MODULE – 9 LECTURE NOTES – 2

ACTIVE MICROWAVE REMOTE SENSING

1. Introduction

Satellite sensors are capable of actively emitting microwaves towards the earth’s surface. An active microwave system transmits electromagnetic radiation of near constant power in the form of very short pulses. These pulses will be concentrated into a narrow beam which is used for remote sensing. Active microwave systems are capable of measuring the electromagnetic waves returned from targets after they undergo reflection and atmospheric attenuation (reduction of radiation due to atmospheric particles like ice, ozone, water vapor etc). Once we know the transmission and reception times of the outgoing and incoming waves, we can easily arrive at a map showing the returned power within a three dimensional space that comprises of all the sampling volumes. This technique is generally used to track aircraft, ships or speeding automobiles. Active microwave systems can be either ground based (weather radars) or satellite based (TRMM) in nature. The most commonly used type of active microwave sensor is RADAR which is an acronym for radio detection and ranging. They have widespread applications in weather monitoring, coastal mapping, atmospheric studies, hazard mitigation studies etc. As the earth’s surface represents an interface between a refractive and conducting medium, a thorough understanding of its interaction with the electromagnetic wave is essential in order to fully appreciate the detected signal. Without going into extreme detail, this module discusses the principles of active microwave remote sensing systems. Some of the properties and application of synthetic aperture radars (SAR) which is an active radar is also being summarized.
2. Active Microwave Remote Sensing

2.1 Principle of Active remote sensing

A radar system transmits very short pulses of electromagnetic radiation concentrated into a narrow beam at predetermined radial angles. It then measures the amount of power reflected back to the radar antenna backscattered from targets within the sampling volume, as the pulse travels away from the radar. The difference between transmission and reception times of outgoing and incoming waves can be used to produce a map of returned power in three dimensional space involving all sampling volumes.

![Figure 1: Working of radar](image)

If $P_r$ and $P_t$ be the received and transmitted power, the radar equation is given as

$$P_r = 10^{-20} \frac{P_t G^2 \theta^2 \Pi^3 h |K|^2 Z}{1024 L n(2) \lambda^2 r^2}$$

Here $G$ = Antenna gain [A dimensionless quantity denoting ratio of power on beam axis to power from an isotropic antenna at same point]

$\theta$ = Half power beam width (in radians)
\( h \) = Pulse width (m)

\( \lambda \) = Wavelength of the radar (cm)

\( Z \) = Radar reflectivity factor (mm\(^6\) m\(^{-3}\)).

If \( N(D) \) denotes the raindrop size distribution in a unit volume and \( D \) denotes the diameter of the raindrop, by definition, the reflectivity factor can be expressed as proportional to the 6\(^{th}\) moment of rain drop diameter. i.e.,

\[
Z = \int_{0}^{\infty} N(D)D^6 dD
\]

\( r \) = Range or distance to the target (km)

\( K \) = Complex dielectric factor of the targets (dimensionless)

### 2.2 Radar Backscattering

The radar backscatter coefficient is given by:

\[
\sigma^0 = \frac{\sigma}{A}
\]

Where \( \sigma \) is the radar cross section and \( \sigma^0 \) denotes the radar backscatter coefficient. Radar backscatter coefficient depends on the target properties like roughness, dielectric constant and on the radar characteristics like depression angle, frequency, polarization etc. Radar backscatter is affected by dielectric constant of target (like soil). The depth of radar penetration through target like vegetation or soil will largely depend on the frequency used.
2.3 Radar Parameters

a) Azimuth direction: Denotes the direction of aircraft or orbital track of satellite
b) Range Direction: Denotes the direction of radar illumination, usually perpendicular to the azimuth direction

c) Depression angle: Denotes the angle between horizontal plane and microwave pulse

d) Incident angle: Denotes the angle between microwave pulse and a line perpendicular to the local surface slope

e) Polarization: A simple electromagnetic wave will have electric and magnetic fields oscillating in mutually perpendicular directions. If we consider any point in space, the trajectory of the electric field vector will always trace an ellipse. Polarization is defined as the eccentricity, orientation of this ellipse and the direction along which the vector rotates.

![Figure 3: Radar parameters](image)

### 2.4 Synthetic Aperture Radar (SAR)

Usually, a long radar antenna and narrower beam width results in higher azimuth resolution. Hence, precise information regarding a particular object cannot be obtained. At the same time, placing of a very large antenna in space can be very expensive. Hence, a technique is utilized which relies on satellite motion and Doppler principles in order to artificially synthesize the impression of a long antenna so that fine resolution is obtained in azimuth.
Remote Sensing: Advanced Topics

Active microwave remote sensing

direction. The system which uses this technology is known as Synthetic Aperture Radar (SAR) system. As the radar moves in between two pulse transmission, it becomes possible to combine all phases of all echoes and thereby synthesize the impression of a very large antenna array.

A Synthetic Aperture Radar (SAR) is a space-borne side looking radar system which relies on the flight path to simulate an extremely large antenna or aperture electronically. SAR processors store all the radar returned signals as the platform continues to move forward. As radar measures distance to features in the slant range rather than using the true horizontal distance, radar images will be subjected to slant range distortions like foreshortening, layover etc which are discussed below. In addition, backscatter from radar can be affected by surface properties over a range of local incident angles also. For example, for incident angles of $0^0$ to $30^0$, topographic slope dominates the radar backscatter. For angles of $30^0$ to $70^0$, surface roughness dominates. Consequently, for angles $> 70^0$, radar shadows dominate the image.

a). Geometric Characteristics

Consider a tall feature tilted towards the radar (like a mountain). When the radar beam reaches the base of this tall feature before it reaches top, the radar ends up measuring the distance using slant range which will appear compressed with the length of slant feature being misrepresented. This error is called as foreshortening. Layover is the error occurring when the return signals of radar from top of target is received well before the signal from the bottom. Another effect prominent in radar images is the shadowing effect which increases with an increase in the incident angle. Unlike shadows in photography, radar shadows are completely black and are sharply defined. Following the radar shadow, a relatively weak response will be recorded from the terrain that is not oriented towards the sensor.
2.5 SAR applications

a) Synthetic Aperture Radar Interferometry (InSAR)

Synthetic Aperture Radar (SAR) imagery is created by processing of the microwave energy registered at an airborne or satellite borne antennae. The backscattered energy from target (earth surface materials) changes the phase and amplitude of an outgoing microwave energy wave. SAR instruments are capable of recording the intensity and phase of the return pulses of energy and for this reason they are also known as coherent. Interferometric SAR on InSAR uses the phase differences between the return pulses received by two separate SAR antennae in order to construct a pixel by pixel elevation map of ground surface. Both the antennae can either be carried by a single platform leading to single pass interferometry or the signals can be measured at position A on one orbit and at A1 at another orbit leading to repeat pass interferometry.

The raw interferogram is usually represented in the form of an image containing repeated set of fringe patterns wherein each fringe represents a single phase difference cycle of $2\pi$ radians. Each individual fringe is displayed using a complete color cycle. It should be understood that this raw interferogram must be corrected before using it to estimate the surface elevation values. Sometimes, if the phase difference is measured in terms of an angular range of $2\pi$ radians, then phase differences must be ‘unwrapped’ by the addition of appropriate multiples of $2\pi$ before extracting elevation details. This step is essentially called as phase unwrapping and its implementation is very difficult. Another issue is that the interferogram of a completely flat area has a fringe pattern that is parallel to the flight direction. This pattern is essentially caused due to the earth curvature. It is required to remove this flat earth fringe pattern before these fringes can be calibrated in terms of elevation.

The quality of DEMs based on InSAR is affected by a number of factors like system characteristics, baseline length, terrain characteristics and processing parameters. Also radar shadow, overlay and foreshortening can provide additional problems. For more detailed
discussion of the geometric factors that influence SAR interferometry, readers can refer to Gens and van Genderen (1996a and b)

The United States Shuttle Radar Topography Mission (SRTM) used the single pass interferometric approach to create global digital elevation model (DEM) at 30m and 90m resolution respectively. Single pass interferometry offers advantages that target area is viewed by both the antenna at virtually identical atmospheric conditions. The topic of InSAR imagery processing will however not be discussed in this module. Applications of differential InSAR range from movement of crustal plates associated with volcanic activity [Rosen et al (1996)], land subsidence, movement of glaciers and ice streams [Rabus and Fatland (2000)], ocean currents [Goldstein and Zebker (1986)] to elevation modeling [Albertini and Pone (1996), Evans et al (1992), Sties et al (2000)]. Among the various wavelengths within microwave spectrum, the X and L band are more capable of producing better quality DEMs as a decrease in wavelength is known to be accompanied with an increase in height sensitivity. The other factors sensitive to height are incidence angle, slant range distance etc.

b) Soil Moisture Content

Dielectric constant of water is the property which determines the propagation characteristics of an electromagnetic wave wherein the square root of dielectric constant gives the index of refraction for the material. Whenever waves encounter a boundary between two different media, this contrast determines the reflection and transmission coefficients of the electromagnetic wave at the boundary. The microwave remote sensing of soil moisture is dependent on the contrasting values of dielectric constant between water (~80) and that of dry soil (~3.5). This is because the electric dipole of a water molecule tends to align itself with the electric field of microwave frequencies. When we consider frozen water (ice), this motion gets inhibited at about 104 Hertz as the water molecules are bound when frozen. Microwaves have the capability of penetrating up to a few centimeters of bare soil. This property can be utilized to estimate the soil moisture content which is apparent at longer wavelengths. The dielectric constant for water is at least 10 times as that of dry soil. Variation of soil’s dielectric constant with respect to soil moisture content tends to produce variation in soil’s emissivity from 0.95 for dry soils to 0.6 or less for wet soils. These variations can be well captured by both active and passive microwave sensors. The passive sensor observes variations in the thermal emission from soil due to emissivity changes. One thing to note is that microwave frequencies are capable to sense soil moisture up to 5 cm thickness.
Microwave remote sensing using passive sensors have a great potential to estimate soil moisture with a good temporal resolution on a regional scale. Passive microwave radiation penetrates vegetation canopies wherein the vegetation absorbs and reflects part of this radiation from the soil surface.

c) Flood Control

The inability of cloud penetration is the single important disadvantage of optical remote sensing. The use of microwave imagery, particularly radar images circumvent this problem because radar pulse can penetrate cloud cover. The most common approach for flood management is usage of Synthetic Aperture Radar (SAR) imagery simultaneously with optical remote sensing imagery. In a radar image, thresholding is normally employed to segregate flooded areas from non-flooded areas. Change detection techniques are also used as powerful tools to detect flood inundated area within SAR imagery by comparing two imageries taken before and after the flood. SAR imageries acquired on multiple dates can be used to create a false color composite. Presence of vegetation/forest cover offers obstacle to accurately identify inundated areas using SAR image. It relies on the fact that flooded forests tend to produce a bright radar backscatter in contrast to non-flooded forests. Generally flooded areas without any vegetation cover appear dark within SAR imageries. In urban areas, due to the effect of trees, estimation of inundation within these areas is difficult to conduct. The viewer’s ability to segregate flooded areas depends on a combination of wavelength, incidence angle and polarization. Several flood related indices are derived by researchers using the ratio of horizontal and vertical polarizations. Images from Radarsat-1 are preferred more than the images from ERS for mapping flood, as the former is capable of rotating its sensor disseminating the radar signal at different incidence angles. Recent studies of flood mapping use the advantages of both optical and microwave remote sensing technologies for improved interpretation.

d) Oil Spill detection

Microwave remote sensing applications involve monitoring of ocean pollution. Oil slicks over the ocean surface dampen the Bragg waves thereby reducing the radar backscatter coefficient. Light components of the oil tend to evaporate to the atmosphere where the rate of
evaporation is dependent on oil type, spill thickness, wind speed and sea temperature. The main challenge in oil spill detection using microwave remote sensing is to demarcate oil slicks from other nature phenomenon that similarly dampen the short waves and create dark patches. There are essentially termed “look-alikes”. The use of multiple frequency and multi polarization signatures can be used in a discrimination algorithm to differentiate between oil spills and false alarm templates. In addition to oil slicks, different kinds of pollution can cause slicks such as diesel, fish oil, controlled chemical spill etc. However, SAR sensor is unable to distinguish between these different pollutants. One thing to note is the oil slicks get visible in SAR images only for a limited range of wind speeds.

e) Biomass Estimation

Vegetation canopies act as volume scatterers to radar waves. Some waves can penetrate through the thick vegetation canopies and if the radar wavelength is approximately equal to the mean size of plant components, then the volume scattering will be strong. Generally over a dense plant canopy, the backscatter obtained will be strong. Broadly speaking, wavelengths in the range of 2 to 6 cm are considered best for sensing crops (like corn, soyabeans, wheat etc) and tree leaves. This is because, at these wavelengths, volume scattering will predominate more than surface scattering from the underlying soil. For detection of tree trunks/limbs, wavelengths of 10 to 30 cm are considered best. In addition to plant size and radar wavelength, the moisture content of vegetation also affects the radar backscatter. Greater moisture content in vegetation increases the dielectric constant which in turn increases the reflectivity of the crop surface. In other words, leaves with a higher moisture content produce radar backscatter which is greater than dry leaves of the same species.

3. Errors in Radar

Images captured using active remote sensing like radar images will usually be subjected to numerous errors some of which will be discussed here.

a) Speckle

Microwave signals backscattered from the earth’s surface when registered by the sensor can be either in phase or out of phase by varying degrees. The intensity changes will be attributed to atmospheric attenuation effects of scattering, reflection, absorption etc. The phase changes
are normally caused due to the target properties. This alteration in the signals will lead to a pattern of brighter and darker pixels in radar images which gives them a grainy appearance, also known as speckle. Speckle is reduced using image processing techniques, such as filtering in the spatial domain, averaging etc. One such technique is multiple look processing, wherein independent images of the same area are generated and then averaged so as to produce a smoother image. If N be the number of statistically independent images being averaged (number of looks), then the amount of speckle will be inversely proportional to the square root of this value. For example, a four look image will have a resolution cell that is four times larger than a one look image. Hence, the major factors contributing to the overall quality of a radar image are the number of looks and the resolution of a system.

b) Variation in brightness

Radar images especially those from synthetic aperture radar usually contain a gradient in image brightness values in the range direction of the image. There are two reasons for this variation. Firstly, the size of ground resolution cell decreases from near range to far range and secondly, radar backscatter is inversely proportional to the local incident angle. This means that radar images will become darker with increasing range. This will be more pronounced in airborne radar systems with larger range of look angles than the space borne systems. Mathematical models are usually used to correct this effect.

c) Relief Displacement

Relief displacement is a characteristic feature predominantly seen in side looking radar (SLR) imagery. Whenever a radar pulse encounters a vertical terrain feature, the top of the feature is often reached before the base. Hence, the return signals from the top of a vertical feature will tend to reach the radar antenna before the base of the feature. As a direct consequence, it causes the vertical feature to “lay over” the closer features, thereby making it appear to lean toward the nadir. The effect is termed as layover effect which will be more severe at near range. Another effect commonly observed in radar images is the foreshortening effect. Whenever the slope facing radar antenna is less steep than the line perpendicular to the look direction, layover does not occur. Then the slopes of the surfaces won’t be presented in its true size. This effect becomes more predominant as the slope’s steepness approaches perpendicularity to the look direction. Sometimes radar imagery will be affected by another
characteristic feature known as radar shadow wherein the slopes facing away from the radar antenna will return weak signals or no signal at all.

4. Radar Remote Sensing from Space

Several satellites have successfully made possible radar remote sensing from space like the experimental spaceborne systems Seasat-1 and the three Shuttle Imaging Radar Systems (SIR-A, SIR-B and SIR-C). Characteristics regarding these instruments are tabulated below. The point to be noted is that radar images acquired using an airborne system will be subjected to large changes in incidence angle across the image swath. Hence, difficulty will be observed in demarcating the backscatter caused by incident angle variations with that from the backscatter actually related to the structure and composition of surface materials/targets in an image. To circumvent this issue, spaceborne systems have only a small change in incident angle enabling easiness in image interpretation. The European space agency (ESA) launched its first remote sensing satellite ERS-1 followed by ERS-2 on July 17, 1991 and April 21, 1995 respectively. Launched in a sun synchronous orbit at an inclination of 98.5° and altitude of 785 km, the revisit period of the system is about 16 to 18 days. ERS-1 and ERS-2 carry sensors operating in C, Ku band and an along track scanning radiometer. An advanced polar orbiting Earth observation satellite is Envisat-1, which has an Advanced Synthetic Aperture Radar (ASAR) system onboard it operating in C band. In the image mode, ASAR generates four look high resolution images of 30 m resolution.

Table 1: Characteristics of major Experimental SAR Systems

<table>
<thead>
<tr>
<th>SAR Systems</th>
<th>Launch Date</th>
<th>Wavelength band</th>
<th>Polarization</th>
<th>Azimuth Resolution (m)</th>
<th>Range Resolution (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEASAT-1</td>
<td>June 27, 1978</td>
<td>L band (23.5 cm)</td>
<td>HH</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>SIR-A</td>
<td>November, 1981</td>
<td>L-band</td>
<td>HH</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>SIR-B</td>
<td>October 1984</td>
<td>L-band</td>
<td>HH</td>
<td>25</td>
<td>15-45</td>
</tr>
</tbody>
</table>
The National Space Development Agency of Japan developed the JERS-1 satellite launched on February 11, 1992. It included an L band SAR operating in HH polarization. Similarly, the Canadian remote satellite Radarsat-1 was launched on November 28, 1998 in a sun synchronous orbit at an altitude of 798 km. Radarsat was primarily launched for the purposes of coastal surveillance, land cover mapping, agriculture monitoring etc. However, the near real time monitoring can be extended for disaster management studies like oil spill detection, flood monitoring, landslide identification, identification of soil moisture etc.

5. Sources of Microwave Data

Globally available microwave data from satellite borne sensors are now made available to end users. An entire list of these data products obtained in microwave and other regions of the electromagnetic spectrum can be obtained from the link

[http://reverb.echo.nasa.gov/reverb/#utf8=%E2%9C%93&spatial_map=satellite&spatial_type=rectangle]

Two major satellites whose products have been widely used for research purposes are discussed namely that of AMSR-E and TRMM data.

a) Advanced Microwave Scanning Radiometer (AMSR-E)

AMSR-E is a passive microwave radiometer which utilizes 12 channels and 6 different frequencies from 6.9 to 89.0 GHz in the horizontal and vertical polarization. The main objectives of this satellite was to measure geophysical parameters like precipitation, oceanic water vapor, cloud water, near surface wind speed, sea surface temperature, snow cover, sea ice etc. The United States NASA and JAXA of Japan are involved in the algorithm development and implementation for analyzing data from AMSR-E. For each Earth Observing System (EOS) instrument, there exists a suite of data products. As of october 4, 2011, AMSR-E antenna has stopped working due to aging lubricant in the mechanism. However, the data products along with corresponding metadata and associated documentation are archived and distributed by the Snow and Ice Distributed Active Archive (DAAC) at the National Snow and Ice Data Center. Details regarding the AMSR-E EOS standard data
products are available from the link [http://wwwghcc.msfc.nasa.gov/AMSR/data_products.html ].

b) Tropical Rainfall Measuring Mission (TRMM)

The TRMM satellite is a joint mission between the National Aeronautics and Space Administration (NASA) of the United States and the National Space Development Agency (NASDA) of Japan. Launched in December 1997 into orbit, the main objectives of TRMM are to measure rainfall and latent heat of condensation exchange of the tropical and subtropical regions of the world. The main instruments onboard TRMM are the TRMM Microwave Imager (TMI), the precipitation radar (PR) and the Visible and Infrared Radiometer System (VIRS). Two additional instruments are also present in TRMM namely the Clouds and Earth’s Radiant Energy System (CERES) and the Lightning Imaging System (LIS). More details about the TRMM sensor package can be obtained in Kumerrow et al (1996). Further discussion will be limited to the availability of TRMM microwave products.

The standard TMI data are made available as the first level 1B11 data containing calibrated microwave brightness temperatures captured in 5 frequencies of 10.65, 19.35, 21, 37 and 85.5 GHz in both horizontal and vertical polarizations except for the 21 GHz frequency channel that measures data using just the vertical polarization. The details regarding data available are tabulated below.
Table 2: TRMM Satellite data products from the active and passive sensors of PR and TMI

[trmm.gsfc.nasa.gov/data_dir/data.html]

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1B11</td>
<td>Calibrated TMI (10.65, 19.35, 21, 37 and 85.5 GHz) brightness Temperatures at 5 to 45 km resolution over a 760 km swath</td>
</tr>
<tr>
<td>1B21</td>
<td>Calibrated PR (13.8 GHz) power at 4 km horizontal and 250 m vertical Resolutions over a 220 km swath</td>
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<tr>
<td>2A12</td>
<td>TMI Hydrometeor (cloud liquid water, precipitation water, cloud ice, Precipitable ice) profiles in 14 layers at 5 km horizontal resolution, along With latent heat and surface rain, over a 760 km swath</td>
</tr>
<tr>
<td>2A21</td>
<td>PR (13.8 GHz) normalized surface cross section at 4 km horizontal resolution And path attenuation (in case of rain) over a 220 km swath</td>
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<td>2A25</td>
<td>PR (13.8 GHz) rain rate, reflectivity and attenuation profiles at 4 km horizontal, and 250 m vertical resolutions over a 220 km swath</td>
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<td>3B42</td>
<td>3 hourly 0.25 x 0.25 degree merged TRMM and other satellite estimates</td>
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<td>3B31</td>
<td>Rain rate, cloud liquid water, rain water, cloud ice, graupels at 14 levels for a latitude band from 40 degree N to 40 degree S from PR and TMI</td>
</tr>
<tr>
<td>3A26</td>
<td>Rain rate probability distribution at surface, 2 km and 4 km for a latitude band from 40 degree N to 40 degree S from PR</td>
</tr>
</tbody>
</table>

As it is not possible to include all the details regarding all the available satellites operating in the microwave spectrum, interested readers can seek more information regarding satellites having active sensors like RISAT-1, RISAT-2, RADARSAT-2, ALOS PALSAR, TERRASAR etc.