Chapter 1 : INTRODUCTION

1.1 REMOTE SENSING

Remote sensing is a broad collection of multidisciplinary techniques and methodologies to acquire information about the environment, Earth's surface, atmosphere, and agriculture through "Remote" measurements. It is a procedure of sensing and monitoring an object or area in terms of its physical characteristics by detecting the reflected and emitted radiations from a distance (normally from the satellite or aircraft). It includes the visual scheme of human eyes, ultrasound and X-ray systems in medical science, laser scanning for atmospheric constituents, and sonar sounding of sea level. Remote sensing utilizes electromagnetic radiation as an information carrier from the target to the sensing device. It involves the interaction of electromagnetic radiations to the targeting object. The radiations, reflected, transmitted, or emitted by the object are captured by the sensors to find the target information. These sensors can be mounted on different platforms such as automotive vehicles, aircraft, rockets, hot air balloons, drones, space shuttles, and satellites.

Remote sensing is part of countless possible innovations due to the roaming of the satellites around our Earth. Satellites play a crucial role in developing various technologies such as global mapping, GPS, urban planning, etc. The primary applications of remote sensing are the study of Earth’s surface, Earth’s atmosphere, LU/LC management, climate change monitoring, agriculture, drought, etc.

1.2 MICROWAVE REMOTE SENSING

In particular, Microwave remote sensing employs low-frequency electromagnetic radiations that have a wavelength range from 1 mm to 1 m and a frequency range from 0.3

GHz to 40 GHz (commonly termed as microwaves) as an observation tool. Because of the larger wavelength than the visible and infrared radiations, microwaves exhibit the property of higher penetration through clouds, fog, atmospheric gases, and vegetation. The higher wavelengths are not susceptible to atmospheric scattering, which disturbs the shorter optical wavelengths. This property allows the microwave radiations to be detected under almost every weather and environmental condition, that leads to data collection at any time. Microwave sensing includes both passive and active forms of remote sensing [1].

Each object of our environment emits some amount of microwave energy, but the amount is usually very small. The passive microwave sensors detect the naturally released microwave energy by the objects within their field of view. This energy can be associated to the temperature or amount of water available in the object or surface. The passive microwave remote sensors are characteristically scanners and radiometer that detect microwave radiations. A passive sensor records the microwave energy, which can be (1) emitted from the atmosphere, (2) reflected by the Earth's surface, (3) emitted by the surface of the Earth or (4) transmitted through the subsurface (Figure 1.1). Because of the longer wavelengths, the microwave energy is lesser than the optical wavelengths. Thus, the field of view should be significant to record enough energy. Therefore, maximum passive microwave remote sensors are characterized by coarse pixel resolution.

Passive microwave remote sensing has many applications, including hydrology, meteorology, and oceanography. By observing "at" or "through" the atmospheric windows, meteorologists utilized passive microwave sensing to determine the atmospheric profiles and estimate the atmosphere's water and ozone content. Hydrologists are using passive microwaves to measure the amount of the moisture in the upper surface of soil due to the higher penetration through clouds, fog, and canopy layer, which is necessary for the soil surface study. In Oceanography, the monitoring of sea ice, streams, and surface winds, and the detection of pollutants, such as plastic content and oil slicks, are the chief applications of the passive microwave remote sensing.

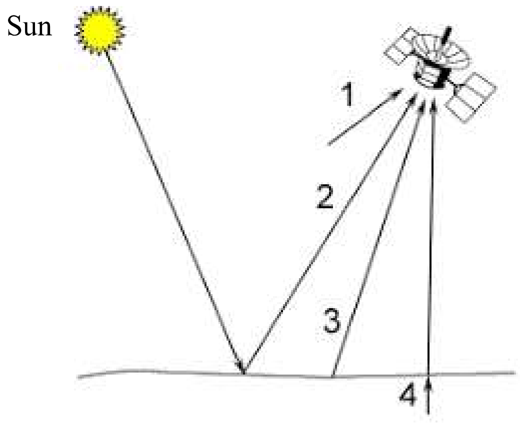

Figure 1.1 Passive microwave remote sensing processes.

(**Source:** https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/earthsciences/pdf/resource/tutor/fundam/pdf/fundamentals_e.pdf)

Active microwave sensors are accompanied by a radiation source that generates its own radiations to illuminate the target and a separate sensor for detecting the reflected radiation from the target (Figure 1.2).

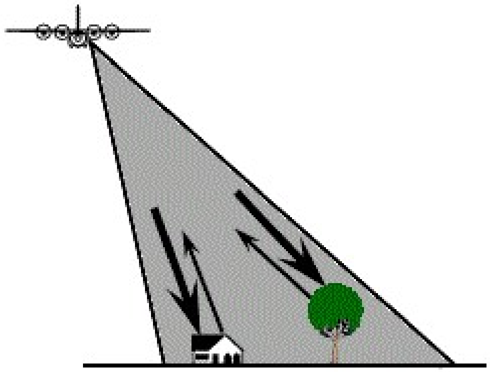

Figure 1.2 Active microwave remote sensing.

(**Source:** https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/earthsciences/pdf/resource/tutor/fundam/pdf/fundamentals_e.pdf)

Active microwave sensors are classified into two categories, (1) Imaging sensors and (2) non-imaging sensors. RADAR (RAdio Detection and Ranging) is one of the imaging sensors, it transmits its own generated microwave radiations towards the targeting object and then detects the reflected signals. These back signals are then employed to generate the image of the target. The power of the backscattered signals is utilized to differentiate different targets, and the time lag between the transmitted and backward signals is used to decide the target's distance from the RADAR. Non-imaging sensors mainly include altimeters and scatterometers. These instruments take observations only in one dimension rather than two, as likely for imaging sensors.

1.3 CLASSIFICATION OF MICROWAVE SPECTRUM

Table 1.1 Classification of microwave frequency bands.

Frequency range	Wavelength range	IEEE band
0.3-1 GHz	100 to 30 cm	P band
1-2 GHz	30 to 15 cm	L band
2-4 GHz	15 to 5 cm	S band
4-8 GHz	5 to 3.75 cm	C band
8-12 GHz	3.75 to 2.5 cm	X band
12-18 GHz	2.5 to 1.6 cm	Ku band
18-26 GHz	1.6 to 1.2 cm	K band
26-40 GHz	1.2 to 0.75 cm	Ka band

The microwave region of the electromagnetic spectrum is further classified into several bands of different frequency regions, and these bands are denoted by an alphabet and starts from P-band. Many organizations allocate these letters to different frequency bands. The classification provided by IEEE (Institute of Electrical and Electronics Engineers) is the most used classification of the recent era [2], which is presented in Table 1.1. The lowermost frequency band of microwave frequency region is P-band, whereas the highest frequency band is Ka-band. Every band has different applications according to their penetration power of microwave radiations. The P-band has the highest penetration power due to lowest frequency region and can penetrate up to root zone soil layer. Whereas, the L-band frequency region is the more appropriate range for the monitoring of the surface soil moisture due to the significant penetration in the surface of soil. This frequency band faces less interference in heavy rain fading, clouds, fog and vegetation layer.

1.4 APPLICATIONS OF MICROWAVE REMOTE SENSING

Since microwave belongs to the low frequency and a longer wavelength, therefore, it has a capability to penetrate clouds and so that can operate in every weather condition. In Remote sensing, microwave remote sensing has unique and stand-alone applications. In microwaves, the frequency larger than 15 GHz is susceptible to water clouds, and greater than 10 GHz can be attenuated by heavy rains. Therefore, the low-frequency bands of microwave, especially the L-band, have a lot of applications in the monitoring/mapping of soil and vegetation.

The microwaves are not dependent on Sun as a source of radiation because they can detect signals generated by self-emission of the targeting object. Thus, microwave sensors are capable of operating during the day as well as at night. The microwaves can penetrate through vegetation and soil more deeply rather than optical waves and this penetration is greater in dry vegetation and dry soil compared to green vegetation and moist soil. The penetration of microwaves is highly dependent on the amount of moisture, and it reduces in the presence of moisture in any material due to the inconsistency of the dielectric constant between water and dry soil.

Microwave remote sensing has a lot of applications in various fields, such as in land use/land cover, oceanography, atmosphere, and planetary science [3, 4]. Microwave remote sensing can be utilized to study different targets on the Earth's surface. Many natural materials such as soil, vegetation, forest, and snow have been successfully monitored by using this technique. Due to the property of high penetration, it is extensively used for the monitoring/mapping of soil moisture, crop growth variables, flood mapping, snow, in the forestry area, sea-state measurement, ocean geoids studies, profiling of temperature and moisture of the atmosphere, study of minor constituents in the atmosphere, monsoon studies, and wind measurement.

1.5 MICROWAVE SPACE-BORNE OBSERVATIONS

Many Indian and International space agencies have used the microwave for various Earth observational missions. Some of them are listed in Table 1.2,

Table 1.2 A comprehensive list of all microwave operating satellites.

S. No.	Satellite	Launch date	Type of sensor	Polarization	Frequency band
1	Scanning Microwave Spectrometer on NASA Nimbus-6 (SCAMS)	June 12, 1975	-	-	K and Ka-band

2	Scanning Multichannel Microwave Radiometer on NASA/JPL SeaSat (SMMR_SeaSat) and Nimbus-7 Satellites (SMMR_Nimbus-7)	June 26, 1978 [SeaSat] October 24, 1994 [Nimbus-7]	Passive	H, V	C, X, K and Ka-band
3	ESCAT (ERS-1 and -2)	July 17, 1991 [ERS-1] April 21, 1995 [ERS-2]	Active	VV	C-band
4	Japan Earth Resources Satellite (JERS) -1: Synthetic Aperture Radar	February 1992	Active	HH	L-band
5	SAR on Radarsat-1 and -2	November 1995 [R-1] December 2007 [R-2]	Active	HH, VV, HV, VH	C-band
6	NASA Scatterometer on JAXA (Japanese) (NSCAT)	August 17, 1996	Passive	H, V	Ku-band
7	Special Sensor Microwave Imager (SSM/I) on Defence Meteorological Satellite Program (DMSP)	December 12, 1999	-	-	K- and Ka-band
8	Advanced Microwave Sounding Unit (AMSU) on NASA's AQUA	May 4, 2002	-	-	K- and Ka-band
9	ESTAR	June/July 2002	Passive	H	L-band

10	WindSat	January 6, 2003	-	-	C, X, Ku, K, and Ka-band
11	Advanced SAR (ASAR) on ESA Environmental Satellite (EnviSat)	March 1, 2005	Active	HH, VV, VV/HH, HV/HH, VH/VV	C-band
12	ALOS-1 PALSAR	January 2006	Active	HH or VV, HH+HV or VV+VH	L-band
13	ASCAT	October 2006	Active	VV	C-band
14	TerraSAR-X	June 2007	Active	VV	X-band
15	Soil Moisture Ocean Salinity Mission (SMOS)	November 2009	Passive	H, V	L-band
16	TanDEM-X	June 21, 2010	Active	VV	X-band
17	RISAT-1	April 2012	-	-	C-band
18	ALOS-2 PALSAR-2	May 2014	Active	HH or VV, HH+HV or VV+VH	L-band
19	Soil Moisture Active Passive (SMAP)	2015	Passive	H, V	L-band
20	Surface Water and Ocean Topography (SWOT)	2020	-	-	Ku, K, Ka-band

All of the above-described microwave sensors are designed for different applications. This thesis mainly focuses on monitoring soil moisture, and the L-band is the most appropriate frequency band for soil moisture remote sensing. Therefore, only L-band SMAP data products have been chosen because of the lowest reported RMSE (0.04 cm^3/cm^3) [5].

1.6 SOIL MOISTURE: DEFINITION AND ITS SIGNIFICANCE

The global water cycle illustrates how water circulates through the atmosphere, the soil, rivers, wetlands, and seas in its liquid, solid, and gaseous forms. Water has an impact on everything on the surface of the earth and in the ocean, including animals, vegetation, and materials. Water is essential to life in all of its forms, and humans have evolved like a hydraulic civilization. There are significant gaps in information about where water is retained, where it is flowing, and how rapidly it is circulating on a global scale, and water content in the soil surface is one of them. It is well understood that global climate change is influenced by a variety of factors, one of which is soil moisture. The topsoil portion of the surface soil is essential for human existence since it is where the food we consume grows and where all other plants live. The soil moisture content indirectly affects us in many ways. Soil moisture is characterized as the total amount of water in the land's unsaturated soil surface, which is obtained through rainfall infiltration, snow melting, and capillary action of groundwater content. It is an important variable for many ecological, climatological, and hydrological applications [6]. Accurate knowledge of soil moisture is necessary for agricultural irrigation management [7], drought monitoring [8, 9], and weather forecasting [10]. Apart from this, it is also recognized as an essential variable for the universal water and energy cycle because of its involvement in the heat and water exchange. The soil moisture also controls the exchange of trace gases such as Carbon dioxide [11], which controls the atmospheric boundary and, therefore, the weather and Earth's climate.

The soil moisture content controls various processes of terrestrial surface and climate system, and its degree of former saturation is significant for the river catchment response to rainfall or the melting of the snow, generation of the subsequent flood, and partitioning the rainfall into runoff and infiltration and sometimes runoff itself. Overland flow is most likely to occur in wetter soils or where the saturated soil is more extensive. Therefore, the accurate knowledge of soil moisture content provides a potential for infiltration, overland flow, runoff, floods, and erosion, as well as its influence on the streams, infrastructure, reservoirs, and therefore on human life. It is also responsible for water resource management, ecological studies, plant water condition, growth, and productivity. It is also essential for the management of irrigation and cultivation in agriculture.

The soil surface is basically classified into two categories; unsaturated soil layer and saturated soil layer. The layer which separates these two surfaces is termed water table. The measure of water content in unsaturated soil surface is identified as soil moisture. Further, the soil moisture content is also categorized into two categories; surface soil moisture and root zone soil moisture as shown in Figure 1.3. The measure of moisture content up to the depth of 5 cm in the soil is recognized as the surface soil moisture, and the moisture

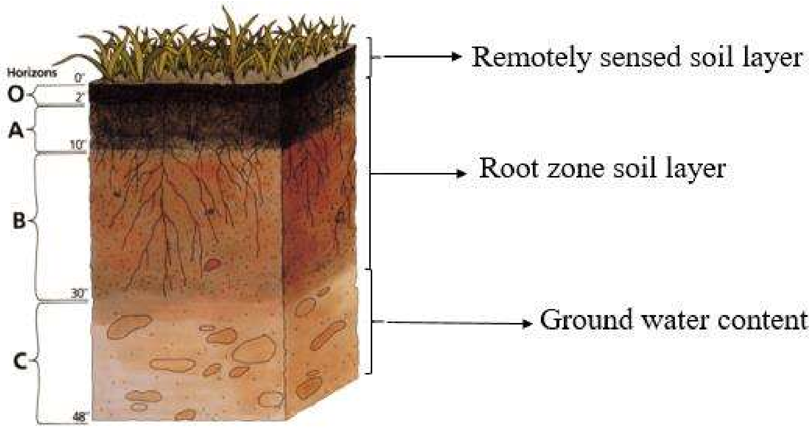

Figure 1.3 Soil Profile.

Source: http://nesoil.com/properties/horizons/index.htm available below 5 cm and up to the water table is recognized as root zone soil moisture, which is accessible by the plants. In practice, only surface soil moisture can be determined more easily than the root zone soil moisture due to its availability on the upper surface. After the root zone soil layer, there is a layer of soil that contains the ground water (Figure 1.3).

The soil moisture is mathematically stated as a dimensionless ratio of two volumes or two masses. These dimensionless ratios are reported either in the form of percentages or decimal fractions. The soil moisture content usually be present in the unsaturated soil surface, where soil pores are filled with more air than water. Water enters in the unsaturated soil surface by various processes as listed above, such as infiltration or capillary action of groundwater, and exists by vaporization or by perlocation across the water table to the saturated soil surface or the groundwater.

1.7 SOIL MOISTURE ESTIMATION

Presently, the soil moisture can be determined in three ways; ground measurements, with airborne sensors, and space-borne observations, each method has some advantages and disadvantages. The ground-based measurements are most accurate but limited to some areas. It can be classified in two categories; (a) point measurement using some soil sensor or probe, (b) estimation over a small region using ground-based sensors. Numerous instruments utilizing different types of technologies have been developed for point measurements (Transiometers, Neutron probe, Electrical resistance blocks, Gravimetric, Time Domain Reflectometer (TDR)). In ground-based observations, sensors are either mounted on an automotive vehicle or with ground-based equipment. These sensors are either active or passive, depending on data collecting circumstances.

The airborne observations can monitor the broad area but cannot provide global measurements, if it does, then the temporal revisit frequency will be poor. Also, data values are not as accurate as in ground measurements. The airborne measurements can be performed by using active or passive sensor mounted on an aircraft, airplane, or drone. The space-borne observations have capability of global monitoring and can deliver data values on a daily basis, but there may induce some errors due to the clouds, fog, rain, or vegetation. Therefore, microwave range is the most appropriate frequency region to monitor the soil moisture as described in section 1.2. Many microwaves active and passive spaceborne sensors have been launched since 1970 for the monitoring/mapping of the surface soil moisture, includes Sentinel-1, AVHRR (Advanced Very High-Resolution Radiometer), SMOS (Soil Moisture Ocean Salinity), SMAP (Soil Moisture Active Passive), AMSR-E (Advanced Microwave Scanning Radiometer on the Earth Observing System), SMMR (Scanning Multichannel Microwave Radiometer). Currently, two satellites, SMAP and SMOS, used the L-band (1-2GHz) frequency range, and provide daily global soil moisture data. Among them, SMAP reported the lowest RMSE value of 0.04 cm^3/cm^3.

1.8 BIOPHYSICAL PARAMETERS

The microwave observations are sturdily influenced by the covering vegetation layer. The vegetation layer is characterized by some biophysical parameters e.g., Vegetation Water Content (VWC), plant biomass, and Leaf Area Index (LAI). These variables are very necessary for modelling the radiation transfer across the Earth's atmosphere. The VWC denotes the volume of water content in the green vegetation, and plant biomass expresses the total weight of the green vegetation. LAI denotes the total leaf area in an ecosystem. These are necessary variables for the evaluation of attenuated radiations through or due to the vegetation layer.

In soil moisture remote sensing, it is required to characterize the vegetation attenuation to extract the information of soil surface. Therefore, various algorithms utilized these biophysical parameters to model radiations accurately. The VWC is the most significant variable for characterizing vegetation attenuation among all the vegetation parameters.

1.9 ZEROTH-ORDER RADIATIVE TRANSFER MODEL (RTM)

A large number measurements have been carried out in microwave frequency region to study the soil surface properties using the feasibility of microwave airborne and space-borne sensors. However, to better interpret the interaction of electromagnetic signals with the soil surface, a good understanding of transportation of radiation through our atmosphere is essential. “Radiative transfer" refers to a physical phenomenon of energy transfer in the form of electromagnetic radiation that explains the propagation of radiations through our atmosphere as controlled by absorption, emission, and scattering processes. The radiative transfer equation quantitatively summarises these interactions and used in a variety of fields, including optics, astrophysics, atmospheric science, and remote sensing.

In remote sensing, RTM is used for the monitoring of soil surface and biophysical parameters. The soil surface radiation transfer equation comprises elements that correspond to soil emission, vegetation emission, vegetation emission further reflected by soil surface, and further scattering of these radiations by vegetation. The RTM for the monitoring of soil surface is formalized in several ways depending on the vegetation cover or probable order of scattering via vegetation layer. The order of the scattering is increases with the vegetation conditions; for example, sparse vegetation produces very little or no scattering, whereas dense vegetation produces the first or higher orders of scattering. The radiative transfer equation corresponds to zero-order scattering is known as the zeroth-order RTM and also known as the Tau-omega model as the tau (Vegetation Optical Depth (VOD)) and omega

(Single scattering albedo) are the main parameters of this equation. This model provides a suitable approach for the monitoring of soil moisture under low vegetation region. It comprises all possible factors caused due to the geometry of the soil surface and low vegetation. Basically, this model describes a connection between the thermal emission of the earth's surface and the amount of moisture in the soil surface.

1.10 REVIEW OF LITERATURE

1.10.1 A review on SMAP soil moisture product

At first, NASA announced on February 2, 2008 that SMAP would be among two new start missions planned in FY08. The Earth Science Division (ESD) of NASA Headquarters' Science Mission Directorate (SMD) concluded that SMAP will be executed as a direct mission within the NASA Earth Systematic Mission (ESM) program overseen by Goddard Space Flight Center (GSFC). The Jet Propulsion Laboratory (JPL) was in charge of the overall operation of the SMAP project. On January 31st, 2015, the SMAP satellite was launched. It has an L-band radar and radiometer, which delivered worldwide radar backscatter and brightness temperature data every 2-3 days. SMAP was designed to obtain the soil moisture up to the top 5 cm of soil surface and its freeze-thaw condition [12] and to deliver three Level 2 (L2) geophysical soil moisture products: radiometer-only (36 km), radar-only (3 km), and a composite product radar/radiometer (9 km) (also known as enhanced product). The radar ceased working on July 7, 2015, although the radiometer is still operational. Later, Sentinel-1 radar backscatter was substituted for SMAP radar backscatter in order to produce the composite product at a 9 km spatial resolution [13]. The project of SMAP designed a comprehensive calibration and validation plan that has been developed and implemented to assess random errors and spatial/temporal biases in the satellite-based soil moisture estimates [14]. The plan comprises five methods: 1) in-situ core validation sites; 2) in-situ small networks; 3) satellite product intercomparison; 4) model-based product intercomparison; and 5) field experiments [15].

SMAP monitors the Earth at L-band frequency range, with an incidence angle of 40° and worldwide coverage acquired every 2-3 days on average. There were various algorithms have been proposed for the SMAP soil moisture retrieval baseline algorithm such as SCA with two polarizations (H and V), Dual Channel Algorithm (DCA), Multi-Temporal Dual Channel Algorithm (MT_DCA), and Land Parameter Retrieval Model (LPRM). Among the four soil moisture retrieval approaches proposed for the SMAP L2 SM P product, only the SCA is addressed because the evaluation based on the in-situ data from core validation sites revealed that it is the best overall alternative [16]. It provided estimations of soil moisture with a maximum inaccuracy of 0.04 cm^3/cm^3, which was the

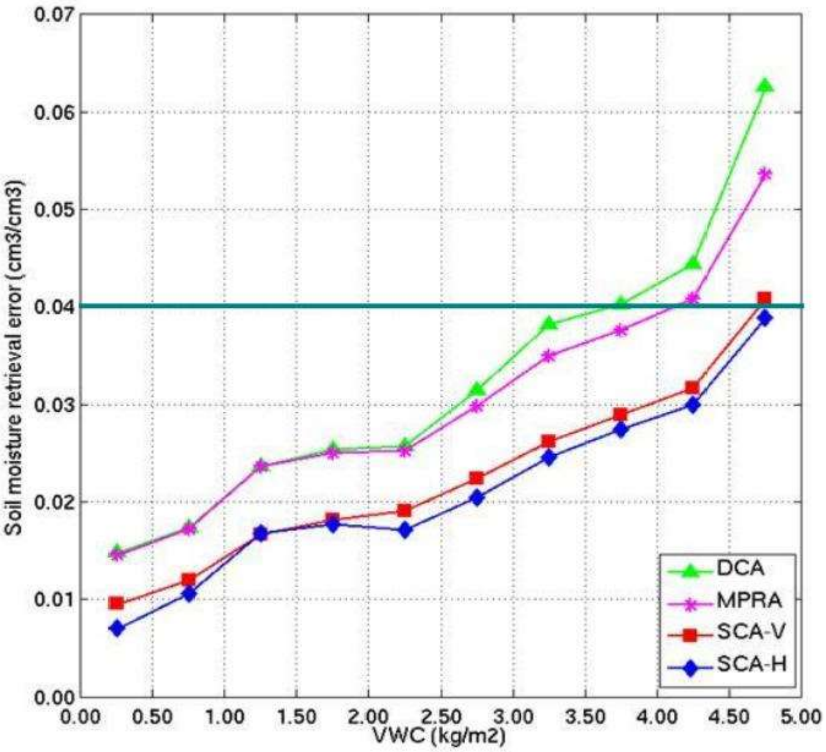

Figure 1.4 Accuracy of all proposed SMAP L2 soil moisture retrieval algorithms that were estimated in 2015.

Source: https://nsidc.org/sites/default/files/spl2smp_e-v005-userguide.pdf lowest obtained RMSE among all algorithms (Figure 1.4). Therefore, SCA had been chosen as the baseline algorithm for the SMAP L2 soil moisture data product (From 2015 to 2021). Later, after some improvements, a new version of SMAP L2 soil moisture has been announced in 2021, with DCA as the baseline algorithm instead of SCA. [17]. The DCA has been observed to perform slightly better than SCA across some agricultural fields core validation sites, however, its overall performance is similar.

SMAP soil moisture data product has been utilised by many researchers for soil moisture assessment and downscaling, drought monitoring, irrigation analysis, and evapotranspiration measurements. Chan et al., [16] present an overview of the Level 2 SMAP Soil Moisture Product (SMAP L2 SM P) and also its validation against ground observations acquired from various data sources from March 31, 2015 to October 26, 2015, which shows that, based on a number of metrics, the V-pol Single Channel Algorithm (SCA-V) produced the best performance among the algorithms analysed for SMAP_L2_SM_P. The average accuracy of soil moisture retrievals was 0.038 m^3 /m^3 ubRMSD, which is close to the SMAP mission objective of 0.040 m^3 /m^3. Ashok et al., [18] evaluates the applicability of SMAP soil moisture product from passive L-band radiometer to developing agricultural drought indices. Eswar et al., [19] also monitors the drought conditions using the SMAP soil moisture product and studies how the dynamics of soil moisture respond to variations in the drought conditions over a period of time. P. M. Lawston et al., [20] explores SMAP's enhanced soil moisture product for capturing irrigation signals in three semiarid sites of the western United States. Purdy et al., [21] utilizes the SMAP soil moisture data product to estimate global evapotranspiration. In addition to these studies, the SMAP data continues to be one of the most widely used data sets, and a lot of scholars are utilising it in accordance with their individual preferences.

1.10.2 A review on estimation of soil moisture

Soil moisture remote sensing has turn out to be a wide area of research in the recent era. Many researchers and scientists have given their attention to this area along with the development and advancement of new instruments and satellites. There are three possible ways for the quantification of soil moisture; ground-based measurements, airborne analysis, and space-born observations. All the available data sets and satellites for estimation of terrestrial soil moisture is described in details in [22]

(a) Soil moisture estimation using ground-based measurements

The ground-based estimation of soil moisture content can be classified in two ways; point measurements using a probe and estimation over a small area using ground-based instruments. The point measurement of soil moisture is further classified into broad categories; gravimetric, nuclear-based, electromagnetic, tensiometer-based, hygrometric, and emerging techniques [23-28]. Based on these techniques, various instruments were also developed for the assessment of soil moisture, such as time-domain reflectometry, frequency domain reflectometry, Stevens Hydra probe, tensiometers, and neutron moisture meters [28]. Robock et al., [23] provide a global soil moisture data bank, which contains soil moisture information from over 600 sites throughout the world, including the former Soviet Union, China, Mongolia, India, and the United States. The majority of the data are in-situ gravimetric measurements of soil moisture that extend at least 6 years and, in most cases, more than 15 years. Dorigo et al., [26] produced a new data hosting center named as International Soil Moisture Network (ISMN), which provides information of ground-based soil moisture for more than 500 station. It utilizes a COSMOS sensor, that measures the amount of moisture in an area based on the relative abundance of slow (thermal) neutrons against fast neutrons. Dobriyal et al., [27] gave a review study of measurements of soil moisture through the Time Domain Reflectometry (TDR) and Ground Penetrating Radar (GPR).

Similar to point measurements, various sensors have also been developed to obtain soil moisture information on a small region [29-32]. Claudia Notarnicola et al. [29] developed a C-band FM-CW (Frequency Modulated-Continuous Wave) scatterometer to monitor surface soil moisture. This scatterometer provides a normalized Radar Cross-section (RCS) between +10 dB and -40 dB in the range of incidence angles 10˚ to 60˚. R. Mardeni et al., [30] have presented the perception of GPR for measuring soil moisture. D. K. Gupta et al., [31] provided a comprehensive evaluation of several machine learning approaches to predict the soil moisture via an X-band bistatic scatterometer, designed in the specular direction of incidence angle 20-70˚ for HH and VV polarizations. Whereas, H. A. A. Julham et al., [32] developed a wireless soil sensor system where a soil moisture circuit along with two electrodes have been used and these electrodes act as a sensors. These ground-based observations are able to provide an accurate measurement of soil moisture; however, these techniques are not really useful for obtaining this information over a large area or on a global scale.

(b) Soil moisture estimation using airborne observations

The airborne observations are also categorized into two categories such as observations with active and passive sensors. Many researchers have invented and used these sensors with an airborne platform for monitoring/mapping soil moisture [33-38]. E. Njoku et al., [33] have presented a Passive/Active L/S-band (PALS) sensor to study the potential of multichannel active/passive microwave remote sensing for soil moisture observations. Michael P. Finn et al., [34] used a hyperspectral airborne instrument along with a SWIR (Short Wavelength Infrared) sensor flown from 2005 to 2007 to monitor the soil moisture content. Marion Pause et al., [35] utilized airborne spectrometer data values for creating the maps of LAI and then used these maps with L-band brightness temperature data product to retrieve soil moisture. And Hong quan Wang et al., [36] investigated soil moisture estimation via airborne passive microwave data obtained during the Soil Moisture Active Passive Validation Experiment (SMAPVEX) at two spatial resolutions. Thomas., [37] provide a study of natural terrestrial gamma radiation flux measurements at the soil surface to estimate areal soil moisture. Data from airborne gamma radiation is collected across 240 flight lines and utilized to determine real-time, areal soil moisture. Min-Guk Seo et al., [38] utilized a quadrotor unmanned aerial vehicle as a sensing platform to acquire soil moisture data with high spatial resolution. Airborne mapping is appropriate for studying a broad area, but space-borne observations are necessary to obtain soil moisture information worldwide on a regular basis. The global coverage provided by an airborne sensor will take a long time and also can't provide daily updates for the same area.

(c) Soil moisture estimation using spaceborne observations

Various satellites have been designed and launched for the global monitoring/mapping of soil moisture content. Most of these satellites are operating in the microwave region, such as Sentinel-1 SAR, AVHRR, ASCAT, SMOS, SMAP, etc. Some optical satellites, including Sentinel-2, Landsat, and MODIS (Moderate Resolution Imaging Spectroradiometer), are also utilized for the assessment of Earth' surface soil moisture. Many researchers have spent their precious time to retrieve soil moisture from these satellites accurately. Jackson et al., [39] provide a study of soil moisture estimation from Special Satellite Microwave/Imager (SSM/I) satellite datasets over a grassland. Alexakis et al., [40] provided a simulation method to elaborate Sentinel-1 and Landsat-8 data products to evaluate soil moisture content. Zhang and Zhou [41] provided a theoretical review on estimating soil moisture using optical and thermal data sets. S. Sharma., [42] provided a detailed overview on soil moisture estimation using active and passive microwave spaceborne observations. Zhang et al. [43] introduced an algorithm for SAR data (Radarsat-2, TerraSAR-X, and Sentinel-1 A), and Kerr et al. [44] proposed an approach for SMOS datasets for estimating soil moisture using the Tau-omega model. This model is based on the zeroth-order of Radiative Transfer Model (RTM), and is the most appropriate approach for the retrieval of soil moisture at the L-band frequency range (1 to 2 GHz).

1.10.3 A review on zeroth-order RTM

Vegetation can play an important role in controlling surface fluxes, particularly in areas with more complex terrestrial water, energy, and carbon cycles. The photosynthetic cycle is often affected by the amount of root-zone water stored in the surface below. As a result, precisely measuring surface soil moisture, particularly for vegetated surfaces, is crucial to understanding the interconnection of these cycles at the land surface, which has consequences for global atmospheric carbon monitoring and weather prediction.

The thermal emissions as from Surface of the Earth are measured by passive microwave sensors as brightness temperatures at the relevant frequencies (L-, C-, and X-bands). These sensors contribute in the global assessment of soil moisture [45]. The retrieval of moisture content in the soil surface through passive microwave sensors necessitates the implementation of an algorithm that can correlate brightness temperature to soil moisture. A body emits radiation by nature, hence a land covered by a canopy would predominantly radiate thermal emissions from the surface soil, canopies, atmospheric, and cosmic surroundings. RTM is used to represent these effects, and it is a key component of the soil moisture retrieval algorithm from passive microwave sensors. The fundamental principle behind an RTM is that brightness temperatures are closely associated with the soil-water medium's dielectric properties. Surface soil emissions are then attenuated by soil surface roughness, which amplifies emissions also while mixing them through polarizations. The atmosphere is often assumed to be transparent at lower frequencies (sensitive to soil surface) [46], leading in the exclusion of attenuations caused by the atmosphere and cosmic background. Aside from these aspects, vegetative attenuation also observed to have a considerable influence on the measured TB value. [47].

The Tau-omega vegetation model suggested by T. Mo et al., [48] is the most used RTM. The Tau-omega model excludes the numerous scattering effects that have been observed in the vegetation cover. The model includes two parameters: the single scattering albedo (ω) and VOD (τ). The VOD measures the amount of water in the leaves and woody components above- biomass. [49]. Numerous studies have attempted to extract vegetation information that complements the information collected from optical indices such as the NDVI, EVI, etc, as emissions from the foliage are directly controlled by the canopy water content [50-52]. Alternatively, A measures the scattering effects of the canopies like a fraction of the scattering efficiency to the overall extinction efficiency. The Tau-omega model transforms the brightness temperature of a microwave radiometer in to the soil moisture. This method provides a promising understanding of the solar radiation scattering mechanisms. M. Neelam and B. P. Mohanty., [53] investigates the sensitivity of brightness temperature (H- and V-polarization) to physiological factors, including surface temperature, surface roughness, soil moisture, and plant characteristics during Southern Great Plains Experiment'1997 (SGP'97), Oklahoma, Soil Moisture Experiment'2002 (SMEX02), Iowa, Soil Moisture Experiment'2004 (SMEX04), Arizona, Soil Moisture Active Passive Validation Experiment'2012 (SMAPVEX12), Winnipeg. Many studies used this model with zeroth-order scattering [10, 54-57]. Davenport et al., [54], Srivastava et al., [10], and Srivastava et al., [10] used this model on SMOS, whereas, Chan et al., [56] and S. Suman et al., [57] employed this approach on SMAP satellite. Park et al., [58] provided a time-varying omega parameterization for the well-established zeroth order radiative transfer model for SMAP soil moisture estimate. It is also used in the baseline algorithm of SMAP soil moisture products [59]. Apart from it, L. Karthikeyan et al., [60] explain in detail the evaluation of RTM parameters for retrieving VOD and soil moisture from AMSR-E observations. The Tau-omega model also used as the basis algorithm of SMAP soil moisture product. This basis algorithm of SMAP requires some improvements, such as correct measured roughness parameter for agricultural lands and VWC at better temporal resolution with microwave datasets.

1.10.4 A review on Disaggregation of satellite soil moisture

Low-frequency microwave region of electromagnetic spectrum can determine soil moisture content more correctly because of its sensitivity to the soil surface as well as a significant penetration through the vegetation layer. At present, NASA's SMAP and ESA's SMOS are the only two satellites incorporating a radiometer with L-band for mapping soil moisture globally. Both of these satellite missions produce global soil moisture maps with a spatial resolution of 36-40 km. However, finer spatial soil moisture information is critical to understand various hydrological processes and for the prediction of the consequence of soil moisture variability on many environmental activities, weather, and climate change. Initially, SMAP was also incorporated with an L-band radar having a 3-km spatial resolution for the disaggregation of radiometer soil moisture up to 9 km [61]. But the radar has stopped working due to a technical issue after three months of operation. Later, a new approach was given by N. N. Das et al. [13] and [62] to rescale the SMAP radiometer soil moisture up to 9, 3, and 1 km by using Sentinel backscattering in the place of radar backscattering data. These products are now accessible globally, although with poor temporal resolution (12 days) except for the 9 km product, which is available daily, still, it has a poor spatial resolution for various land management and agriculture applications. Researchers have established multiple methods for the disaggregation of satellite soil moisture product by using several land surface parameters available at the optical wavelength [7, 63-65]. Most optical algorithms are built on the polynomial regression relations of soil moisture with (Land Surface Temperature) LST, and NDVI (Normalized Difference Vegetation Index) (Triangle method). Carlson., [66, 67] firstly proposed the Triangle method to evaluate the soil moisture, but later it was utilized by many researchers for the purpose of downscaling the satellite soil moisture [68-71]. Fang et al. [72] developed a new method based on the Thermal Inertia theory to produce soil moisture data product with higher spatial resolution. This algorithm is mainly based on the principle of Minacapilli et al. [73], which previously used an airborne platform to estimate soil moisture using the Thermal Inertia theory. Besides, a different and more physical and theoretical methodology known as the DISPATCH (DISaggregation based on Physical and Theoretical scale CHange) method was introduced by Merlin et al. [63] and based on the Soil Evaporative Efficiency (SEE). SEE is calculated by using LST and vegetation index. Furthermore, Molero et al. [74] and Colliander et al. [65] also used this method with some modifications. Apart from all these algorithms, still more accurate measurement of finer resolution soil moisture is required because, in the Thermal Inertia theorem, it is complex to derive different relations for different intervals of NDVI on a spatial and temporal scale. Similarly, the Dispatch method is also very complicated to formulate due to the dependency of the selection of zones on vegetation condition and the calculation of vegetation temperature. The Triangle method may also generate some bias errors because of the dependency on regression coefficients.

1.10.5 A review on monitoring of Vegetation Water Content (VWC)

The covering vegetation layer on the land highly influences the soil's microwave remote sensing. The canopy layer can be characterized through some biophysical parameters such as VWC. It is a crucial factor for the parameterization of attenuation caused by the vegetation layer while monitoring soil moisture. Presently, the VWC is assessed by primarily two approaches. The conventional method is based mainly on the optical satellite datasets, which generate global VWC maps through vegetation indices such as NDVI, NDWI (Normalized Difference Water Index), and LAI. M. Han et al., [75] and Jackson et al., [76] utilized NDVI, and Ying Gao et al. [77] and Jasmeet Judge et al., [78] used NDVI and NDWI both for the estimation of VWC. Chen et al., [79] also used NDVI and NDWI derived from MODIS datasets to estimate VWC. Apart from it, Chen et al., [80] further introduced a approach with NDWI alone for the same purpose. Another process given by Yilmaz et al., [81], expressed the VWC as the function of canopy Equivalent Water Thickness (EWT), Dry and Fresh weight of the crop. Zhang et al., [82] provided a detailed review on the VWC estimation using optical datasets and also explore the advancement in research of VWC retrieval by using spectral reflectance, spectral water index and RTM. Although, several atmospheric surroundings and solar radiance can influence the optical datasets during the data acquisition.

A different approach which includes the observations of the active radar in the microwave region, can also be classified in two ways; ground measurements (using an airborne platform, drone, or automotive radar, etc.) and space-borne radar observations (Synthetic Aperture Radar, RADARSAT, POLSAR). Huang et al., [83] utilized SMAP airborne radar (L-band) for the mapping of VWC. Whereas Kim et al., [84] used a multi-frequency polarimetric scatterometer, and Srivastava et al., [85] used a different ground-based SMAP simulator for VWC retrieval. M. H. Cosh et al., [86] utilized an aircraft-based experiments in the National Airborne Field Experiment 2006 (NAFE'06) for the measurements of VWC

In microwave space-borne measurements, Szigarski et al., [87] utilized a SMAP L-band radar, whereas Mandal et al., [88] utilised Sentinel-1 SAR data to calculate vegetation indices for VWC estimate. But, the SMAP L-band radar stopped working in 2015. Therefore, in this thesis the Sentinel-1 satellite data is used for estimating microwave VWC.

1.11 MOTIVATION OF THE STUDY

Microwave remote sensing has been shown to be an accurate technology for monitoring soil surface properties throughout the last two decades. In microwave remote sensing, the most important frequency range for the analysis of the soil surface is the low-frequency band i.e., L-band. Because of the high penetrating power through clouds, vegetation, rain, and other atmospheric constituents, it is extremely sensitive to the soil surface. Presently, two satellites are providing soil moisture data in the L-band frequency range, named SMOS and SMAP. The SMAP was launched in 2015 and showed the RMSE error of 0.04 cm3/cm3 in the estimation of soil moisture. The baseline algorithm of SMAP is the Single-Channel Algorithm (SCA), built on the equation of the zeroth-order RTM, also identified as the Tau-Omega model. This algorithm has various essential parameters such as single scattering albedo, soil dielectric constant, soil surface roughness, Vegetation Optical Depth (VOD), and surface temperature. The accurate modelling of SCA requires precise measurements of these variables. In the Algorithm Theoretical Basis Document (ATBD) of SMAP soil moisture, the surface roughness parameter’s stated value for croplands is provided as 0.108, but the ground observation of croplands of Northern India illustrates the greater surface roughness. Therefore, its accurate measurement is mandatory for the accurateness of SCA.

VOD is also an essential factor in the approach of SCA, and its measurement process described in SCA also needs some improvements. Jackson et al., [89] provided an equation that uses NDVI to determine VWC, from which the VOD is obtained. Presently, the ATBD uses the MODIS NDVI product (MOD13A2) to estimate VWC. Since the MODIS NDVI product is an optical dataset and available at the temporal revisit frequency of 16 days, this may induce some error because of the operational frequency range of SMAP is being microwave and providing data daily. Therefore, it is required to evaluate VOD in a microwave region and also on a daily basis.

Remote sensing and microwave radiometers have a strong relationship in the area of monitoring soil moisture. The spatial resolution acquired by a microwave radiometer depends on the aperture's diameter and the altitude of the satellite platform above the Earth. Therefore, it requires either a bigger aperture size or a low altitude of the orbit to attain a finer spatial resolution. However, reducing a satellite platform's height will affect the mission's life and also decrease its temporal resolution. However, the issue of a bigger aperture size was resolved in two satellite missions; SMOS by ESA [90] and SMAP by NASA [12, 91]. Initially, SMAP utilized an antenna along with a bigger aperture and an L-band radiometer and radar to produce high-resolution soil moisture data. The SMAP radiometer and radar acquired 36 km and 3 km spatial resolution, respectively. The resultant combined product provided by SMAP had a pixel size of 9 km. However, the SMAP radar stopped after some time, and only radiometer data was left. Recently, N. N. Das et al. [13] and [62] presented a new approach that utilized the SAR data along with the SMAP radiometer to deliver soil moisture at 9 km [13] and 3 km along with 1 km [62]. In this process, the SMAP radar backscattering was replaced by the SAR backscattering. However, because of its limited spatial resolution, the 9 km product does not provide much information for numerous hydrological applications, and the 3 and 1 km product is not available daily. Therefore, measuring the comprehensive and accurate information of soil moisture spatially and temporally is very significant. Many applications, such as water resource management [92], weather forecasting [10], drought analysis [8, 9], agriculture production [93], and irrigation management [7], require knowing the soil moisture content at the regional scale.

1.12 RESEARCH OBJECTIVES

The research work of this thesis is mainly based on the estimation and downscaling of the satellite soil moisture. The specific research objectives are,

→ Estimation of soil moisture using a zeroth-order RTM

→ To improve the accuracy of soil moisture estimation by improving the baseline algorithm of SMAP

→ Evaluation of existing downscaling approaches for soil moisture

→ To develop a new approach for downscaling of soil moisture

→ Development of an approach for the estimation of VWC in the microwave region and its validation against ground measurements.

1.13 ORGANISATION OF THESIS

This thesis describes the work performed during a five-year period, from July 2017 to June 2022. The thesis is organized into seven chapters. The brief information of these chapters is described below,

CHAPTER 1 is the thesis's introductory section, and it discusses the basics of microwave remote sensing, soil moisture, biophysical parameter, research background, research objectives, and motivation of the study. It also provides a comprehensive literature survey on the monitoring of soil moisture and biophysical parameters.

CHAPTER 2 contains comprehensive information on satellite data and ground truth data, as well as the research methodology.

CHAPTER 3 examines the surface roughness characterization for the SCA and the disaggregation of SMAP soil moisture. This chapter investigates the sensitivity of the surface roughness parameter for three spatial resolutions of SMAP soil moisture**.** It is found that *h* is ranging from 0.2 to 0.4 for the agricultural region for the L-band frequency region. The optimization of surface roughness for soil moisture evaluation and downscaling indicates that the surface roughness parameter is a very sensitive parameter for soil moisture estimation and disaggregation

CHAPTER 4 discusses the improvements in SCA by optimizing surface parameter and daily VWC instead of the 16-day average VWC. The appraised soil moisture through the E_SCA is further used in three downscaling approaches along with the already available SMAP soil moisture product to observe the accuracy of E_SCA in evaluating and downscaling soil moisture. The estimated soil moisture through E_SCA shows a good accuracy when compared to the in-situ soil moisture. This chapter also discusses an intercomparison study of already available downscaling approaches including the Triangle method, Dispatch method, and the Thermal Inertia-based method which indicate that the Thermal Inertia-based approach is the best performing approach among the prescribed techniques and the use of estimated soil moisture through E_SCA in these downscaling approaches instead of the original SMAP soil moisture product significantly improves the downscaling accuracy.

CHAPTER 5 discusses the development of new vegetation modulated soil moisture index, developed by using MODIS LST and MODIS NDVI to minimize the vegetation effects. This index is then used for the downscaling of SMAP soil moisture. The downscaling results are then compared with the already available algorithm's results and it is found that the newly developed algorithm performs well in comparison to the already available algorithms.

CHAPTER 6 discusses the further improvements in SCA by utilizing a microwave VWC product instead of an optical one. The microwave VWC is assessed by using three vegetation indices (DPRVI, RVI, and CCR) of Sentinel-1 dual-polarized SAR data in three machine learning approaches (RF, SVR, ANFIS). This projected VWC is then used in SCA to evaluate soil moisture and to verify the estimated VWC product. The results demonstrated that the combination of DPRVI with SVR shows a good accuracy in the estimation of VWC as well as in the estimation of soil moisture through SCA

CHAPTER 7 contains the general conclusion of the thesis as well as the future work plan.

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