacy of data generated from a space platform.

Following the successful implementation of the experimental missions of Bhaskara satellites, ISRO took a decision to have a dedicated remote sensing satellite series with capabilities similar to the contemporary earth observation satellites, which could provide uninterrupted, and assured operational services. This lead to the conceptualization of the Indian Remote Sensing Satellite programme and the first IRS-1A was launched in 1988. In comparison to Bhaskara, considerable improvements were made in the satellite mission, namely, orbit and attitude control, spatial and spectral resolutions of payloads as well as reliability aspects needed for an operational mission. Subsequent to IRS-1A, more satellites, namely IRS-1B, IRS-P2, IRS-1C, IRS-P3 and IRS-1D were launched in 1991, 1994, 1995, 1996, and 1997 respectively. But the real breakthrough in microwave remote sensing started with the launch of IRS-P4 (Oceansat-1) satellite in 26 May 1999 that carried, Multi channel Scanning Microwave Radiometer (MSMR), with 6.6, 10, 18 and 21 GHz frequencies in both horizontal and vertical polarizations. First time MSMR provided an opportunity for extensive measurement of various atmospheric and oceanic parameters over a swath of about 1350 km from a sun-synchronous orbit. The operationally derived geophysical parameters from MSMR are wind speed, cloud liquid water, water vapour and sea surface temperatures over the global oceans (Gohil et al., 2000, Pokhrel et al. 2003, Varma et al. 2003, Gairola et al. 2004, and Varma et al. 2002). IRS-P6 (Resoursesat 1), launched in 2003 has among other improvements, a better multispectral imaging capability compared to earlier missions. IRS-P5 (Cartosat 1), launched in 2005, aimed to provide data with higher resolution for cartographic and precision mapping applications, while IRS-P7 (Cartosat 2), an advanced remote sensing satellite carrying a panchromatic camera capable of providing scene specific spot imageries was launched in 2007. Recently Cartosat 2A, identical to Cartosat was launched in 2008. The Indian Remote Sensing Satellite system is the largest constellation of remote sensing satellites for civilian use in operation today in the world. With the launch of CARTOSAT-2A, the constellation now has eight satellites in operation – IRS-
Chapter 1 - Introduction

1D, OCEANSAT-1, Technology Experiment Satellite (TES), RESOURCESAT-1, CARTOSAT-1, CARTOSAT-2 and the latest CARTOSAT-2A and IMS-1. All these are placed in polar sun-synchronous orbit and provide data in a variety of spatial, spectral and temporal resolutions to enable several applications to be undertaken relevant to the national development.

India has made significant contribution in satellite meteorology through its operational Indian National Satellite System (INSAT) programme. Basically INSAT is a series of multipurpose geostationary satellites launched by ISRO to satisfy the telecommunications, broadcasting, meteorology and search-and-rescue needs of India. Commissioned in 1983, INSAT is the largest domestic communication system in the Asia-Pacific Region. It is a joint venture of the Department of Space, Department of Telecommunications, India Meteorological Department, All India Radio and Doordarshan. The overall coordination and management of INSAT system rests with the Secretary-level INSAT Coordination Committee. The first four satellite in first generation INSAT series were procured from USA. Each of them carried twelve C-band telecommunication transponders, two high-power S-band TV broadcast transponders, a Very High Resolution Radiometer (VHRR) for meteorological earth imaging and a data relay transponder for relay of meteorological, hydrological and oceanographic data from unattended land and ocean-based platforms. The VHRR in INSAT-1 series is capable of full disc imaging in the visible (0.55-0.75μ) and thermal IR (10.5-12.5μ) with the spatial resolution of 2.75 km and 11 km respectively. The second generations, INSAT-2 series of satellite, were all designed and built by ISRO and carries an improved version of VHRR with 2 km resolution in the visible and 8 km in IR (Joseph et al 1994). In this series 2-A and 2-B, were launched in 1992 and 1993 respectively. The latest in this series INSAT-2E has been launched on April 3, 1999. This has an additional water vapour channel at 6.7μ for studying the convection by observing the middle level moisture and the winds. It has also a 3 channel Charge Couple Device (CCD) camera with 1 km resolution for studying vegetation dynamics. The three channels are in the 0.52-0.59, 0.62-0.68 and 1.55-1.7μ. It has also the possibility of delineating clearly the ice, cloud boundaries and thus for better estimation of winds during daytime. Of the INSAT-3 series 3-B and 3-C were launched in 2000 and 2002 respectively. ISRO has also launched a set of
Chapter 1 – Introduction

experimental geostationary satellites known as the GSAT series. Kalpana-1, ISRO's first dedicated meteorological satellite, was launched by the Polar Satellite Launch Vehicle on September 12, 2002. The satellite was originally known as MetSat-1. In February 2003 it was renamed to Kalpana-1 by the then Indian Prime Minister Atal Bihari Vajpayee in memory of Kalpana Chawla – a NASA astronaut who perished in Space Shuttle Columbia. The Kalpana-1 satellite is located at 74.2 degrees longitude, over the equator. The operational products from INSAT include cloud liquid water at different levels, maps of outgoing long wave radiation and quantitative precipitation estimates (QPE). In this thesis I have estimated the QPE values from Kalpana-1 satellite radiances and applied them for inter satellite comparison purposes with TRMM. The Thesis broadly focuses on the remote sensing of precipitation, specifically retrieval, intercomparison, and validation studies. Information from the infrared, water vapor, visible and microwave data acquired from various sensors on board satellites has been utilized for this purpose. Specific objective of the study is to develop rainfall retrieval algorithm using IR, MW, WV, VIS, and merged IR-MW observation from various satellite data over Indian land and oceanic regions, intercomparison of these algorithms with different satellite products, and validation of these algorithms using ground based rain-gauge and Doppler weather radar. The various satellites used for the present study includes Defense Meteorological Satellite Program (DMSP) - Special Sensor Microwave Imager (SSM/I), Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI), TRMM/ Precipitation Radar (PR), Kalpana-1, and Meteosat.

1.2 Objective and area of study

The principal objective of the present study is to develop precipitation estimation algorithm for Indian land and oceanic regions using satellite data. Various techniques have been developed using infrared, microwave and merged infrared and microwave measurements. This becomes more relevant in view of future INSAT-3D and Megha Tropique missions.
Chapter 1 - Introduction

The main objectives of the thesis are

1. To develop an algorithm based on IR measurement to estimate the rainfall over Indian tropics.
2. To develop the rainfall estimation algorithm based on microwave measurement.
3. To develop a rainfall estimation technique based on merged IR and microwave measurements.

The area of the present study is Indian tropics (30°S/40°N, 40°E-120°E). This tropical area is selected for the study due to many reasons. The tropics play an important role in the global hydrological cycle, and tropical rainfall is the critical component of this cycle. Three-fourth of the atmosphere's heat energy derives from the release of latent heat of condensation in the process of precipitation. Two-thirds of the global precipitation occurs in the tropics. The variability of tropical rainfall affects the lives and economics of more that half of the world's population. Precipitation data in the tropics are vital to understanding, monitoring, and modeling of significant climate variations, such as El Nino phenomenon and 'green house' effect. Major source of the rainfall in this study area is South-West (S-W) and North-East (N-E) monsoon. Since the economy of India depends on the agriculture and this in turn depends on the rainfall, so this area of study is of very significance for the rainfall related study.

1.3 Significance of the study

The accurate estimation of rainfall is important for the numerous applications ranging from the synoptic scale forecast, initialization of numerical models, thunder storm & flash floods, crop yield modeling, soil moisture evolution, hydrological structure design, water supply forecast to developing climatology, global change studies, El-Nino forecast etc. The importance of satellite remote sensing for the present study is multifold. Whether it is synoptic continuous and long-term global observation or very high frequency of temporal and spatial coverage or three-dimensional knowledge of any rain systems, rain measurements through the conventional methods can not solve the purpose. The discontinuous nature of rainfall due to being highly variable in space and time cannot be
Chapter 1 – Introduction

a true representative of a larger area by the point measurements like rain-gauges and thus the remote sensing from space platforms provides a suitable supplement. In addition the rainfall measurement over oceans and some of the difficult terrains are not in place and thus is possible only through satellite remote sensing.

The present study is highly relevant in number of counts. First, it will add on the improvements in the retrieval processes over Indian region, second it will provide valuable experience and insight into a number of technological aspects in Indian perspective, third the retrieval of rainfall from Indian satellite along with other working satellites viz. TRMM, SSM/I, Meteosat will synergistically be able to estimate the rainfall with good accuracy over the Indian region where the economy depends largely on the agriculture which in turn depends on the rainfall. This study is a pioneering attempt in terms of the rain retrieval from Indian and International satellite for rain retrieval algorithm for various applications and preparation of rainfall climatology.

In past very fewer efforts have been made in rainfall estimation over Indian region, so there is a need for the development of rainfall retrieval techniques over Indian tropics. The studies conducted in the present thesis would also provide first hand experience and thus pave the way for the advanced algorithm development for the retrieval and applications of the rainfall with desired accuracy for future satellite missions like, joint INSAT-3D and Indo-French Megha-Tropiques and Global Precipitation Mission (GPM).

1.4 Precipitation

1.4.1 Precipitation Process

In meteorology, precipitation is water in either solid or liquid form that falls in Earth's atmosphere. Major forms of precipitation include rain, snow, and hail. When air is lifted in the atmosphere, it expands and cools. Cool air cannot hold as much water in vapor form as warm air, and the condensation of vapor into droplets or ice crystals may eventually occur. If these droplets or crystals continue to grow to large sizes, they will eventually be heavy enough to fall to Earth's surface. Study of precipitation involves three processes, 1) the processes which introduce water in the atmosphere as water vapour, 2) the processes which cause the conversion of these invisible vapour to visible
Chapter 1 - Introduction

clouds and, 3) the process which cause the cloud droplets to grow in size to fall as precipitation over the. There are three processes which yield the precipitation. These include:

a. Evaporation process
b. Condensation and formation of the cloud droplets
c. Formation of Precipitation

a) Evaporation: Evaporation is the slow vaporization of a liquid and the reverse of condensation. A type of phase transition, it is the process by which molecules in a liquid state (e.g. water) spontaneously become gaseous (e.g. water vapor). Generally, evaporation can be seen by the gradual disappearance of a liquid from a substance when exposed to a significant volume of gas. In the process of evaporation, water from open water surfaces (e.g. ocean), from pools on the ground surface or from water contained within the earth’s surface materials, either natural or man-made or transpired from vegetation, is introduced into the atmosphere as water vapour (water vapor is defined as the presence of water as an invisible gas in the atmosphere). Evaporation is an essential part of the water cycle. Solar energy drives evaporation of water from oceans, lakes, moisture in the soil, and other sources of water.

Evaporation will occur whenever a water surface is exposed to overlying air, which remains unsaturated with respect to water. Even the precipitation intercepted by vegetation is also available for evaporation back into the atmosphere. The vegetation can also intercept fog or low cloud and thus increase the precipitation input e.g. in California (Oberlander., 1956) or Southern Africa (Nagel., 1956). In case of open water surface, which is air-water interface, there will be an exchange of water molecules in both directions and the evaporation into adjacent air will only take place if there is a net movement of molecules into the air from the water body. The evaporation is supported by unsaturated and free air flow as it helps in redistributing water vapour vertically and horizontally, with the result that drier air is brought down into contact with the water surface. Also higher temperature assist evaporation as at higher water temperature the molecules have a higher energy level and may more easily break away from the water.
surface, also at higher air temperatures the receiving air possesses a greater capability to receive water vapour. Thus the amount of water vapour atmosphere can contain is a function of its temperature.

Evaporation will also occur where water is contained within materials exposed to the air, e.g. within soil profile, where the character of the soil itself, its material and texture, grain size, grain size distribution and surface roughness and colour, all determine that the detail of the process is far more complex. A major factor here is albedo of soil surface which in turn is governed by its texture and color and also very importantly by its water content.

There are many factors affecting the rate of evaporation. These include:

1. Concentration of the substance evaporating in the air:
   
   If the air already has a high concentration of the substance evaporating, then the given substance will evaporate more slowly.

2. Concentration of other substances in the air:
   
   If the air is already saturated with other substances, it can have a lower capacity for the substance evaporating.

3. Concentration of other substances in the liquid (impurities):
   
   If the liquid contains other substances, it will have a lower capacity for evaporation.

4. Flow rate of air:
   
   This is in part related to the concentration points above. If fresh air is moving over the substance all the time, then the concentration of the substance in the air is less likely to go up with time, thus encouraging faster evaporation. This is the result of the boundary layer at the evaporation surface decreasing with flow velocity, decreasing the diffusion distance in the stagnant layer.

5. Inter-molecular forces:
   
   The stronger the forces keeping the molecules together in the liquid state, the more energy one must get to escape.

6. Pressure:
   
   In an area of less pressure, evaporation happens faster because there is less exertion on the surface keeping the molecules from launching themselves.
Chapter 1 - Introduction

7. Surface area
   A substance which has a larger surface area will evaporate faster as there are more surface molecules which are able to escape.

8. Temperature of the substance:
   If the substance is hotter, then evaporation will be faster.

9. Density:
   The higher the density, the slower a liquid evaporates.

Evapotranspiration from vegetated areas is also a major contributor of water vapour in the atmosphere. Evapotranspiration is a significant water loss from a watershed. Types of vegetation and land use significantly affect evapotranspiration, and therefore the amount of water leaving a watershed. Because water transpired through leaves comes from the roots, plants with deep reaching roots can more constantly transpire water. This transpiration of water is a part of the plants growth through the process of Photosynthesis. The rate of transpiration in plants are governed by two factors first, the general level of the photosynthesis reaction at the time. (Depends on the availability of solar light) and second, the adequate supply of moisture is available to the plant through its root system. If the soil surface is dry then a increase in plants input cover will increase overall evapotranspiration, but if it is kept wet an increase in density will have little effect on evapotranspiration rates (Thornthwaite and Hare., 1965).

The evaporation from oceans reach around 2000 mm/yr in western pacific and Central Indian ocean (Pruppacher., 1982) and thus provides a significant contribution to the atmosphere moisture. There is a marked diurnal variation of evaporation and particularly in the higher latitudes, a strong seasonal fluctuation between summer and winter. All this processes leads to water vapour in the atmosphere which typically averages about 4% by volume of the atmosphere and about 90% of the atmosphere’s total water content (all three phases) is confined to the lowest 6 km of the atmosphere (Pruppacher, 1982).

b) Condensation and formation of Cloud droplets:
   Generally, upward motion of moist air is a prerequisite for cloud formation, downward motion dissipates it. Ascending air expands and cools adiabatically and, if sufficiently
moist, some of the water vapour condenses to form cloud droplets. The atmospheric water vapour acts as a raw material for the formation of clouds for which two fundamental factor are needed, first, there is sufficient moisture in the air to condense out in the first place, in addition to initial cooling below its dew point temperature, second, a medium on which the condensation can take place these are known as Cloud Condensation Nuclei (CCN) and their concentration may have an impact on the intensity or likelihood of any resulting precipitation. Bretherton et al. (2004) found that a minimum water vapor path of 40 mm is required for the formation of rain bearing clouds. In general air contains a large numbers of CCN's, which acts as embryos on which the water vapor may condense to produce cloud droplets. CCN's have diameter of about 0.1 - 10 μm or more and are found in concentration of a few 100 per cubic centimeter of air. They are light enough to be suspended in the air. The smallest of these CCN's up to 0.2 micron diameter are called ‘Aitken nuclei’, those between 0.2 and 2.0 microns, “large nuclei”, and upwards from 2.0 microns, ‘giant nuclei’. Their size distribution and concentration vary considerably from place to place. There exists a significant diurnal variation in concentration of CCN’s over many places. CCN’s come from many sources, particularly blowing soil, volcanoes, smokestacks, pollen, salt from ocean spray and the sulphates, produced by phytoplankton, in the marine atmosphere. In addition, nuclei are formed in the atmosphere as a result of chemical reactions involving gases such as sulfur dioxide and nitrogen oxide. The most favorable nuclei are hygroscopic, that is, they have a marked ability to accelerate the condensation of water. Example of hygroscopic nuclei is acid particles and sea salt. Condensation on ordinary table salt, sodium chloride, may begin when relative humidity is only 75 percent. Magnesium chloride is even more hygroscopic, and condensation can start with relative humidities below 70 percent. Charlson et. al (1987) indicate that a major source of cloud condensation nuclei may be dimethylsulphide from ocean areas, produced by the actions of planktonic algae. Condensation at saturation and in the presence of CCN is not as obvious as might appear. It is very difficult for water to condense on to the very smallest aerosol since the saturation vapour pressure is significantly high over markedly curved surfaces than it is over gently curving or plane surfaces. Condensation will therefore take place preferentially on the larger aerosol. This is known as “curvature effect”. Some of the
Chapter 1 - Introduction

aerosols are hygroscopic and thus it is possible for condensation to take place even though the air is not completely saturated with water. This is “solute effect”. Therefore condensation typically favors the larger aerosol, where the smaller curvature (closer to a plane surface) is associated with the nuclei which may also be hygroscopic.

The typical water droplet cloud contains about $10^9$ water droplets per cubic meter and their radii ranging from 1 to 60 μm. This range of size become crucially important in understanding the production of precipitation within warm clouds (whose temperature are greater than $0^\circ C$), where a large range in drop size is thought to encourage precipitation production.

Clouds form as air rises, expands and cools. The initial cooling of an air parcel is always initiated by some external event like uplift of the air within the atmosphere and the initiation of this uplift may be caused by one or more numbers of factors such as (i) Convection (ii) Convergence (iii) Orographic uplift (iv) Frontal uplift.

i) **Surface heating and free convection (Thermal uplift):** Some areas of earth’s surface are better absorbers than others and, therefore, heat up more quickly. The air in contact with these ‘hot spots’ becomes warmer than its surrounding. A hot “bubble” of air – a thermal- breaks away from the warm surface and rises, expanding and cooling as it ascends. As the thermal rises, it mixes with the cooler, drier around it and gradually loses its identity. Its upward motion now slows. Frequently, before it is completely diluted, subsequent rising thermals penetrate it and help the air rise a little higher. If the rising air cools to its saturation point, the moisture will condense and cloud will form.

ii) **Topography (Orographic uplift):** Horizontally moving air obviously can not go through a large obstacle, such as a mountain, so the air must go over it. Forced lifting along a topographic barrier is called “orographic uplift”. Often, large masses of air rise when they approach long chains of mountains. The lifting produces cooling, and if the air is humid clouds form.

iii) **Widespread ascent due to the flowing together (convergence) of surface air:** Widespread convergence of air masses also forces air upward causing cloud formation. Low-pressure systems are associated with converging air.
iv) Uplift along weather fronts or frontal uplift: Slightly warmer and less dense air may be forced to gradually rise over colder, denser air at a warm front in temperate latitudes, which causes the formation of stratus clouds over hundreds; even thousands of square miles.

c) Formation of Precipitation: Cloudy weather does not necessarily mean that precipitation will occur. In fact, clouds may form, linger for many days, and never produce precipitation. Clouds are made of extremely small droplets (too small to fall as rain) having an average diameter of 0.02mm, which is less than one-thousandth of an inch. The size of typical rain drop is 2 mm. The diameter of a typical cloud droplet is 100 times smaller than a typical raindrop. Cloud droplets require only slight upward air currents to keep them suspended. Those droplets that do fall descend slowly and evaporate in the drier air beneath the cloud. We know that condensation begins on tiny particles called condensation nuclei. The growth of cloud droplets by condensation is slow and, even under ideal condition; it would take several days for this process alone to create a raindrop. It is evident, then that the condensation process by itself is entirely too slow to produce rain. Yet, observations show that clouds can develop and begin to produce rain in less than an hour. Since it takes about one million average size clouds droplets to make an average size raindrop, there must be some other process by which cloud droplets grow large and heavy enough to fall as precipitation. Even though all the intricacies of how rain is produced are not yet fully developed, two important processes stand out: (1) the collision-coalescence process and (2) the ice crystal (or Bergeron) process.

(1) Collision-coalescence process (Precipitation processes within warm clouds): In clouds with top warmer than -15°C (5°F), collision between droplets can play a significant role in producing precipitation. Within the warm cloud there is an updraft of air caused by air coming together or converging at a point beneath the cloud. After the air converges, it is forced upward. This process is what initially helps to build the cloud and now that it has formed, it continues and carries smaller cloud droplets up into the cloud while larger droplets stay suspended within the cloud or even fall downward slowly. Now, with billions upon billions of cloud droplets hanging out in the cloud, some of them are bound to bump into each other. This is where the term, "collision" comes
Chapter 1 - Introduction

into play. As the cloud droplets experience millions of collisions, they sometimes join together (or coalesce) and form larger cloud droplets. The larger cloud droplets then fall faster (because they have a higher terminal velocity) and collide with smaller droplets in their path. Studies done in laboratories have shown that not all collisions result in coalescence, that is to say, that some of the drops break apart after colliding. The studies have shown that "coalescence appears to be enhanced if colliding droplets have opposite (and, hence attractive) electrical charges... especially in thunderstorm precipitation coalescence where strongly charged droplets exist in a strong electrical field". Almost by definition warm clouds are shallow clouds, however, the opportunity for drop growth to precipitation size is increased where there is greater cloud depth (Singleton, 1960) although as Mason (1952) pointed out for clouds with little or no turbulent motion, it is unlikely that precipitation can be produced from most warm clouds. However, shower production from ordinary non-glaciated cumulus is often by means of coalescence (East and Marshall, 1954).

(2) Ice crystal process (Precipitation processes within cold clouds): This is also known as the Bergeron Findeisen Process (after Tor Bergeron and W. Findeisen), or cold rain or ice crystal process. It is the formation of precipitation in the cold clouds of the mid and upper latitudes by ice crystal growth. The equilibrium vapor pressure over water is greater than the saturation vapor pressure over ice, at the same temperature. Therefore in a mixed phase cloud, the liquid water will be out of vapor pressure equilibrium and will evaporate to reach equilibrium. The water droplets will move toward the lower pressure over the ice and diffuse onto the ice crystals. The vapor will be condensed and freeze onto the ice crystal, causing it to grow larger. In order for the Bergeron Process to occur, supercooled water droplets and ice crystals must be present together in the cloud. The most common way to form an ice crystal starts with an ice nucleus in the cloud. Ice crystals can form from heterogeneous deposition, contact, immersion, or freezing after condensation. In heterogeneous deposition, an ice nucleus is simply coated with water. For contact, ice nuclei will collide with water droplets that freeze upon impact. During immersion, an ice nucleus will hit a water droplet and instantly freeze it. Water can also condense onto an ice nuclei and then freeze. Water will freeze at different temperatures depending upon the type of ice nuclei present. Ice nuclei cause water to freeze at higher
temperatures than it would spontaneously. For pure water to freeze spontaneously, called homogenous nucleation, cloud temperatures would have to be -42 degrees Celsius. As the ice crystals grow, they can bump into each other and splinter and fracture, resulting in many new ice crystals. There are many shapes of ice crystals to bump into each other. These shapes include hexagons, cubes, columns, and dendrites. The process of ice crystals sticking together is called aggregation. This happens when ice crystals are slick or sticky at temperatures of -5 degrees Celsius and above, because of a coating of water surrounding the crystal. The different sizes and shapes of ice crystals fall at different terminal velocities and commonly collide and stick. When an ice crystal collides with supercooled water its called accretion. Droplets freeze upon impact and can form graupel. Eventually this ice crystal will grow large enough to fall. It may even collide with other ice crystals and grow larger still through collision coalescence, aggregation, or accretion. The Bergeron Process often results in precipitation. As the crystals grow and fall, they pass through the base of the cloud, which may be above freezing. This causes the crystals to melt and fall as rain. There also may be a layer of air below freezing below the cloud base, causing the precipitation to refreeze in the form of ice pellets. Similarly, the layer of air below freezing may be at the surface, causing the precipitation to fall as freezing rain. The process may also result in no precipitation, evaporating before it reaches the ground, in the case of forming virga.

1.4.2 Types of Precipitation

While falling, rain drops and snowflakes may be altered by atmospheric conditions encountered beneath the cloud and transformed in to other forms of precipitation that can profoundly influence our environment. The brief description of all types of precipitation is as follows:

1. Rain: Most people consider rain to be any falling drop of liquid water. To the meteorologist, however, that falling drop must have a diameter equal to, or greater than 0.5 \( \text{mm} \) (0.02 inch) to be considered rain. Rain is liquid precipitation that reaches the surface in the form of drops that are greater than 0.5 millimeters in diameter. The intensity of rain is determined by the accumulation over a given time. The concentration
Chapter 1 - Introduction

of raindrop typically range from 100 to 1000 per cubic meter. Among all the forms of precipitation, the one which affects each and every human being's life considerably is rain. Categories of rain are light, moderate, and heavy. According to its rate of fall, meteorologists classify rain as:

a) Light - less than 2.5 mm/hr
b) Moderate - 2.5 to 7.6 mm/hr
c) Heavy - more than 7.6 mm/hr

It must be noted that this definition of light, moderate, and heavy rainfall is different for the different region.

2. Rain shower: Raindrops encountered by rapidly rising updrafts grow in size, if the updrafts weaken or change direction and become a downdraft; the suspended drops will fall to ground as a sudden rain shower.

3. Cloudburst: The rain shower from cumulonimbus clouds is brief and sporadic, but if the shower is excessively heavy, it is termed as cloudburst.

4. Acid rain: When falling rain combines with gaseous pollutants, such as oxides of sulphur and nitrogen, it becomes acidic, and thus is termed as acid rain; it has an adverse effect on plants and water resources.

5. Snow: It is frozen precipitation with crystalline structure in the form of aggregate of ice crystals. In summer, the freezing level is usually high and the snow flakes falling from a cloud melt before reaching the surface. In winter, however, the freezing level is much lower, and falling snow flakes have a better chance of survival. In fact, snow flakes can generally fall about 300 m (or 1000 ft) below the freezing level before completely melting. When the warmer air beneath the cloud is relatively dry, the snow flakes partially melt. As the liquid water evaporates, it chills the snow flakes, which retards its rate of melting. Consequently, in air there is relatively dry, snow flakes may reach the ground even when the air temperature is considered above freezing. In fact, much of the precipitation reaching the ground actually begins as snow. The fate of snow to reach the ground in its original form depends on the freezing level and the atmospheric conditions beneath the cloud. Snow falling from developing cumulus clouds is often in the form of flurries. These are usually light showers that fall intermittently for short duration and produce only light accumulation. A more intense snow shower is called a snow squall.
Chapter 1 - Introduction

These brief but heavy falls of snow are comparable to summer rain showers and, like snow flurries, usually fall from cumuliform clouds. A more continuous snowfall (sometimes steadily, for several hours) accompanies nimbostratus and altostratus clouds. When a strong wind is blowing at the surface, snow can be picked up and deposited in to huge drifts. Drifting snow is usually accompanied by blowing snow; that is, snow lifted from the surface by the wind and blown about in such quantities that horizontal visibility is greatly restricted. The combination of drifting and blowing snow, after falling snow has ended, is called as ground blizzard. A true blizzard is weather condition characterized by low temperature and strong winds (greater than 30 knots) bearing large amount of fine, dry, powdery particles of snow, which can reduce the visibility to only few meters.

6. Drizzle: Fine uniform drops of water whose diameters are smaller than 0.5mm are called drizzle. Most drizzle fall from stratus clouds; however small raindrops may fall through air that is unsaturated partially evaporate and reach the ground as drizzle.

7. Freezing drizzle: Freezing Drizzle is liquid precipitation that reaches the surface in the form of drops that are less than 0.5 millimeters in diameter. The drops then freeze on the earth's surface.

8. Virga: Virga is precipitation that evaporates before reaching the ground. Sometimes rain falling from cloud never reaches the surface because of low humidity of atmosphere which causes rapid evaporation of raindrops causing size of drops smaller and consequently decrease fall of rate and thus they appear to hang in the air as a rain streamer. These evaporating streaks of precipitation are called virga.

9. Fall streaks: The dangling white streamers of ice crystals beneath the cirrus clouds are known as fall streaks. The bending of the streaks is due to the changing wind speed with height. Ice crystals and snowflakes falling from high cirrus clouds, which subsequently sublimate (changes from ice to vapor), are called fall streaks. They often appear as dangling white streamers. Moreover, fall streaks descending into lower, super cooled clouds may actually seed them.

10. Sleet: Sleet is nothing more than frozen raindrops. Sleet occurs when there is a warm layer of air above a relatively deep sub-freezing layer at the surface. The layer above freezing will allow for liquid precipitation but as the drops hit the cold layer, they will freeze and hit the ground as frozen water droplets. Sleet usually doesn't last long and
mainly occurs ahead of warm fronts during winter months. They have small diameter, which is less than 0.5mm. They bounce on impact with the ground or other object.

11. Freezing rain: Freezing rain is probably the most dangerous type of precipitation. They are super cooled droplets freezing on impact with cold surfaces. It is most commonly found in a narrow band on the cold side of a warm front, where surface temperatures are at or just below freezing. There is no noticeable difference between freezing rain and rain so people ignore the fact that it can cause such things as black ice on roadways. Freezing rain occurs when there is a shallow layer of air at the surface that is below freezing followed by a layer of above freezing air above it. The precipitation will fall through the warmer layer so it will not freeze over. When it hits the sub-freezing layer it will cool but not freeze. Since the surface temperature is below freezing, objects in contact with the air are also below freezing. The super-cooled water droplets will freeze on contact to these surfaces. This can cause problems with ice forming on roadways while it is raining.

12. Snow pellets: When ice-crystals collide with super cooled water droplets freezing them into a spherical aggregate of icy matter (rime) containing many air spaces. The much bigger accumulation of rime is called graupel and during winter when freezing level is at a low elevation, the graupel reaches the surface as a light, round clump of snow like ice called snow pellet. They are white, opaque grains of ice about the size of an average raindrop. They are brittle, crunchy and bounce (or break apart) upon hitting a hard surface and usually fall as showers, especially from cumulus congestus clouds. When the diameter of snow pellets is less than 1mm it is known as snow grains. In a thunderstorm, when the freezing level is well above the surface, graupel that reaches the ground is called soft hail.

13. Hail: Hail is dense precipitation ice that is at least 5 millimeters in diameter. It forms due to ice crystals and supercooled water that freeze or stick to the embryo hail stone. Soft hail is whiter and less dense since it has air bubbles. Soft hail occurs when hail grows at a temperature below freezing by ice crystals and small supercooled water and cloud droplets merging onto the hail. Hard hail occurs when liquid water drops freeze on the outer edges of the hailstone after the outer edge is above freezing. The
freezing of supercooled water releases latent heat and this can result in the outer edge of the hail stone warming above freezing. Then the water refreezes creating solid ice. Hail will commonly have soft ice and hard ice layers when it is sliced open.

1.5 Basis of Remote Sensing

1.5.1 Nature of light and electromagnetic radiation

In 18th century, light was thought to be wave motion in all-pervading medium called "ether", just as sound is waves in air. Later, it was pictured as the oscillations in electric and magnetic fields (not needing medium like ether- even in vacuum and in certain materials - 'transparent/ semi-transparent' ones), in a systematic way so as to propagate energy as waves. Still later, light was modeled as very small particles, called "photons", which are abstract packets of energy without mass, but their propagation is governed by statistical distribution which looks like waves. Therefore, all observed phenomena, characteristic of wave nature, can still be explained despite particle nature of light. Further, evidence of similar energy as light, but undetected to human eye, mounted up. On the shorter wavelength side, certain atoms when excited and de-excited, give off ultraviolet, X-rays etc., and nuclear reactions give gamma-rays. The color with the longest wavelength detectable by our eye is red (the intermediate sequence of increasing wavelength is VIBGYOR). On the other side of red, longer wavelengths were named infrared (Actually ultra means 'more than' and infra means 'less than', but this apparent interchanges of prefixes is best explained in terms of frequency). It is also worth noting that earlier experiments concluded that the wavelength of emission of light depended upon the temperature of the body, because heating the body to very high temperatures produced light while on cooling it only heat was produced. Later, even radio waves used in broadcasting radio/T.V., were included in a wider definition of electromagnetic waves. The term radiation loosely refers to a source of energy sending out energy to farther/distant places. Electromagnetic radiation is the propagation of this energy by wave like behavior of electric and magnetic fields associated with this energy. In the context of remote sensing by satellites, E.M. radiation plays a crucial role since that is the only type of energy that can propagate through vacuum to reach from earth to satellite outside the
earth’s atmosphere. The satellite measures the received energy and hence several basic terms connected with radiant energy or radiance, are desirable to be defined and known. Also some relationships (based on geometry of propagation) among different quantities are found. The unit of radiant energy naturally is Joule.

Radiant flux is radiant energy flowing past a point per second, so it is naturally measured in Watts (Joules/Sec.). But the total radiant flux through a plane will depend on its area, so to standardize radiant flux density is defined per unit area (W/m²). For a source, radiant flux density is called exitance (symbol M), and for a receiver/detector, radiant flux density is called irradiance (symbol E). Radiant flux density per unit solid angle is called radiance (symbol L) with units W/m²/sr. From a given area/source, radiation may emanate in different directions, and it may be same (isotropic) or different in different directions. Radiance is a useful fundamental quantity of measurement, particularly in satellite remote sensing, because it does not depend on the height (altitude) of the satellite. If the satellite moves to a higher altitude, the irradiance it gets from given target-region of the earth will decrease as the square of the distance by spreading all energy over a sphere of area (proportional to square of radius). But so also will the solid angle, keeping radiance fixed. Generally, a body may emit (or a detector may detect) radiation in a range of wavelengths. The radiation may vary with wavelength. The radiance at a particular wavelength is measured as `radiance per unit wavelength interval`, called `spectral radiance` (l) (unit W/m²/sr/μm). When integrated over all wave lengths, this gives the total or integral radiance (L). This gives the idea that spectral radiance can not be finite non-tapering function of wavelength, or else the integral will explode to infinity, which is not realistic. In the `classical` wave picture or wave theory of E.M. radiation, the spectral radiance of a cavity can be shown to vary as wavelength to the -4 power. This not only makes the spectral radiance itself explode at small wavelengths (high frequencies), but also the total radiance, integral of above being wavelength to the -3 power, explodes – as if the total energy of a cavity is infinite. Besides theoretical difficulty, this does not match observations either – the radiance spectrum tapers at both low and high wavelength ends. This was the basis of photon (particle) theory of Max Planck (1901 AD) and derived an acceptable spectrum, famously known as “Planck’s
distribution function". Albert Einstein (1916) later explained Planck's theory in terms of transition probabilities

1.5.2 Black body radiation and laws

The ideal black body notion is of primary importance in studying thermal radiation and electromagnetic radiation energy transfer in all wavelength bands. Being an ideal radiation absorber, the black body is used as a standard with which the absorption of all real bodies is compared. The black body emits the maximum amount of radiation and, consequently, it is used as a standard for comparison with the radiation of real physical bodies. This notion, introduced by G. Kirchhoff in 1860, is so important that it is actively used in studying not only the intrinsic thermal radiation of natural media, but also the radiation caused by different physical nature. Moreover, this notion and its characteristics are sometimes used in describing and studying artificial, quasideterministic electromagnetic radiation (in radio- and TV-broadcasting and communications). The emissive properties of a black body are determined by means of quantum theory and are confirmed by experiment.

The black body is so called because those bodies that absorb incident visible light will seem black to the human eye. The term is, certainly, purely conventional and has, basically, historical roots. For example, we can hardly characterize our sun, which is, indeed, almost a black body within a very wide band of electromagnetic radiation wavelengths, as a black physical object in optics. Though, it is namely the bright-white sunlight, which represents the equilibrium black-body radiation. In this sense, we should treat the subjective human recognition of colors extremely cautiously. So, in the optical band a lot of surfaces really approach an ideal black body in their ability to absorb radiation. However, outside the visible light region, in the wavelength band of IR thermal radiation and in the radio-frequency bands, the situation is different. So, the majority of the earth's surfaces (the water surface, ice, land) absorb infrared radiation well, and, for this reason, in the thermal IR band these physical objects are ideal black bodies. A black body is an ideal body which allows the whole of the incident radiation to pass in to itself (without reflecting the energy) and absorbs within itself this whole incident radiation (without passing on the energy). This property is valid for radiation corresponding to all
wavelengths and to all angles of incidence. The radiation emitted by a black body is known as black body radiation (BBR). BBR is isotropic, homogeneous, unpolarised and depends only on temperature. It is more intense than the radiation from any other body at same temperature. The spectral distribution of energy in the BBR at a given temperature is independent of the material, shape and size of the body. Although all material above absolute zero in temperature emits radiation, but none of the real material is a perfect blackbody. Some material comes very close to being black body in some wavelength ranges. The radiation inside a cavity whose walls are thick enough to prevent any radiation from passing directly through them can be shown to be the radiation that would be emitted by a blackbody thus BBR is also known as cavity radiation. The general thermodynamics considerations allowed Kirchhoff, Boltzman and Wein to derive rigorously a series of important laws controlling the emission of heated bodies. However, these general considerations were insufficient for deriving a particular law of energy distribution in the black body radiation spectrum. It was W. Wien who advanced in this direction more than the others. Wien spread the notions of temperature and entropy to thermal radiation and showed, that the maximum radiation in the black body spectrum displaces to the side of shorter wavelengths with increasing temperature (the Wien displacement law); and at a given frequency the radiation intensity can depend on temperature only, as the parameter appeared in the ($v/T$) ratio where $v$ is frequency and $T$ is temperature. In other words, the spectral intensity should depend on some function $f(v/T)$. The particular form of this function has remained unknown. Wien derived the law of energy distribution in the black body spectrum (the Wien radiation law). However, as was soon made clear, the formula of Wien’s radiation law was correct only in the case of short (in relation to the intensity maximum) waves. Rayleigh and Jeans derived the spectral distribution of thermal radiation on the basis of the assumption that the classical idea on the uniform distribution of energy is valid. However, the temperature and frequency dependences obtained basically differed from Wien’s relationships. Wien’s expression for spectral energy distribution was invalid at high temperatures and long wavelengths. This circumstance forced Planck to turn to considerations of harmonic oscillators, which have been taken as the sources and absorbers of radiation energy. Using some further assumptions on the mean energy of oscillators, Planck derived
Wien's and the Rayleigh-Jeans law of radiation. Finally, Planck obtained the empirical equation, which very soon was reliably confirmed experimentally on the basis, first of all, of the Wien-Lummer black body model. Searching for the theory modifications which would allow this empirical equation to be derived, Planck arrived at the assumptions constituting the quantum theory basis.

According to quantum statistics principles, the spectral volume density of radiation energy can be determined by calculating the equilibrium distribution of photons, for which the radiation field entropy is maximum. Main laws describing the characteristics of blackbody are as follows:

**Plank's law**: Plank described the complete spectral distribution of blackbody radiation at a given temperature $T$ on the basis of quantum hypothesis. He assumed that blackbody is made up of oscillators having only discrete energy given by

$$E = nhv$$

where $v$ is the frequency of the oscillator, $h$ is plank's constant and $n$ is an integer known as quantum number, also these oscillators emit or absorb energy in packets of $hv$. The average energy of Plank's oscillator is

$$\hat{E} = h\nu(\exp(h\nu/kT) - 1)$$

Using this spectral brightness of blackbody is given by

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1} \quad \text{(in terms of wavelength)}$$

$$B_\nu(T) = \frac{2hv^3}{c^2} \frac{1}{e^{hv/\nu kT} - 1} \quad \text{(in terms of frequency)}$$

where $B$ is blackbody spectral brightness, $W \, m^{-2} \, Sr^{-1} \, Hz^{-1}$

**Characteristics of Plank's Law**

All the laws stated above are the special cases of Plank's law

**(I) Stefan-Boltzmann's law**: The total brightness $B$ for a blackbody at a temperature $T$ is the integral of $B_\nu$ (or $B_\lambda$) over all frequencies (or all wavelengths) thus,
Chapter I - Introduction

\[ B = \int B_\nu d\nu \]

\[ = \frac{2h}{c^2} \int_0^{\nu_m} \frac{\nu^3}{e^{\nu/kT} - 1} d\nu \]

On solving and simplifying the above integral we get

\[ B = \frac{\pi \sigma T^4}{\pi} \]

(II) **Wien Displacement Law:** It gives the frequency (or wavelength) at which the Planck law has the maximum specific intensity. The frequency at which maximum radiation occurs \((\nu_m)\) increases with temperature. This can be obtained from Planck's law by setting derivative of \(B_\nu\) with respect to \(\nu\), equal to zero for \(\nu = \nu_m\). Thus for a given value of \(T\)

\[ \frac{dB_\nu}{d\nu} = \frac{d}{d\nu} \left( \frac{2h\nu_m^3}{c^2} \frac{1}{e^{\nu_m/kT} - 1} \right) = 0 = \frac{2h}{c^2} \left[ \frac{3\nu_m^2}{e^{\nu_m/kT} - 1} - \frac{\nu_m^3 h}{kT} \frac{e^{\nu_m/kT}}{(e^{\nu_m/kT} - 1)^2} \right] \]

The above equation can be simplified to find \(\nu_m\) in Hz as:

\[ \nu_m = 5.87 \times 10^{10} \ T \]

and the corresponding wavelength in meters is \(\lambda_m = c / \nu_m\)

\[ \lambda_m = 5.098 \times 10^{-3} / T \]

to find maximum specific Planck emission in wavelength one can set derivative of \(B_\lambda\) with respect to \(\lambda\), equal to zero for \(\lambda = \lambda_m\)

\[ \frac{d}{d\lambda} \left[ \frac{2hc^2}{\lambda^3} \frac{1}{e^{hc/\lambda kT} - 1} \right] = 0 \]

and solving the equation we get

\[ \lambda_{max} = 2897/T \]
Chapter 1 – Introduction

(III) Wien’s radiation law: For short wavelengths, an approximation to Plank’s law is Wien’s radiation law. For $h\nu / kT >> 1$,

$$\left( \frac{1}{e^{h\nu / kT} - 1} \right) = \frac{1}{e^{h\nu / kT}} = e^{-h\nu / kT}$$

and Plank’s law in frequency domain reduces to

$$B_\nu = \frac{2h}{c^2} \nu^3 e^{-h\nu / kT}$$

(IV) Rayleigh-Jeans law: For long wavelengths the approximation of Plank’s law becomes Rayleigh-Jeans law. If $h\nu / kT \ll 1$, then

$$e^{h\nu / kT} - 1 = \left[ 1 + \left( \frac{h\nu}{kT} \right) + \left( \frac{h\nu}{kT} \right)^2 \frac{1}{2} + \cdots \right] - 1 \approx \frac{h\nu}{kT}$$

and Planks’ law becomes,

$$B_\nu = \frac{2\nu^2 kT}{c^2} = \frac{2kT}{\lambda^2}$$

This is Rayleigh-Jeans approximation and is very much useful in microwave region of the spectrum.

(e) Kirchhoff’s law:

All the above fundamental laws are essentially concerned with radiant intensity emitted by a blackbody. The amount of radiant intensity is associated with the emitting wavelength and the temperature of the medium. A medium may absorb radiation of a particular wavelength, and at the same time also may emit radiation of the same wavelength. The rate at which emission takes place is a function of temperature and wavelength. This is the fundamental property of a medium under the condition of thermodynamic equilibrium (characterized by uniform temperature and isotropic radiation) and was proposed by Kirchhoff on 1859. Thus for a given wavelength $\lambda$ the emissivity $\varepsilon_\lambda$ is equal to the absorptivity $A_\lambda$.
1.5.3 Gray Body Radiation

Natural bodies may generally be assimilated to gray-bodies. Unlike blackbodies, gray-bodies do not absorb all received radiation but reflect or transmit part of it. Likewise, a gray-body does not emit as much as a blackbody at the same temperature. Thus a gray body is characterized by incomplete absorption and emission i.e. both emissivity and absorptivity of the gray body is less than 1. Also if the surface emissivity is independent of wavelength, then the body is called a "gray" body, in that no particular wavelength (or color) is favored. We are fortunate that the objects around us are gray-bodies since this is the reason why we can see them as they reflect the part of solar radiation that they do not absorb.

The spectral gray body radiance is given by

\[ E(\theta, \phi, T) = \varepsilon_{\lambda}(\theta, \phi, T)E_{\lambda}^* \]

where \( \varepsilon_{\lambda}(\theta, \phi, T) \) is direction spectral emissivity along direction \((\theta, \phi)\) and \(E_{\lambda}^*\) is spectral radiance of a black-body with temperature \(T\). Emissivity ranges between 0 and 1 depending on the dielectric constant of the object, surface roughness, temperature, wavelength, look angle etc, if epsilon is equal to 1, then we have a black body and if epsilon is equal to 0, then we have a white body.

Figure 1.1: Spectral emittance at a given temperature for Black and Gray body.
1.5.4 Source of Electromagnetic Radiation for remote sensing

The sun is primary source of radiation in passive remote sensing in the optical and near IR wavelength region (about 0.4 to 2.5 μm). The sun may be assumed to be a blackbody with surface temperature around 6000°K. The sun’s radiation covers ultraviolet, visible, IR and radio frequency regions and the maximum exitance occurs around 0.55μm, which is in the visible region. However, the solar radiation reaching the surface of the earth is modified by the intervening atmosphere.

In passing through the atmosphere, electromagnetic radiation is scattered and absorbed by gases and particulates. Besides the major atmospheric gaseous components of molecular nitrogen and oxygen, other constituents like methane, helium, water vapor, ozone, nitrogen compounds, etc., play an important role in modifying the incident radiation energy spectrum. The strongest absorption occurs at wavelengths shorter than 0.3μm primarily due to ozone. There are certain spectral regions where the electromagnetic radiation is passed through without much attenuation and these are called atmospheric window. Remote sensing of the earth’s surface is generally confined to these wavelength regions. Atmospheric windows used for remote sensing are 0.4-1.3, 1.5-1.8, 2-2.6, 3.0-3.6, 4.2-5.0, 7.0-15.0μm and 1cm to 30cm wavelength regions of the electromagnetic spectrum. Even in the atmospheric window regions, scattering by the atmospheric constituents produces spatial redistribution of energy.

When observing earth at wavelengths beyond a few micrometers, the emission of earth becomes the dominant source for passive remote sensing. That is, the observation is made essentially on the basis of change in temperature and/or emissivity. For active remote sensing, the sensors themselves carry the source of radiation. In Optical Infra-Red (OIR) region various types of lasers are used depending on the wavelength requirement. Currently active sensors in the OIR region seldom used for the earth resource survey. However they are very useful for studies of atmospheric constituents and winds. In the microwave region, active sensors use pulsed EM radiation. These radiations are produced by suitable electronic circuits and the final power level is achieved by Traveling Wave Tube Amplifiers.
Chapter 1 - Introduction

1.5.5 Propagation of Electromagnetic Radiations through Atmosphere (Scattering / Absorption / Transmission)

The electro-magnetic radiations (EMR) received and, for some, transmitted by remote sensing sensors pass through the atmosphere. Thus the effect of the atmosphere on EMR of various wavelengths or frequencies is very important to know.

As the electromagnetic field interacts with the atmosphere, a slight reduction in field strength takes place, except at certain discrete frequencies where EMR is almost totally absorbed. This attenuation is caused by the loss of energy from EMR to the various gas and other molecules that make up the atmosphere. The amount of attenuation depends in large part on the frequency of EMR; in general, the higher the frequency, the greater the attenuation. At the higher frequencies, where the very short wave lengths are near the mean diameters of atmospheric particles and molecules, scattering becomes important. Atomic and molecular absorption curtails transmission at certain frequencies or broad bands

**Scattering:** Dust, smoke, haze, and O₂, CO₂, H₂O (vapour), and other particles and molecules attenuate and scatter the incoming EMR from the sun and other sources and the EMR reflected from the earth’s surface and objects on or above the surface.

Two types of scattering take place: Rayleigh and Mie (Ulaby et al., 1981). Rayleigh scattering is caused by a pure or Rayleigh atmosphere consisting entirely of gas molecules. Mie scattering is caused by water particles, dust, smoke, industrial byproducts and other aerosols, which are termed Mie particles. The real atmosphere contains a varying concentration of Mie particles, depending upon geographical location, time of day, meteorological conditions, and other factors. Mie particles are largely restricted to lower atmosphere, mostly below 5000 m. Atmosphere is predominantly Rayleigh above 5000 m, and effective Rayleigh scattering ends above 10,000 m.

The particle size and their composition (to lesser extent) influence the amount and nature of scattering. For a Rayleigh atmosphere the scattering is proportional to $\lambda^{-4}$. A true
Chapter 1 - Introduction

Rayleigh atmosphere rarely exists and, a real atmosphere that exists over most of the earth's surface results in a mixture of both Rayleigh and Mie scattering. The mixed scattering is proportional to $\lambda^{-1.3 \pm 0.6}$ (Ulaby et al., 1981). Scattering plays by far the most important role in the transmission of EMR in the visible portion of the electromagnetic spectrum. About $10^6$ of the amount of scattered EMR is absorbed. In the portion of electromagnetic spectrum on either side of the visible, however, absorption plays a much greater role and, for longer wavelengths at least, scattering is insignificant to nil.

Absorption: There are certain atmospheric constituents which absorb and reradiate EMR of specific frequencies. The amount of absorption varies with wavelength of radiation. An atmospheric constituent may behave very differently if exposed to radiation of different wavelengths. Because of this absorption, certain single frequencies or bands in the infrared and microwave portion of electromagnetic spectrum can not be used to obtain remote sensor data from the earth surface and objects on and above it within the atmosphere. On the other hand, measurements at these frequencies provide a great deal of information on the composition and concentration of certain constituents in the earth's atmosphere. This information is of considerable value in analysing remote sensing data, especially of frequencies near the principal absorption bands.

Transmission: The transmittance of a target or medium (like atmosphere) is defined as the ratio of radiation at a distance $x$ within it to the incident radiation. The transmission of EMR in relation to absorption and scattering is already discussed above. It is obvious that, in order to conserve energy, the sum of reflection/scattering, absorption and transmission must be equal to the incident radiation. Because of wavelength dependency, the relations between reflection/scattering, transmission and absorption vary across the electromagnetic spectrum. These relationships also depend upon angle of incidence, e.g., if the angle of incidence is low, the proportion of reflected energy may exceed the combine proportion of reflected/scattered and transmitted energy, whereas, if angle of incidence is high, the transmitted energy may be more.
1.6 Signatures of precipitation and clouds in remote sensing data

For over five decades, satellite meteorology had focused on observation of global cloud cover and interpretation of cloud patterns as indicators of the development and movement of weather systems. Clouds occupy a crucial place in the hydrological cycle, acting as the link between the condensation of the atmospheric water vapor and occurrence of precipitation. Presence of clouds and precipitation affects the transmission of radiation. There are certain signatures that clouds and precipitation can exhibit in infrared, visible, and microwave satellite measurements.

Clouds having large depth and high cloud water content and cloud ice contents show greater reflectivity in visible channel of satellite imagery. So higher is the reflectivity of the clouds greater is the probability of the precipitation but there is an exception of this fact. It is since snow also shows greater reflectivity it is difficult to distinguish the snow from the clouds and precipitation. Animation of images can reveal clouds moving over the stationary snow surface beneath.

Infrared radiances are measure of the temperature of the radiating surface. Clouds in the infrared measurements exhibit low brightness temperature. So lesser is the brightness temperature greater is the probability of finding a cloud with its top at very high altitudes. So, rainy clouds exhibit a very low brightness temperature in the infrared measurements.

As far as microwave measurements are concerned precipitation and clouds over ocean is easy to distinguish, because the warm, unpolarized emission from precipitation and clouds contrasts strongly with the cold, polarized emission from the ocean surface. However, the primary problems of detection is the lack of a spectrally distinct signature between non-precipitating cloud and liquid precipitation. The most common solution is to define a clear cut threshold of non-precipitating column cloud liquid water (CLW), beyond which any emission is assumed to be due to liquid precipitation.

Land has very variable emissivity in the microwave region. The main problem with precipitation and cloud detection over land lies in the relatively warm, and unpolarized nature of land surface emission. The signature of liquid precipitation may be very weak (or even non-existent) against this variable land background. As a result of the above
Chapter 1 - Introduction

problem, algorithms for detection of rain over-land rely on the depression in brightness temperature due to the scattering primarily by ice (and liquid) particles present in the atmospheric hydrometeor. This detection method fails, of course, in the case of warm-cloud precipitation having no significant ice phase. Apart from these major signatures, there are many defined proxy signatures that precipitation and clouds exhibit, these includes: Polarization Corrected brightness Temperature (PCT), Scattering Index (SI), Polarization Difference (D). These signatures will be discussed in the subsequent chapters.

1.7 Physical basis of precipitation monitoring using satellites

Although the first weather satellite was launched in 1960, it was not until 1966 that the first operational weather satellite system was inaugurated using two polar-orbiting satellites of a "cartwheel" variety. Not surprisingly, attention in the early years of satellite meteorology was focused on those atmospheric phenomena which could be observed relatively directly in the visible and infrared wavebands such as cloud types and systems rather than others which could be assessed relatively indirectly or inferentially such as rainfall rates and distributions. Thus the earliest research which proposed a method for the systematic evaluation of rainfall from the cloud contents of weather satellite images appeared as late as the tenth year of satellite operations. In this and following researches, it was assumed that satellites were, in effect, in competition with conventional systems in the monitoring of precipitation. However, direct measurement of rainfall from satellites for operational purposes has not been generally feasible because the opacity of clouds prevents direct observation of the precipitation with visible, near-infrared and thermal infrared sensors. But improved analysis of rainfall can be achieved using both satellite and conventional ground-based data. Satellite data are most useful in providing information on the spatial distribution of potential rain-producing clouds. Useful data can be derived from satellites used primarily for meteorological purposes, including polar orbits such as NOAA-N and DMSP, TRMM and geostationary satellites such as GOES, GMS Meteosat, Kalpana, and INSAT-3A, but their visible and infrared images can only provide information about the cloud tops. However, since these satellites do provide frequent observations, even at night with the thermal sensors, the characteristics of
potentially precipitating clouds and the rates of changes in cloud area and shape can be observed. From those observations, estimates of rainfall can be made which relate cloud characteristics to instantaneous rain rates and/or rain total over time (Barret, 1988).

The approaches used in making quantitative estimates of rainfall by using satellites can be divided into two streams:

1.7.1 Visible and Infrared techniques:

The availability of meteorological satellite data has produced a number of techniques for extracting the most important information on precipitation from satellite imagery of clouds in the visible and/or infrared wavebands (Barret, 1988). These techniques have led to the development of three dominant approaches: the cloud indexing approach, the thresholding approach, and the life-cycle approach. Cloud indexing, which is time independent, identifies different types of rain clouds and estimates the rainfall from the number and the duration of clouds or their area. Thresholding techniques consider that all clouds with low upper-surface temperature are likely to be rain clouds. Life-cycle methods are time dependent and consider the rates of changes in individual convective clouds or in clusters of convective clouds. All these methods are essentially empirical in that they use statistical coefficients based on historical cloud and ground measured rainfall. They will be addressed in the following subsections.

(a) Cloud indexing techniques

These techniques rely on visible and infrared data to characterize a cloud type or temperature which is then related to rainfall via empirical relationships. Different methods have been used to calibrate the indices to give rainfall estimates. The Earthsat method (Moses and Barrett, 1986) is an operational rainfall estimation scheme that has been developed to provide input to crop yield models and commodity forecasting systems. The Earthsat method uses a regression approach to estimate 6 hour precipitation from cloud temperature and empirical information for the major crop-growing regions of the world.
Chapter 1 - Introduction

The result of the regression calculation can be further modified by consideration of synoptic station reports. Experienced meteorologists can usually improve upon these estimates by improving the vertical motion fields through interpretation of the satellite imagery. The Bristol method uses an empirical relationship between satellite determined cloud indices, climatic indices dependent on the mean monthly rainfall, and 12-hour rainfall totals. A family of curves has been developed by some researchers (e.g. Barrett, 1981) in tropical and mid-latitude zones. These studies indicated a consistent increase in precipitation amounts from dry to hot-humid climates, but also indicated that higher-intensity rain clouds could not often be differentiated from lower-intensity rain clouds. Hence there is a need to treat each pixel location separately and in the light of climatological information. The BIAS (Bristol/NOAA interactive system) method has been developed on the basis of Bristol method (Barrett et al., 1986). It is the cloud indexing types which have, in one form or another, shown most flexibility and which have yielded the first results in support of operational rainfall monitoring programme.

(b) bi-spectral techniques:

Clouds that are bright in visible images are more likely to precipitate than dark clouds because brightness is related to optical depth and thus to cloud thickness. Clouds that are cold in IR images are more likely to precipitate than warm clouds because cold clouds have higher tops than warm clouds. There are exceptions to these rules, however, stratus clouds are bright, but do not rain as much, nor as often, as cumulonimbus clouds. Cirrus clouds are cold but do not produce as much precipitation as some warmer clouds. Bispectral methods attempted to combine these rules by saying that clouds which have the best chance of raining are both cold and bright. Lesser amount of precipitation can be expected from cold-but-dark clouds (cirrus) and bright -but-warm clouds (stratus).
Chapter 1 – Introduction

(c) Life cycle technique:

Life cycle techniques are designed to provide rain estimates from any type of convectional clouds by taking into objective consideration of the growth or dissipation of individual clouds with time. This approach implicitly recognizes that convective clouds exhibit different rainfall intensities during their growth and dissipation cycle.

The Woodley-Griffith technique was developed initially to predict rainfall over south Florida as part of the Florida area cumulus experiment (Griffith et al. 1978). This method uses an empirically derived relationship between calibrated ground- based radar echoes and geostationary satellite imagery of cloud areas. A time-cycle relationship between the radar echo area and the cloud area is developed for discrete time intervals during the lifetime of the cloud. The relationship used in the Woodley- Griffith technique can be found in this paper.

A family of life-cycle techniques with the more specific purpose of evaluating and monitoring high-density events has been developed from the work of Scofield and Oliver (1977 a). By originally using half- hourly rainfall amounts for convective systems from tropical air masses, an analyst can then use a decision tree to make rainfall estimates at different points. This technique is divided into three parts: first, the active portion of the convective system is delineated; second, an initial estimate of rain rate is made from thermal infrared image alone; then, third, the changes in two consecutive images (visible and thermal infrared) are evaluated to find clues that would indicate heavier rainfall.

Scofield (1986) has developed a series of seven convective and five extratropical cloud categories that can be used to help meteorologists improve their estimates of heavy precipitation across a range of different weather situation. The categories have been developed from satellite data, ground radar, surface and upper-air data, and from precipitation characteristics. Each category is based on the life cycle of the cloud pattern and cloud-top temperature changes as well as the other information.
(d) Cloud Model Techniques:

To improve precipitation estimation techniques based on visible and IR satellite data, it is necessary to build the physics of the cloud into retrieval process. One way to this is through the use of cloud models. Several investigations have attempted to use cloud models to relate satellite observations to precipitation. The Scofield and Oliver (1977) developed a rainfall estimation scheme for the purpose of operationally estimating convective rainfall, particularly heavy rainfall. The scheme is based on conceptual cloud model. This technique is not automated but rather relies on the judgment of a satellite meteorologist to locate precipitation-associated signatures in satellite images and to assign appropriate rain rate to points affected by these features. The technique is subjective but it can take into account phenomenon that automated technique can not.

All of these methods used in the past involve manual interpretation of imagery from meteorological satellites. Because of the factor of human interaction, the number of images that can be handled daily is limited. The human interaction factor also makes the analysis procedure subjective. Snijders (1991) undertook a study to evaluate these three methods to monitor rainfall over West Africa using automated processing of full-resolution digital data, being 2.5 km by 2.5 km for the visible channel and 5 km by 5 km for the thermal infrared channel, from the Meteosat satellite. The purpose of this study was to make a direct comparison of these techniques for the same area and period of time. The results indicated that none of the techniques yielded better results than the others, but there were distinct differences in the performance. The cloud indexing method and threshold techniques performed best at the lower latitude, while the life cycle techniques performed best at the higher latitudes.

There are many variables affecting the radiances observed by these methods, such as sun elevation, satellite-sun azimuth angle, layered clouds, reflectivity of underlying surfaces, snow and ice surfaces, shadows etc. Eliminating errors caused by these is possible in some cases with statistical or physical methods. Some of them are so complex, that they have to be neglected in a real time application. It is time consuming to analyze a raw satellite image affected by these errors. Pylkkö and Aulamo (1991) discussed a method to
"teach" the computer to do the analyzing. They used data from satellite images to find ways to automatically analyze the probability of rainfall. The first results showed that the Meteosat data can be used to analyze rainy areas in synoptical scale. These products definitely supply useful information to help monitor rainfall.

1.7.2 Microwave techniques

Clouds are opaque in the VIS and IR spectral range and precipitation is inferred from cloud top structure. At passive MW frequencies precipitation particles are the main source of attenuation of the upwelling radiation. MW techniques are thus physically more direct than those based on VIS/IR radiation. The emission of radiation from atmospheric particle results in an increase of the signal received by the satellite sensor, while at the same time the scattering due to hydrometeors reduces the radiation stream. Type and size of the detected hydrometeors depend upon the frequency of the upwelling radiation. Above 60 GHz ice scattering dominates and the radiometers can only sense ice while rain is not detected. Below about 22 GHz absorption is the primary mechanism affecting the transfer of MW radiation and ice above the rain layer is virtually transparent. Between 19.3 and 85.5 GHz, the common passive MW imagers’ frequency range, radiation interacts with the main types of hydrometeors, water particles or droplets (liquid or frozen). Scattering and emission happen at the same time with particles or droplets (liquid or frozen). Scattering and emission happen at the same time with radiation undergoing multiple transformations within the cloud column in the sensor’s field of view (FOV). At different frequencies the radiometers observe different parts of the rain column as for other parts of the spectrum, MW radiation is absorbed (but not scattered) by cloud droplets, water vapor and oxygen thus making precipitation estimates based on absorption potentially difficult. Precipitation drops strongly interact with MW radiation and are detected by radiometers without the IR strong biases. The biggest disadvantage is the poor spatial and temporal resolution, the first due to diffraction, which limits the ground resolution for a given satellite MW antenna, and the latter to the fact that MW sensors are consequently only mounted on polar orbiters. The matter is further complicated by the different radiative characteristics of sea and land surfaces underneath. Sea surface has a relatively constant and low emissivity i.e. 0.4, so that the radiation emitted from it is small and precipitation
(emissivity around 0.8) will increase the amount of radiation detected by the sensor through emission. The high sea surface polarization also contrasts very much with the low polarization of rain. Land surfaces have a high and variable emissivity (in the range 0.7 to 0.9), close to that of precipitation, and low polarization. The emissivity is dependent upon the characteristics of the surface including vegetation and moisture content. Rainfall over land will increase the upwelling radiation stream but at the same time will absorb radiation introducing considerable difficulties in the identification of rain areas. Scattering is thus the key to the MW rainfall estimation techniques over land and the 85.5 GHz channel of the SSM/I is very sensitive to scattering from small particles.

Microwave techniques have a great deal of promise for measuring rainfall and have been employed for many years to provide rainfall datasets because of the potential for sensing the rain itself and not a surrogate of rain such as the cloud type. Microwave radiation with wavelengths of the order of 1 mm to 5 cm results in a strong interaction between the raindrops and the radiation. This is because the drop size is comparable with the wavelength.

Passive microwave radiometers on the Electrically Scanning Microwave Radiometers (ESMR-5, 19.35 GHZ) have yielded measurements of naturally-emitted microwave radiation from the surface of the Earth, and the water content of the atmosphere. ESMR-5 data have been processed to give, among other outputs, maps of instantaneous precipitation intensities. Passive microwave approaches are being developed further through experimentation.

Allison et al (1975) have shown that ESMR data is very useful in delineating areas of rainfall over the oceans and gives qualitatively good comparisons with rainfall data. Wilheit et al (1977) used a radio active transfer theoretical model which includes scattering effects and concluded that, despite the difficulties in interpreting rain rate, it can be used to estimate the higher rainfall rates. This technique has also been used to estimate weekly, monthly and annual rainfall maps for the major ocean areas.

Some researchers have opened up a new range of possibilities for the development of rainfall algorithms over land. A more recent rainfall algorithm is based on the difference
in measured brightness temperatures at two frequencies, as suggested by Gordy (1984). This algorithm is based on the relationship between emissions and frequency, which decreases for most surfaces but increases for dry snow, old sea ice and in the presence of scattering caused by raindrops. Ferraro et al (1986) developed a classification approach for identifying rain as well as other geophysical features. Their classification scheme is based on the difference in two vertical polarized frequencies plotted against their average.

The polarization algorithm suggested by Grody (1984) is based on the collocation between two polarizations at the same frequency so that the surface emissivity effects are minimized and the precipitation effects enhanced. Although the relationship between the rain rate and the microwave response is fairly well understood, there are several limitations in this approach. One of the more serious is the unknown depth of the liquid rain layer, especially in areas where warm rain forms without an ice phase. The effect of cloud density which is made up of small droplets less than 50*μm in diameter has not been accounted for and is a potential source of error that could perhaps be solved with multifrequency measurements. There is also work to be done on improving the modelling of the scattering model to represent more realistic ice particle geometries. But the design of rainfall retrieval algorithms over land is fraught with difficulties, the worst of which lead to ambiguities. Furthermore, passive microwave data is less easily and less frequently available. Finally these problems do not begin to address the more fundamental problems of measuring rainfall. These include the great spatial and temporal distribution of rainfall and the fact that instantaneous rain rates are being measured when, in fact, what is needed is the integrated rainfall volume over some time period. Therefore, combining visible, infrared and passive microwave data may be the best satellite or satellite improved rainfall monitoring method. So the trispectral technique is the next step in the development of rainfall algorithms. In the first examination of the potential of combining visible, infrared and passive microwave, a hybrid approach (Barrett et al., 1988) investigated the use of scanning microwave multichannel radiometer (SMMR) passive microwave data in support of BIAS discussed in 4.1.1 for rainfall monitoring in several areas of the globe where they could overlay the SMMR data on to the BIAS
Chapter 1 – Introduction

images. Although not a definitive study, it was concluded that the passive microwave
data could be useful in helping to

1) Locate the leading and trailing edges of rain areas.

2) Confirm the extent and organization of rain areas especially if no visible/infrared data
were available.

3) Locate heavy-rain areas where cumulonimbus cells are located within stratiform
clouds

4) Locate areas of rain that could not normally be identified by BIAS.

More recently, the potential of the combination of spaceborne radars and passive sensors
for rainfall profiling have been examined (Wilheit, 1990). The general consensus is that
radar/passive instrument complement can provide a better characterization of the rain
systems. It is much easier to achieve a wide swath for the measurements with a
radiometer than with radar.

Weinman, J. A. et al (1988) developed an algorithm to seek rainfall profiles from
multifrequency, dual polarization passive radiometers operating in combination with a
radar that operates under condition that produce significant extinction. The algorithm was
solved that yield a robust solution of the radar equation subjected to constraints imposed
by measurements of dual polarized multifrequency microwave radiances. Using
simulated data, it was shown that single frequency radar operating from space in
conjunction with a multispectral radiometer may be able to provide cost effective
measurements of global tropical rainfall distributions. Weinman et al (1988) have shown
that the passive microwave results may be used to constrain the radar equation, obtaining
good vertical profiles of rain rates as well as surface values.

1.8 Conclusions

On the basis of extensive overview of precipitation theory and measurements it is
concluded that present study is very useful for the estimation of precipitation using
remote sensing. In this chapter a brief outlook of the thesis along with its relevance in present context is given. The importance, objective and area of study is explained in this chapter. The basic physics involved in the precipitation process, starting from evaporation to cloud formation and finally leading to precipitation is briefed. The numerous types of precipitation i.e. all form of water falling upon the earth’s surface viz. drizzle, virga, rain, fall streaks, flurries, snow squalls, blizzard, sleet, freezing rain, freezing drizzle, snow pellets, snow grains and hail are briefly introduced. The basics of remote sensing useful for precipitation and related theories are also given. The signatures of the cloud and precipitation regarding remote sensing are also discussed in this chapter. The physical basis behind the precipitation measurements in visible band, infrared band and microwave band and the brief history of precipitation measurement using these bands are briefly discussed.