CHAPTER 4

Precipitation estimation using Microwave data

4.1 Introduction
   4.1.1. Limitations of the IR based rainfall estimates
   4.1.2. Use of microwaves in rainfall monitoring
   4.1.3 Earlier Research in use of microwaves in precipitation monitoring
   4.1.4. Indian efforts
   4.1.5. Development of regional scattering index scheme for Indian tropics

4.2 Data used for the study
4.3 Methodology
4.4 Results and discussions
   4.4.1. Comparison of present technique with Ferraro global scheme
   4.4.2. Comparison with GPROF algorithm
   4.4.3 Validation with rainfall from Automatic Weather Station rain gauge
   4.4.4 Validation with rainfall from Doppler Weather Radar (DWR)

4.5 Conclusions
Chapter 4- Precipitation estimation using Microwave data

4.1 Introduction:
The spaceborne measurement and monitoring of rainfall is a topic of major interest since it influences the global hydrological cycle and the nature of climate variability. The development of rainfall estimation techniques based on remote sensing measurements from space has registered tremendous progress and realistic achievements over the last three decades. However, there are limitations too and newer and better measurement and estimation techniques are developed on a continuous basis. The ability of space based measurements to provide a 2-dimensional distribution of rainfall over large areas with sufficiently frequent sampling in time, especially over data sparse oceanic regions, facilitates us with a tremendously powerful tool to detect, closely monitor systems like monsoon and study the genesis and evolution of the furious tropical cyclonic storm. In chapter 3, an effort was made to estimate the rainfall for the Indian tropics based on the Infrared observations from the geo-stationary satellites. However, it is observed that infrared based estimates suffer from certain limitations.

4.1.1. Limitations of the IR based rainfall estimates:
The rainfall from the Infrared and Visible are inferred indirectly from the top of the clouds. Significant errors existed because these channels could not penetrate cloud layers. Results in chapter 3 show that although standard GPI works well for the larger temporal and spatial scales (daily/monthly over 1°X1°/2.5°X2.5° GRID box), it does not work for the smaller temporal and spatial scales. Results further show that these estimates are not always accurate over land and particularly over the mountain regions, where rainfall is more orographic than convective also these threshold (235 degree Kelvin) may not hold well where the rainfall is originating predominantly from warm clouds. Rainfall intensity gets frequently overestimated when high cirrus clouds or anvil clouds appear in the field of view. Proposed MGPI algorithm shows improvement over the standard GPI technique but like other infrared and visible techniques it is an indirect measurement. On the other hand, microwave channel data are less influenced by cloud layers and therefore more suitable for rainfall intensity estimation (Liu and Curry 1992; Negri et al. 1994; Barret and Bellerby 1992; Ferraro et al. 1992; Grody et al. 1991; Spencer et al. 1989).
Chapter 4- Precipitation estimation using Microwave data

4.1.2. Use of microwaves in rainfall monitoring:

The importance of microwave remote sensing to better rainfall estimation has been demonstrated by some new experiments, such as the Tropical Rainfall Measuring Mission (TRMM) and the Earth Observing System (EOS). On the other hand, microwaves due to large wavelength can penetrate the clouds and thus provide more direct precipitation measurements. Also, microwaves are largely insensitive to the presence of ice in thin cirrus clouds but only suffer its poor resolution capability. It is from relatively recent times that the microwave measurements from satellites are being recognized for precipitation measurements application. Over the years, passive microwave (PM) instruments on earth orbiting platforms have been providing valuable information for precipitation estimation. The applications that benefited from microwave rainfall estimates include weather forecasting, climate analysis, and hydrological studies. Utilizing the frequency and polarization discrimination of passive microwave (PM) measurements from space, it has been successfully demonstrated that satisfactory rainfall retrievals both over land and oceanic areas are feasible. Microwave radiances reaching satellite altitudes from precipitating clouds containing aspherical ice, combined phase hydrometeors and the background atmosphere (cloud liquid water, water vapor and gaseous constituents etc.) within the instrument field of view. The upwelling radiation observed by a microwave radiometer is expressed as an equivalent brightness temperature $T_b$ and the ability of passive microwave radiometer to infer rainfall depends largely on the contrast between the observed brightness temperatures over raining and non-raining areas.

Utilizing the frequency and polarization discrimination of passive microwave measurements from space, it has been successfully demonstrated that satisfactory rainfall retrievals both over land and oceanic areas are feasible. It has been seen that satellite estimates based on passive measurements portray the rainfall as accurately as radar both in terms of relative intensity and spatial distribution. Two theories, the emission and the scattering theory are frequently adopted to estimate rainfall intensity with microwave data (Janowiak et al. 1995). The former uses the observed emitted radiations from atmospheric liquid particles to estimate the rainfall intensity. The observed radiation is sensitive to the surface emissivity, so it is only applied to oceanic regions owing to the
sea surface emissivity being low and homogeneous, and it is believed that this theory is more appropriate for rainfall estimation in areas beneath stratified clouds or shallow convective clouds. The latter method may be employed to estimate the rainfall intensity by measuring the extinction of the microwave radiation caused by the particles of liquid water or ice. However, it is only suitably applied to deep convective systems. The high and variable emissivity of the land surface greatly complicates the signal from the liquid hydrometeors. The liquid hydrometeors could increase or decrease the observed radiation depending upon the surface emissivity, which is a function of the rain that has fallen over a time scales of days. So rainfall retrievals over the land are more difficult than the ocean retrievals due to the large and variable emissivity of the land surface. Specifically the high emissivity effectively masks the emission signature that is related directly to the liquid water contents in the atmosphere. Instead only the brightness temperature depression due to the scattering from the upper portion of the clouds is readily observed. The scattering index must then be converted to the rainfall rate using statistical relation between the ice aloft and the base of cloud.

A further complication that arises over land is the lack of the consistent background against which to compare the brightness temperature depression. To alleviate this problem caused by the varying emissivity associated with change in surface characteristics (e.g. surface wetness, snow cover, vegetation etc.) as well as temperature variability, a rain/no rain temperature depression, a threshold is required. The accurate retrieval of rainfall intensity from satellite data must involve the scattering and emission signals, respectively, which makes the retrieval process complex. Moreover much research has used ground-based rain gauge data to evaluate the accuracy of the rainfall intensity estimation of satellite data. There has always been the problem that sensors mounted on satellite measure whole vertical column, but that raindrops or ice particles aloft do not fall to the ground instantly. It is thus only meaningful to compare the rain gauge measured rainfall intensity with those retrieved from satellite data for a certain time period.

The successful use of PM-based rain estimates in applications from various fields encourages the continuation of efforts toward the development of more advanced rain
Chapter 4- Precipitation estimation using Microwave data

retrieval algorithms, despite obvious limitations associated with the low sampling frequency of orbiting platforms carrying PM sensors.

4.1.3 Earlier Research in use of microwaves in precipitation monitoring:
The relative research using ground based microwave radiometer data began in the 1970s (Ulaby et al. 1981). Guiraud et al. (1979) used a dual channel microwave radiometer to measure the precipitable water vapor. They indicated that ground-based microwave radiometer can be used to monitor precipitable water better than radiosonde data can. Emission and scattering based techniques were used to estimate the rainfall intensity from the microwave observation of satellite data. Early work by Wilheit et al. (1977, 1991) presented rainfall algorithm that is purely emission based, using 19.35 GHz frequency using ESMR data. Further modification to the algorithm was made by using statistical technique for multichannel data in the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) data (Wilheit and Chang 1980). Liu et al. (1998) developed such emission and scattering indexes for global scale, but for the monthly time scale. Coupling of emission and scattering signal was also attempted by Petty (1994a, b) in order to overcome problem such as saturation of emission signal at lower frequency and high rain rates, and the low sensitivity of the scattering signal to low rain rates. Algorithm developed by Wilheit et al. (1977) was applied to the study of tropical cyclones energetics by Adler and Rodgers (1977). A global atlas of oceanic rainfall for the years of 1973 and 1974 was generated by Rao et al. (1976) using a modified version of the Wilheit et al. (1977) rainfall algorithm. Rao and Theon (1977) examined the atlas and discussed many previously unknown features of oceanic precipitation. Much criticism of this atlas was traced to poor quality control in the ESMR dataset prompting NASA to reprocess the entire Nimbus 5 ESMR record. Shin et al. (1990) used the reprocessed ESMR dataset and an improved algorithm based on brightness temperature histograms to reanalyze the global rainfall fields for 1974. Mohr and Zipser (1996a) used microwave radiometry to identifying mesoscale convective systems (MCS) from the SSM/I data using PCT approach. In addition to empirical algorithms, which generally rely on a bulk statistical relationship of surface rain rate and observed brightness temperature, precipitation retrieval from passive microwave satellite data using radiative transfer...
Chapter 4- Precipitation estimation using Microwave data

models have been developed (Wu and Weinmann 1984; Kummerow et al. 1996, and 2001, Haferman et al. 1997). These physically based algorithms require a solution of the radiative transfer equation for each observed datum value and involve assumptions concerning the rain and cloud structures within the model. Smith et al. (1992) and Mugnai et al. (1993) incorporated a dynamic cloud model to specify hydrometeor vertical structures for input into the radiative transfer model and showed that the relationship of rain rate and brightness temperature varies depending upon the particular vertical hydrometeor profile present. The physically based algorithms were mainly investigated in over ocean retrievals. Such physically based retrieval over land are few and have not indicated better performance relative to purely statistical algorithms (Druen and Heinemann 1998), which are conceptually simpler and more practical for applications. Currently the 85 GHz channel in DMSP-SSM/I (F10, F11, F12, F13) and TRMM-TMI offers better possibilities of rainfall estimation. Shih et al. (1992), estimated precipitation over the tropics using only the 19.35 GHz data channel. Wilheit et al. (1991) used multichannel microwave measurements for the rainfall retrieval. Negri et al. (1989) discussed meteorological interpretations with the false color images of 85 GHz (HH, VV) and 37 GHz (VV) for precipitation processes and clarification of land, ocean and sea ice types with SSM/I. Berg et al. (1992) estimated and analyze interannual variations in the tropical oceanic rainfall using data from SSM/I. Gairola et al. (2003) described some of the remote sensing techniques for the estimation of the rainfall from passive and active microwave measurements form space. Recently Kumar et al. (2009) presented evolution of precipitation features in high frequency SSM/I measurements over Indian tropics. In addition to various SSM/I sensors presently available for the rainfall estimation, the Tropical Rainfall Measuring Mission (TRMM) provides the best opportunity with all type of passive (MW and VIS/IR) and active (MW) sensors onboard. These satellites provide the best opportunity to estimate the rainfall. Kumar et al. (2009) compared the version 5 and version 6 rainfall products of PR on board TRMM.

Though the SSM/I and TRMM have been very extensively used for rainfall measurements, the further effort to improve these measurements is still continuing, and would receive further impetus with planned constellation of satellites planned under coming Global Precipitation Mission.
Chapter 4- Precipitation estimation using Microwave data

4.1.4. Indian efforts:
Indian journey in microwave measurements began with the launch of 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 SAterllite 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 (Hariharan and Pandey 1983). Studies related to rainfall retrieval were also been carried out using SAMIR data (Gohil et. al., 1981). 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. 98
Chapter 4- Precipitation estimation using Microwave data

2004, and Varma et al. 2002). Gairola et al. (2003) presented an overview of the methodologies for rainfall retrievals from microwave measurements. IRS-P6 (Resourcesat 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. Indo-French project Megha-Tropiques is set to be launched sometimes in 2011.

4.1.5. Development of regional scattering index scheme for Indian tropics:
In the present study the basis for the rainfall retrieval over Indian land and oceanic regions comes from the work of Grody et al. (1991), who developed a global scattering index (SI) at 85 GHz using SSM/I data. Further refinement of technique was described by Ferraro and Marks (1995). However it is found that this scattering index is highly variable with regions and seasons as well as the platform. In the present chapter a regional scattering index is developed specifically for the Indian land and oceanic regions (50°E - 120°E and 20°S - 40°N, figure 17) using SSM/I F13 data and then a relationship is established between rainfall and scattering index for the land and ocean separately using TRMM PR observed rainfall and this has been reported in a paper by Mishra et al. (2009). A global relationship between the rainfall and the scattering index developed by Ferraro and Marks 1995 to estimate the rainfall was also used to compare the results of the derived regional relationship between the rainfall and the scattering index. Validation of both regional as well as the global scheme is carried out with the ground observation to test the strength of this regional scheme. Inter-comparison with 2A12 data of TRMM followed from Goddard Profiling (GPROF) algorithm (Kummerow et al. 1996) has been performed to check the applicability of the algorithm in view of the algorithm development for Indo-French Megha-Tropiques mission to be launched from India sometime in 2011.
Chapter 4- Precipitation estimation using Microwave data

4.2. Data used for the study:
For the present study the 19, 22 and 85 GHz channel brightness temperature swath data of SSM/I (F13) data was downloaded from ftp site (ftp://ghrc.nsstc.nasa.gov/pub) for the years 2005, 2006 and 2007. The current study also utilizes the latest version 6 of data from the TRMM Science Data and Information system (TSDIS) 2A25 algorithm. The 2A25 data for the years of 2005, 2006 and 2007, and 2008 were used for the calibration with scattering indices in the present study. In present chapter for the intercomparision of the precipitation estimates, the GPROF (2A12) data for the years of 2005, 2006, 2007 and 2008 is also used. Further, for the validation of the present algorithm the AWS rain gauge data during July and September 2007 is used.
In the present study 1.0° elevation data of DWR during the post monsoon months of years 2007 and 2008 are used to produce the surface rainfall for the comparisons with the rainfall from the present regional scheme. The details of these data sets are given in chapter 2.

4.3. Methodology:
Present study consists of two steps, in the first step region specific ‘scattering index’ is developed using combination of the 19, 22 and 85 GHz channel, both over Indian land and oceanic regions separately. The second step establishes a new relationship between the scattering index and the rain rate using the TRMM PR data mainly following Ferraro and Marks (1995). Here it should be noted that the additional use of 37 GHz channel may result in a smaller error than the two channel algorithm (i.e. 19GHz and 22GHz). However 37 GHz channel can exhibit the scattering effect and therefore was not used to estimate the non scattering contribution at 85GHz. Since the 19 and 22-GHz channels are relatively unaffected by scattering, these observations from SSM/I are used for estimation of 85 GHz brightness temperatures during non-scattering conditions.

For the development of the scattering index, the following form of relationship between 19, 22 and 85 GHz is established under non rainy conditions.

\[ F = A + B \times T_v(19) + C \times T_v(22) + D \times (T_v(22)^2) \]  \hspace{1cm} (1)
Chapter 4- Precipitation estimation using Microwave data

where F=85 GHz channel Brightness temperature. \( T_v(f) \) is vertically polarized brightness temperature in kelvin at frequency ‘f’.

The value of A, B, C and D were derived by assembling a data set (17652 data points over the land and 19762 data points over the ocean) of SSM/I F-13 over Indian land and oceanic regions under non-rainy condition separately. For the land region the value of the coefficients were found as follows:

\[
A = 448.6809, \quad B = -1.5456, \quad C = -0.6020, \quad D = 0.0055
\]

with standard error of estimates = 1.3513 and the correlation coefficients of 0.93

Similarly for the oceanic regions the values of coefficients were found as follows:

\[
A = -362.4467, \quad B = 1.1379, \quad C = 3.5247, \quad D = -0.0078
\]

with Standard Error of Estimate = 1.8261 and a correlation coefficients of 0.91. Once the value of A, B, C and D are calculated, value of F is obtained and then scattering index at 85 GHz channel is defined as

\[
SI(85) = F - T_v(85)
\]  

for all the database (both raining and non-raining). For non-raining cases the value of the SI is suppose to be ideally zero. From this step onwards, the index SI could be used to separate the scattering and non-scattering signals for a given set of independent data.

Figures 4.1 and 4.2 show the comparisons between the derived F and observed 85-GHz vertically polarized measurements for the land portions and oceanic portions respectively. Now the SI has been calibrated with Precipitation Radar measurements from Indian land and oceanic regions. For this calibration purpose 1895 collocated data points over land and 1987 over the oceans were used. Figures 4.3 and 4.4 show the scatter plot between the SSM/I scattering index and the PR rainfall for the land and oceanic regions respectively.
Chapter 4- Precipitation estimation using Microwave data

Fig. 4.1. Comparison between the derived $F$ and observed 85-GHz vertically polarized measurement for the land portion

Fig. 4.2. Comparison between the derived $F$ and observed 85-GHz vertically polarized measurement for the oceanic portion
Chapter 4- Precipitation estimation using Microwave data

![Graph showing relationship between scattering index and rainfall rate](image)

**Fig 4.3.** Scatter plot between the scattering index from the SSM/I and rainfall from PR for the land portion

![Graph showing relationship between scattering index and rainfall rate](image)

**Fig 4.4.** Scatter plot between the scattering index from the SSM/I and rainfall from PR for the oceanic portion

Different types of fit were tested but following two relations (power law) were found to work best for the land and oceanic regions (giving best statistics) separately over Indian land and adjoining oceans respectively.

For the land application:

\[ RR \ (\text{mm/h}) = 0.0268 \times (SI)^{1.5978} \]

For the oceanic application:

\[ RR \ (\text{mm/h}) = 0.0118 \times (SI)^{1.4985} \]
Chapter 4- Precipitation estimation using Microwave data

\[ RR \text{ (m/h)} = 0.0268 \times (SI)^{1.5978} \]  \hspace{1cm} (3)

with standard error of estimate 1.1375 and correlation coefficients of 0.86

For the ocean application:

\[ RR \text{ (mm/h)} = 0.0118 \times (SI)^{1.4985} \]  \hspace{1cm} (4)

with standard error of estimate 0.9097 and correlation coefficients of 0.82

where RR is rain-rate in millimeters/hour.

The above two equations over land and ocean are applied to get the rainfall using scattering index. Further we have also used the following global relationship developed by the Ferraro and Marks 1995 to estimate the rainfall.

\[ RR \text{ (mnlh)} = 0.00513 \times (SI)^{1.9468} \]  \hspace{1cm} (5)

4.4 Results and discussions:

Finally the rainfall rate using the above equations (3) and (4) is calculated during the pre-monsoon, post-monsoon, monsoon, and cyclonic cases of the years 2005, 2006, 2007, and 2008 at 0.5°X0.5° grid box for the Indian land and oceanic regions. The approach of rainfall estimation in this chapter is intercompared with the rainfall from TMI (2A12 algorithm) i.e GPROF algorithm both qualitatively as well as quantitatively at the grid box of 0.5°X0.5°. Further validations using AWS rain gauges and the DWR is also performed. In this chapter we have also compared the rainfall obtained from the Ferraro global scheme (equation 5) with those obtained from the regional scheme.

4.4.1. Comparison of present technique with Ferraro global scheme:

The rainfall estimated from the regional scheme (present technique) is compared with those using the Ferraro global scheme. Two cases were taken for this comparison for brevity.

First case was taken for 23rd July 2008, for which figure 4.5 shows the rainfall rate at 1245 UTC. It is clear from the figure 4.5 that there were multiple localized systems over oceans as well as over the land. Figure 4.6 shows the rainfall rate using the present
Chapter 4 - Precipitation estimation using Microwave data

regional scheme. It is clear from the Figure that all those systems were well picked up by the present scheme also.

Fig 4.5. Rainfall rate using the Ferraro global scheme on 23rd July 2008 at 1245 UTC

Fig 4.6. Rainfall rate using the present regional scheme on 23rd July 2008 at 1245 UTC

It is observed that over the land rainfall values are not well depicted by the global scheme but it is very well depicted by the present scheme.

Another case study is taken for the 17th July 2009 at 0350 UTC. Figure 4.7, and 4.8 show the rainfall rate on that day from Ferraro global scheme and present regional scheme respectively.
Chapter 4 - Precipitation estimation using Microwave data

Fig 4.7. Rainfall rate using the Ferraro global scheme on 17th July 2008 at 0350 UTC

Fig 4.8. Rainfall rate using the Present regional scheme on 17th July 2008 at 0350 UTC
Chapter 4- Precipitation estimation using Microwave data

It is again clear that over the ocean rainfall features are almost same from both the schemes, but over land rainfall events is well captured by the regional scheme. And we will see later in this chapter that this regional scheme is working better than the Ferraro global scheme over the Indian land region (comparison with the AWS rain gauge confirms this in the coming section 3.4.3)

4.4.2. Intercomparison with the GPROF algorithm:
As is mentioned earlier, the present technique was tested for the Indian land and oceanic region during monsoon, pre monsoon and post monsoon season of 2005, 2006 and 2007 and the performance of the algorithm is intercompared with 2A12 (GPROF algorithm) rainfall. Various case studies were carried out and only some of the results will be discussed in the present chapter for brevity. It must be noted here that in order to explore the rainfall features we have taken the subsections of the whole study area for the comparison purpose.

The first case study is taken up on 9th September 2005 (post monsoon season), when there were two localized cloud systems over ocean at the locations 13°N/84°E and 16°N/84°E. Figures 4.9 and 4.10 show the rainfall plots of these systems both by present technique and the TMI-2A12 (GPROF) rain product respectively.

Fig. 4.9. Rainfall rate from the regional scattering index scheme (present technique) on 9th Sept05 at 1240 UTC
Chapter 4- Precipitation estimation using Microwave data

From the figure 4.9 it is clear that the system at 13°N/84°E is splitted in 3 subsystems each having the rainfall values ranging from 4-10 mm/h, with the maximum rainfall of 10 mm at the centre while it decreases away from the system. Further another system at 16°N/84°E is very intense having the rainfall greater than 10 mm at the centre while away from the system the rainfall values decreases up to 4 mm. The structure, pattern as well as the rainfall values from the TMI-2A12 (figure 4.10) were almost same as that from the present technique. Apart from these major systems there was a localized system at 18°N/88°E having rainfall values in the range of 2-6 mm/h from the present technique. Observation from the TMI-2A12 shows the rainfall in the range of 2-8 mm/h at the same location. Here it may be noted that there is a time difference of about 10 minutes between the SSMI and TRMM observations in this case, which may probably be the reason for the slight noticeable difference of the rain patterns.

Second case study is considered during the monsoon period on 14th August 2006, when there were two intense convective systems over land one at 23°N 77°E and another at 29°N 80°E, for which, figures 4.11 and 4.12 show the rainfall plots both from the present and GPROF technique respectively. In both the figures rainfall amount as well as the location of the system match quite well. Rain rate at the centre of the system at 23°N 77°E is about 22 m/h from the 2A12 whereas present method shows this amount to be about 20
mm/h. While outside the centre of the system rain rate is varying from 4-12 mm/h in both the techniques. The rain rate of the system located at 29°N 80°E is in the range 6-14 mm/h both from the present technique as well as the 2A12 data. It is clear from the observations that the patterns, locations, and the rainfall rates of the systems are almost same from both techniques. In this case also, the time difference between the TRMM pass and the SSM/I pass over the system is about 10 minutes.

![Fig. 4.11. Rainfall rate from the regional scattering index scheme (present technique) on 14th August 06 at 0235 UTC](image1)

![Fig. 4.12. Rainfall rate from the TMI-2A12 (GPROF algorithm) on 14th August 06 at 0245 UTC](image2)
A third case study is taken up during a cyclonic case named GONU over the Arabian Sea on 4th June 07. From figure 4.13 and 4.14 one can see the intense cyclonic storm at 64°E 15°N. Present technique estimates rainfall rate as 12 mm at the centre of the system while this amount is varying from 3 to 10 mm outside the centre at 0240 UTC.

Furthermore the rainfall structure from the 2A12 is slightly different from that of present technique. It got split in to two separate subsystems each having the rainfall rate at the centre as 12 mm/h while outside the centre the rainfall rate varies from 3 to 10 mm at 0240 UTC.
Chapter 4- Precipitation estimation using Microwave data

This may be due to the 12 minutes time difference between both the observations. It was further confirmed from the TRMM based 3B42 products (Huffman et al., 2007) of the system that it got split sometimes between the 1200 UTC and 1500 UTC.

Figures 4.15 and 4.16 show the histogram of the rainfall from the 2A12 and the present technique for the 24th September 2007 and 19th July 2007 over land and ocean respectively. Black bar represents rainfall from the 2A12 technique while grey bar represents the rainfall from the present one. From the figure 4.15 it is clear that the frequency of the occurrence of high rainfall are quite matching from both the techniques over the land, while the frequency of the occurrence of the low rainfall values (in the range of 1-3mm/h) are higher in the GPROF algorithm. This may be due to the fact that present technique is scattering based, which is useful in the case of convective hydrometeor system (associated with the high rainfall values) i.e. the rainfall from the ‘non scattering’ hydrometeor is not detected from the present technique.

Fig. 4.15. Histogram of rainfall from TMI-2A12 (GPROF) and regional scattering index scheme (present technique) over land
Further from the figure 4.16 we again observe that the higher rainfall values are well matching from both the techniques, while the frequency of low rainfall values are less observed from the regional scattering based technique over the ocean. This is again due to the fact that rainfall values from the ‘non scattering’ hydrometeor were not detected from the present technique.

Figure 4.17 shows the statistical comparison between the rainfall from GPROF algorithm (TM-2A12) and the present technique over the land region, and table 4.1 shows the associated statistics. For this comparison total 23165 points during the SW-Monsoon and N-E monsoon season of 2007 and 2008 were selected in the grid box of 0.5°X0.5°.
Chapter 4- Precipitation estimation using Microwave data

Table 4.1. Statistics of the comparison between the present technique and GPROF algorithm over land.

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. Of data points</td>
<td>23165</td>
</tr>
<tr>
<td>Correlation coefficients</td>
<td>0.83</td>
</tr>
<tr>
<td>Root Mean Square Error (mm)</td>
<td>1.06</td>
</tr>
<tr>
<td>Bias (mm)</td>
<td>0.682</td>
</tr>
<tr>
<td>Observed mean (mm)</td>
<td>4.64</td>
</tr>
<tr>
<td>Calculated mean (mm)</td>
<td>5.52</td>
</tr>
<tr>
<td>Probability of detection (POD)</td>
<td>0.92</td>
</tr>
<tr>
<td>False Alarm Ratio (FAR)</td>
<td>0.086</td>
</tr>
<tr>
<td>Heidke Skill Score</td>
<td>0.52</td>
</tr>
</tbody>
</table>

It is observed that present technique exhibits a correlation coefficient of 0.83, root mean square error of 1.06, bias of 0.682, POD of 0.92, FAR of 0.086, and a skill score of 0.52 with the GPROF algorithm. It is clear from the statistics that present technique matches very well with the GPROF algorithm over the land region.

Figure 4.18 shows the statistical comparison between the rainfall from GPROF algorithm (TM-2A12) and the present technique over the oceanic region, and table 4.2 shows the associated statistics. For this comparison total 9628 points during the SW-Monsoon and N-E monsoon season of 2007 and 2008 were selected in the grid box of 0.5°X0.5°.

It is observed from the figure 4.18 and the table 4.2 that present technique exhibits a correlation coefficient of 0.81, root mean square error of 0.97, bias of 2.48, POD of 0.89, FAR of 0.18, and a skill score of 0.59 with the GPROF algorithm. So it is clear from the statistics that present technique matches very well with the GPROF algorithm over the oceanic region. The better error statistics over land as compared to the ocean leads us to conclude that the present algorithm is relatively better for the land compared to the oceanic regions.
Chapter 4- Precipitation estimation using Microwave data

Table 4.2. Statistics of the comparison between the present technique and GPROF algorithm over ocean.

<table>
<thead>
<tr>
<th>No. Of data points</th>
<th>9628</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation coefficients</td>
<td>0.81</td>
</tr>
<tr>
<td>Root Mean Square Error (mm)</td>
<td>0.97</td>
</tr>
<tr>
<td>Bias (mm)</td>
<td>2.48</td>
</tr>
<tr>
<td>Observed mean (mm)</td>
<td>9.49</td>
</tr>
<tr>
<td>Calculated mean (mm)</td>
<td>11.97</td>
</tr>
<tr>
<td>Probability of detection (POD)</td>
<td>0.89</td>
</tr>
<tr>
<td>False Alarm Ratio (FAR)</td>
<td>0.18</td>
</tr>
<tr>
<td>Heidke Skill Score</td>
<td>0.59</td>
</tr>
</tbody>
</table>

Fig. 4.18. Scatter plot between the rainfall from present technique and GPROF algorithm over ocean

This is highly desired, as the various types of complex terrains exist in Indian subcontinent. In addition, the south-west and north-east monsoon are the main sources of water through rainfall for various real life operational applications like agriculture, hydrology and heavy rain/flood conditions.

4.4.3 Validation with rainfall from Automatic Weather Station rain gauge:

The rainfall from present technique (rain rate) is validated against the AWS rain gauge observations. We have also compared the rainfall estimated from the Ferraro global scheme (Ferraro and Marks 1995) with the AWS rain gauge. The AWS observations falling within present technique grid (0.5°X0.5°) have been averaged and then compared. For this purpose we have taken data base of 423 data points during 9-15 May 2007, 3-5 July 2007, 18-21 and October 2007 of AWS rain-gauges after averaging rain values within 0.5°X0.5° grid box.
Chapter 4- Precipitation estimation using Microwave data

Figure 4.19. Scatter plot between the rainfall from present technique and AWS rain gauge

Figure 4.20. Scatter plot between the rainfall from Ferraro global scheme and AWS rain gauge

Table 4.3. Comparison of the present technique and Ferraro global scheme with AWS rain gauge.

<table>
<thead>
<tr>
<th>Technique</th>
<th>Present technique</th>
<th>Ferraro technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of data points</td>
<td>423</td>
<td>423</td>
</tr>
<tr>
<td>Correlation coefficients (%)</td>
<td>0.68</td>
<td>0.65</td>
</tr>
<tr>
<td>Root Mean Square Error (mm)</td>
<td>9.35</td>
<td>11.14</td>
</tr>
<tr>
<td>Bias (mm)</td>
<td>-3.64</td>
<td>-6.85</td>
</tr>
</tbody>
</table>

Figure 4.19 shows the statistical comparison between the rain-gauge rainfall and the rainfall from the present technique. Figure 4.20 is similar to the figure 4.19 but here rainfall is from the Ferraro global scheme. And the table 4.3 shows the statistical comparison between the rain-gauge rainfall and the rainfall from the present technique and the rainfall from the Ferraro scheme. It is observed from the figures 4.19 and 4.20 and the table 4.3 that present technique exhibits a correlation coefficient of 0.68, root mean square error of 9.35, and a bias of -3.64 with the AWS rain gauge, while these quantities are 0.65, 11.14 and -6.85 for the Ferraro global scheme. It is clear that the
Chapter 4- Precipitation estimation using Microwave data

The present scheme shows a better comparison from the AWS rain gauge than the Ferraro global scheme and correlation improves from 0.65 to 0.68 in the present technique, while the bias as well as the root mean square errors reduces as compared to the Ferraro global scheme. From the comparison it is evident that present scheme is able to retrieve the rainfall over the Indian land and oceanic regions with better accuracy than that by using the Ferraro global scheme.

4.4.4 Validation with rainfall from Doppler Weather Radar (DWR):

In this section an attempt has been made to validate rainfall from present technique with Doppler Weather RADAR (DWR) in the east coast of peninsular India. DWR is an indigenously developed S band radar over India at Sriharikota at 13° 60'N and 80° 23'E location. The DWR rain values have been derived using Z-R relationship developed during a campaign using 5 fast response rain gauges and a disdrometer deployed at the site. For the meaningful comparison each bin of the radar observation is geo-located and then averaged over the 0.5°X0.5° grid box. The geo-location was done by assuming latitude-longitude to each bin and then averaging it over the 0.5°X0.5° degree resolution.

Here the comparison of the rain rate from the present technique is made with the rainfall from DWR at 0.5°X0.5° grid box. Many cases during the North-East (N-E) monsoon cases of 2008 have been analyzed but only some of them will be discussed for the brevity.

The first case study was carried out during the N-E monsoon season for the 21st October 2008, when there was a large intense system around 13°N/79°E having the rainfall values in the range 2-16 mm/h, further this system consists of two subsystems centered at 12°N/79°E and 14°N/79°E having the rainfall values in the range 8-16 mm/h and 10-14 mm/h respectively. Figure 4.21 shows the rainfall observations from the DWR on that day.
Chapter 4- Precipitation estimation using Microwave data

Regional scattering index scheme (present technique) of rainfall estimation from the SSM/I confirms the presence of the large intense system approximately around 13°N/79°E having the rainfall values in the range of 2-16 mm/h and inside this system there were two subsystems centered at the position 12°N/79.4°E and 14.4°N/79.6°E having the rainfall values in the range 8-16 mm/h and 4-10 mm/h (Figure 4.22). This shows that the position of the system as well as the rainfall intensity are approximately same in both the observation but the location of the second subsystem and rainfall values associated with this subsystem was slight different in the two observations. This may be due the fact that there is a difference of 5 minutes in the two observations. So the system might be shifted eastward and weekend, which lead to the slight difference in the subsystem observations.
Chapter 4- Precipitation estimation using Microwave data

This case study shows that the feature, pattern as well as the rainfall values associated with the hydrometeor system was well picked up by the present technique.

Next case study was undertaken on 22nd Nov 08, when there were two large systems first one centered around 12.6°N/79°E having the rainfall values in the range of 2-9 mm/h and another one centered around 13°N/82°E having the rainfall values in the range of 4-9 mm/h from the DWR observation (Figure 4.23).

Further it is observed that the system centered at 12.6°N/79°E consists of two subsystems, first one centered around 12°N/79°E having the rainfall values in the range of 6-8 mm/h and second one centered around 13°N/79.4°E having the rainfall values in the range 6-9 mm/h. From the SSM/I observation (Figure 4.24) it is observed that both the systems were well captured and the rainfall associated with both these systems are in almost same range as in the RADAR observation. The observation from the present technique also confirmed the existence of two subsystems with almost same location and intensity of the rainfall as that observed from the DWR. However, there is slight shifting in the position of the subsystems, which might be due to the time difference of 7 minutes between the two observations.
Chapter 4 - Precipitation estimation using Microwave data

Fig. 4.23. Rain rate from the DWR on 22nd November 2008 at 1235 UTC

Fig. 4.24. Rain rate from the present technique on 22nd November 2008 at 1242 UTC
Chapter 4- Precipitation estimation using Microwave data

The system was shifted southward and was weakened as was observed from TRMM-3B42 observations. So it clear that the present technique is able to estimate the rainfall correctly.

Figure 4.25 shows the statistical comparison between the rainfall from RADAR observation and the rainfall from the present technique. Total 3123 data points during the selected cases of 2007 and 2008 were considered after averaging them in 0.5°X0.5° grid boxes. Table 4.4 shows the associated statistics of the comparison.

<table>
<thead>
<tr>
<th>Table 4.4. Statistics of the comparison between the rainfall from present technique and DWR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>No. Of data points</strong></td>
</tr>
<tr>
<td><strong>Correlation coefficients</strong></td>
</tr>
<tr>
<td><strong>Root Mean Square Error (mm)</strong></td>
</tr>
<tr>
<td><strong>Bias (mm)</strong></td>
</tr>
<tr>
<td><strong>Observed mean (mm)</strong></td>
</tr>
<tr>
<td><strong>Calculated mean (mm)</strong></td>
</tr>
<tr>
<td><strong>Probability of detection (POD)</strong></td>
</tr>
<tr>
<td><strong>False Alarm Ratio (FAR)</strong></td>
</tr>
<tr>
<td><strong>Heidke Skill Score</strong></td>
</tr>
</tbody>
</table>

Fig. 4.25. Scatter plot between the rainfall from present technique and DWR

It is observed from the figure 4.25 and the table 4.4 that present technique exhibits a correlation coefficient of 0.69, root mean square error of 3.12, bias of -1.18, POD of 0.81, FAR of 0.21, and a skill score of 0.36 with the DWR observations. So it is clear that the rainfall from the present technique matches well with the DWR observations.
Chapter 4- Precipitation estimation using Microwave data

4.5 Conclusions:

Present study focuses on the estimation of rainfall over Indian land and oceanic regions from the SSM/I on the Defense Meteorological Satellite Program (DMSP) F-13. Based on the measurements at 19.35, 22.235 and 85.5 GHz channels of SSM/I Satellite, scattering index (SI) has been developed for the Indian land and oceanic regions separately. These scattering indices were co-located against rainfall from Precipitation Radar (PR) onboard Tropical Rainfall Measuring Mission (TRMM) to develop a new regional relationship between the SI and the rain-rate for the Indian land and oceanic regions. A non-linear fit between the rain-rate and the SI is established for rain measurement. In order to have confidence in the present technique, I have also estimated rainfall using the global rainfall and scattering index relationship developed by Ferraro and Marks (1995). The validation with the ground observation (AWS rain-gauges) shows that the present technique is able to retrieve the rainfall with better accuracy than that from Ferraro scheme which is based on a single set of coefficients for its applicability for global rainfall retrieval. Inter-comparison with the GPROF (2A12 rain product) algorithm shows that present algorithm is able to retrieve the rainfall with good accuracy both qualitatively as well as quantitatively which is highly desired particularly over the south-west and north-east monsoon dominated regions of Indian sub-continent. Further validations using DWR data during the N-E monsoon season is also performed and these validation results show that the present regional scheme developed for the Indian land and oceanic region has the potential to estimates the rainfall with a very good accuracy. In general the oceanic rainfall algorithms (due to the homogeneous background of ocean) perform better than algorithms over land (due to highly varying emissivity of the land). However, in the present case the region specific empirical algorithm performs better over the land than the oceanic regions which was confirmed by the comparison of the present scheme with the GPROF algorithm. Despite the different system configurations and the geometry of PR and SSM/I observations, the rainfall from present technique is quite close to the standard operational products from GPROF algorithm which is not as simple in operation as the present one. The present study also helps in concluding that such empirical rainfall retrieval should be developed regionally based on the different climatic zones of the globe separately. More comprehensive global rainfall retrieval along with
Chapter 4- Precipitation estimation using Microwave data

validation is needed to the efficacy of the methodology; that is planned for the next update of the present method. This present study is taken up to enhance the capability of rainfall retrievals in near future using MADRAS (Microwave Analysis and Detection of Rain and Atmospheric Structures) channel of Indo-French satellite Megha Tropiques to be launched sometime in 2011.