CHAPTER-2: THEORETICAL BASIS AND LITERATURE REVIEW

2.1 POLARISATION OF AN ELECTROMAGNETIC WAVE

Microwaves propagate in wave form with their electrical and magnetic vectors remaining perpendicular to each other and also with reference to the direction of the wave propagation. Figure 2.1 shows propagation of an electromagnetic wave.

![Figure 2.1: Propagation of electromagnetic wave](image)

If electric vector is in the plane of incidence it is called **Vertical Polarisation** and if it is at right angles to the plane of incidence it is called **Horizontal polarisation**. Plane of incidence is the plane containing the incident ray and normal to the reflecting surface at the point of incidence. (Joseph, G, 2005). If there is a component of electrical vector in both vertical and horizontal direction and they are not in phase, then it is **elliptically polarised**. If the electrical vector in both the planes are equal and they are 90 deg out of phase, then the polarisation is said to be **circular**. The most general form of polarised...
light is in elliptical polarisation. Linear and circular polarisations are simply special degenerate cases of elliptical polarisation.

The type of polarisation is determined by the relative magnitude and phase difference between the two orthogonal components of $\vec{E}$. In general, $\vec{E}$ can be described mathematically by

$$\vec{E}(z,t) = \begin{bmatrix} \hat{E}_h(z) \\ \hat{E}_v(z) \end{bmatrix} = \begin{bmatrix} a_h \cos(\alpha r - kz + \delta_h) \\ a_v \cos(\alpha r - kz + \delta_v) \end{bmatrix}$$

(2.1)

Where $a_v, a_h$ are the amplitude and, $\delta_h$ and $\delta_v$ are the $h$ and $v$ phase components of $\vec{E}(z,t)$ respectively and $t$ is time. $\omega r - \kappa z$ is the propagation term where $\omega$ is the angular frequency i.e. $\omega = 2\pi f$, $f$ is the temporal frequency and $\kappa$ is the wave number i.e. $\kappa = 2\pi/\lambda$. At a particular position, say $z=z_0$, the wave is represented by an ellipse called the polarisation ellipse.

![Figure 2.2: Generic polarization ellipse](image)

Figure 2.2 shows a generic polarisation ellipse with its major and minor axes rotated from the reference axes ($h$ and $v$), where $\psi$ is called orientation angle of the ellipse, and $\chi$
is called ellipticity angle. The size of ellipse is given by the semi-major and semi-minor axis \( a \) and \( b \) respectively as shown in the Figure 2.2. The equation for the polarisation ellipse has the following form (Collett 1993),

\[
\left( \frac{E_h(t)}{a_h} \right)^2 + \left( \frac{E_v(t)}{a_v} \right)^2 - 2 \frac{E_h(t) E_v(t)}{a_h a_v} \cos(\delta) = \sin^2(\delta)
\]

(2.2)

Where \( \delta = \delta_e - \delta_h \), phase difference between \( \vec{E}_h(t) \) and \( \vec{E}_v(t) \) components.

Equation 2.2 shows that the polarisation can be characterized in terms of the parameters \( a_h, a_v \) and \( \delta \). Figure 2.2 indicates that the polarisation can also be characterized by the ellipse orientation angle, \( \psi \), and the major and minor axes, \( a \) and \( b \). The semi major axis \( a \), semi minor axis \( b \), orientation and ellipticity angle of the ellipse are obtained by following

\[
\tan 2 \psi = \frac{2 a_h a_v \cos \delta}{a_h^2 - a_v^2}
\]

(2.3)

\[
\tan \chi = \pm \frac{b}{a} \quad -\pi/4 \leq \chi \leq \pi/4
\]

(2.4)

\[
a = a_h^2 \cos 2 \psi + a_v^2 \sin 2 \psi + 2 a_h^2 a_v^2 \cos \psi \sin \psi \cos \delta
\]

(2.5)

\[
b = a_h^2 \sin 2 \psi + a_v^2 \cos 2 \psi - 2 a_h^2 a_v^2 \cos \psi \sin \psi \cos \delta
\]

(2.6)

Figure 2.3 Different polarisations ellipses
Figure 2.3 illustrates different polarisations. Thus the polarisation ellipse is fully characterized using either the elliptical parameters $a_h$, $a_v$, and $\delta$ or by the ellipticity and orientation angles $\chi$ and $\psi$. The next section describes Radar remote sensing system which uses microwave with different polarisation for remote sensing.

2.2 Radar System

Radar{Radio Detection And Ranging}, provide their own illumination. It sends its own radio wave pulses to a target and detects the pulses returned from the target. Thus it is a “RADio Detection” system. At the same time it records the time that the pulse takes between transmissions to reception. Thus it is able to locate the target position. Hence the term “Ranging”. In order to transmit and receive, the radar has an antenna that plays a crucial role in determining the resolution achievable using a radar system. In the early phase of radar development, real aperture radar, RAR was developed. The resolution achievable from RAR is inversely proportional to the length of the antenna. The difficulties in deployment of larger antenna on radar systems led to the development of SAR, Synthetic Aperture Radar. As the name suggests, in Synthetic Aperture Radar the antenna length is synthetically lengthened to achieve better resolutions by post processing of the imaged data. The following section describes the resolution of a Radar system.

2.2.1 RAR: Real Aperture Radar

In a radar system, the antenna transmits a pulse of duration $\tau$ in range direction. From such a transmitted pulse which illuminates the area from near range to far range, separate returns are recorded from near range to far range. The returned signal from near range to far range objects is used to form one range line of the radar image.
As can be observed in Figure 2.4, a signal is transmitted for a duration $\tau$ at speed of light, c. Thus pulse length becomes $c\tau$. Therefore any two objects, which are $c\tau/2$ distance away, are discernible in a radar image. So, we get the resolution of the radar in the slant range direction as

\[
\text{Slant range resolution} = \frac{c\tau}{2}
\]  

(2.7)

When the slant range resolution is converted to the ground range, we obtain the

\[
\text{ground range resolution} = \frac{c\tau}{2}\sin\theta
\]

(2.8)

where $\theta$, is the incidence angle.

RAR and SAR resolve targets in the similar manner in range direction hence there is no difference in range resolution of a SAR and a RAR. While a range line in a radar image is obtained by the return signal from the range direction, the radar shifts by a beam width in the azimuth direction. Hence, once again the pulses are transmitted in the range direction from near range to far range and the return pulses are recorded to form another line. Thus by the transmitted short duration of pulse from near range to far range, the return pulses area in range direction are imaged and the movement of the sensor in azimuth direction yields imaging of consecutive lines on ground. Thus a two dimensional image is formed using a radar system.

As is depicted in Figure 2.5, the radar antenna having beam width $\beta$ illuminates an area of $R\beta$ on ground at slant range distance of $R$. Hence the Azimuth resolution in case of RAR depends upon the slant range distance and the beam width $\beta$.

\[
\text{Azimuth resolution} = R\beta
\]

(2.9)

The beam width $\beta$ is given by, $\beta = \lambda/l$
Where, $\lambda$ is the wavelength, and $l$ is the antenna length

2.2.2 **SAR: Synthetic Aperture Radar**

Achieving fine spatial resolution is always a challenging task for a sensor designer, as many of the land applications require sensor resolutions of the order of meters. The problem of obtaining fine spatial resolution (of the order of meters) becomes more difficult in case of Radar sensors due to the requirement of a very long antenna (of the order of kilometres) to achieve fine resolution in the azimuth direction. For example, in order to achieve a resolution of 10 meters, about a 4 kilometres long Radar antenna is required. Since the fabrication and placement of such a long antenna in space is nearly impossible, the use of radar for various remote sensing applications was not feasible for a very long period of time. This problem could be resolved by synthesizing a very long antenna with the help of a small real antenna on a moving platform by means of signal processing and use of Doppler frequency shift. The concept of synthesizing a long antenna (say 4 km) with the help of a very small antenna (say 10 meters) can be explained with the help of **Figure 2.6**. The target is observed for the first time when the sensor is at position A and is viewed for the last time when the sensor is at position E. Hence the target is in the sight of the sensor from position A to E which in fact is of equivalent distance to that of real aperture beam width, the length of real aperture as is clearly depicted in the **Figure 2.6**.
Figure 2.4: Range Resolution in RADAR

\[ R_{\beta} \]

Figure 2.5: Azimuth Resolution in RAR

Figure 2.6: Synthetic Aperture Radar (SAR) data system
As can be observed, the length of the antenna is synthetically lengthened to \( L \), which is equivalent to the azimuth resolution for the Real Aperture Radar. Thus in case of a SAR the length of synthetically lengthened Antenna is given by

\[
\text{Synthetic length } L = \text{real beam width} \times \text{distance up to ground}
\]

Where Radar beam width = wavelength/antenna length

Hence we get

\[
\text{Synthetic length } L = \left( \frac{\lambda}{l} \right) \times R
\]

(2.10)

Because of two way traverse of the signal, the phase change is equivalent to transmission of signal of wavelength \( \lambda/2 \) for one way transmission. Hence,

\[
\text{Synthetic beam width} = \frac{\lambda}{2R}\beta
\]

\[
\text{Synthetic azimuth resolution} = R \times (\text{Synthetic beam width})
\]

\[
= R \times \left( \frac{\lambda}{2R}\beta \right)
\]

\[
= R \times \frac{\lambda}{2R} \times \frac{1}{\left( \frac{\lambda}{l} \right) \times R} = \frac{l}{2}
\]

(2.11)

Thus in a SAR the azimuth resolution becomes independent of the slant range distance and in contrast to a RAR it is directly proportional to the real antenna length. Thus a shorter real antenna yields finer resolution in case of SAR, and the limitation of RAR of deploying a larger antenna in order to achieve finer resolution is overcome by synthesising a larger antenna during post processing of the Radar returns in a SAR processor.
2.2.3 **PolSAR: Polarimetric Synthetic Aperture Radar**

A polarimetric SAR system measures scattering properties of the target. Polarimetric SAR system illuminates a target with microwaves, which are scattered by the target depending upon its scattering properties. The waves scattered in the direction of the receiving antenna are recorded by the antenna. In general the polarimetric SAR system has both the receiving and transmitting antenna at the same location and so the received energy is referred to as backscatter and how the energy is scattered is given by the scattering matrix. The scattering process at the target of interest can be considered as a function of the electromagnetic fields themselves.

$$
\begin{bmatrix}
E_{\perp}'' \\
E_{\parallel}'
\end{bmatrix} = \frac{e^{-jkr}}{r} \begin{bmatrix}
S_{\perp\perp} & S_{\perp\parallel} \\
S_{\parallel\perp} & S_{\parallel\parallel}
\end{bmatrix} \begin{bmatrix}
E_{\perp}' \\
E_{\parallel}'
\end{bmatrix}
$$

(2.12)

where the matrix $[S_{(\perp,\parallel)}]$ is the scattering matrix and the entries of this matrix $S_{pq}$, for $p, q = (\perp, \parallel)$, are the so-called complex scattering coefficients or complex scattering amplitudes, ‘r’ is the distance between the target and the antenna. The term ($e^{-jkr}/r$) comes due to the propagation effect both, in amplitude and phase. The elements of scattering matrix are obtained from the types of received and incident polarisation. For example

$$
S_{\perp\parallel} = \frac{E_{\perp}'}{E_{\parallel}'} = \frac{\text{Perpendicular Polarised part of scattered wave}}{\text{Parallel Polarised part of scattered wave}}
$$

(2.13)

This is valid only for far field zone, where the plane wave assumption is considered for the incident and scattered field.

In order to appreciate the differences in the information provided by the radar backscatter and the scattering matrix, firstly the relation between the two is examined. Radar
backscatter cross section can be obtained from the scattering matrix by the following equation

\[
\sqrt{S_{qp}}^2 = \frac{\sigma_{qp}}{4\pi} \quad p,q \in (\perp,\parallel)
\]  

(2.14)

It can be deduced from the equations 2.12, 2.13, that the characterization of a given target by means of the scattering matrix allows the possibility to explore the phase information provided by the phase of complex scattering coefficients, and not only the intensity or amplitude. Importance of the phase term can be demonstrated by studying a trihedral and a dihedral observed in a polarisation basis formed with the horizontal and vertical polarisation states (Figure 2.7). The radar cross-section coefficient for both trihedral as well as dihedral is given by

\[
[\sigma]_{\text{Trihedral}} = [\sigma]_{\text{Dihedral}} = 4\pi \begin{bmatrix}
1 & 0 \\
0 & 1
\end{bmatrix}
\]

Whereas the scattering matrix for the trihedral is given by

\[
[s] = \begin{bmatrix}
1 & 0 \\
0 & 1
\end{bmatrix}
\]

and the scattering matrix for the dihedral is given by
It can be observed that the dihedral and trihedral are seen as different objects by analysing scattering matrix which is not possible by means of studying the radar cross section alone. The conclusion which can be extracted is that polarimetry opens the door to consider phase measurements to characterize the targets.

2.3 FULL POLARIMETRY/ HYBRID POLARIMETRY DATA ACQUISITION MODES
In order to acquire data in different orthogonal polarisation a polarimetric SAR transmits microwaves in different polarisation and receives the signals scattered by the target in both orthogonal polarisations. There could be various polarimetric data acquisition modes.

1) Transmit in H as well as its orthogonal polarisation V. Receive the signal in both H as well as V. This gives the observation in HH, HV, VV and VH polarisation combinations.

2) One can also illuminate target in either right or left circular polarised microwave signal and receive the response in both right as well as left circular polarisation. This gives the complex signal in RR, RL, LR and LL polarisation combination. A complete scattering matrix can be generated using the phase and amplitude of the simultaneously acquired signal.

3) Another possibility which is explored more recently by Souyries et al. 2004 and Raney et al 2006 is that of polarimetric data acquisition by hybrid polarimetric mode. In this mode signal is transmitted at $45^\circ$ linear mode or in circular polarimetric mode (either right or left) and is received in horizontal as well as...
vertical polarisation. However, the HV component cannot be recovered in exact amplitude and phase, and it is buried in the noise floor, which could render this approach to be highly incomplete.

2.4 Literature Review
The development of space borne Radar remote sensing technology started way back in 1978 when the first space borne SAR system, SEASAT-A was launched which worked for nearly three months. The SEASAT SAR system provided valuable but highly incomplete data for ocean and land surface applications. Subsequently, L-band shuttle imaging radar missions i.e. SIR-A and SIR-B, were launched in 1981 and 1984, respectively. SIR-A was operated with fixed incidence angle whereas SIR-B had varying incidence angles. The actual revolution in radar remote sensing was triggered after the launch ERS-1 in July 1991. ERS-1 was the first operational space borne SAR sensor and was soon followed by many more SAR sensors like JERS-1, SIR-C/X-SAR, ERS-2 SAR, Radarsat-1 SAR and Envisat-1 ASAR. The availability of SAR data at various incidence angles, frequencies (only on limited basis) and polarisations started an era of enormous possibilities to exploit radar data for many land applications. Oh et al., 1992 and Oh 2004, have developed algorithms to simultaneously retrieve soil moisture and surface roughness retrieval using quad polarised SAR backscatter alone which are applicable over low vegetated terrain. Indian scientists have also explored multi-parametric SAR data for various applications (Navalgund and Patel, 2008, Patel, 2008, Srivastava et al., 2008). In particular, in-depth research has been carried out in the field of soil moisture estimation, agriculture, forestry, wetland and human settlement related studies. Some of the major research work carried out in the Indian sub-continent includes development of a

The new generation radar satellites such as ALOS-PALSAR (JAXA: 2006), Radarsat-2 (CSA: 2007), Cosmo-Skymed (ASI: 2007-09), TerraSARX (DLR: 2007) with advanced polarimetric sensors have given new thrust to the development of advanced techniques in radar polarimetry (Luscombe et al., 2000; Ito et al., 2001; Mathew, 2001). Polarimetry research became active during late 1940s with the introduction of dual polarised antenna technology (Sinclair, 1950; Rumsey, 1951, Kennaugh 1952; McCormick and Hendry, 1973; 1985, Huynen 1965, 1970) and the subsequent formulation of the 2×2 coherent Sinclair radar backscattering matrix (Sinclair, 1950) and the associated 4×4 Kennaugh radar backscattering power density matrix, as summarized in detail in Boerner et al.
(1991, 1987), Boerner, W.M. and El-Arini, M.B. 1981, Krogager 1990, Krogager and Boerner 1996, and Ulaby and Elachi (1990). Recently, a new impulse to radar polarimetry theory was given by Cloude and Pottier (1996) with the introduction of the incoherent target decomposition (ITD) that provides independent tools derived from the target coherency matrix. These tools, which include the entropy $H$, the anisotropy $A$, and the eigenvector parameters (Cloude and Pottier, 1997), were assigned a solid physical interpretation with reference to target scattering mechanisms. Subsequently, a number of polarimetric target decomposition techniques were developed to decompose natural as well as man-made targets in an imaged terrain based on their dominant scattering mechanisms (Freeman and Durden, 1998; Moriyama et al., 2005, Yamaguchi, 2006, Lee 2006). Since 1987, polarimetric SAR data classification has been an active field of research, and various methods for supervised and unsupervised classification have been developed (Lim et al., 1989; Van Zyl, 1989; Rignot et al., 1992; Touzi et al., 1992; Pottier and Cloude, 1995; Cloude and Pottier, 1997; Freeman and Durden, 1998; Lee et al., 1999a; 2001; Ferro-Famil et al., 2001, Cloude 2001). The development of advanced polarimetric decomposition and classification techniques and tools for polarimetric data processing has resulted in an unprecedented use of polarimetric data for geosciences applications including agriculture, forestry, geology, hydrology, oceanography, surveillance, and sea ice observation (Bouman and Hoekman, 1993; Broquetas et al., 2001; Le Toan et al., 1992; Dobson et al., 1992; Imhoff, 1986; Scheuchl et al., 2002; 2005; Onstott and Gaboury, 1989; Saint-Jean et al., 1996; Liu et al., 2005; Rodriguez et al., 2002). Excellent reviews of SAR polarimetry are provided by Boerner et al., 2002, Touzi et al., 2004, Yamada, 2001).
Globally, the usefulness of quad polarisation as well as hybrid polarimetry data for characterizing target vector has been well explored by the scientific community, in India, hybrid polarimetric data is relatively less explored for characterizing a target based upon the physical process that takes place when it interacts with incoming microwave radiation. Fully polarimetric SAR has four channels to obtain complete scattering matrix whereas hybrid polarimetry is a dual channel SAR, wherein the signal is transmitted in a single polarisation and received at two orthogonal polarisations. Hybrid polarimetry is a relatively new concept for SAR for earth observation (R. K. Raney 2006, Souyris et al. 2005, Stacy and Preiss 2006) although it has been used for astronomical and meteorological observations for quite some time (Green, 1968, Cohen 1958, Bussey et al. 2007, Stacy and Campbell, 1993, Torlaschi and Gingras, 2000). There are two major hybrid polarimetric concepts namely the $\pi/4$ mode and the circular transmit linear receive mode. In the $\pi/4$ mode a linearly polarised field at 45$^\circ$ is transmitted and the signal is received at H and V polarisation, i.e. slant-linear transmit, and coherent H&V linear receive, whereas in the circular transmit linear receive type of hybrid polarimetry, a circular polarised signal is transmitted and two coherent orthogonal linear polarised signals are received. (Souyris et. al., 2005, Stacy and Preiss, 2006; Raney, 2006; Raney, 2007a and 2007b; Ainsworth et. al., 2007). Ainsworth et. al. (2007) and Lardeux (2007) attempted quantitative comparisons of classification accuracies between full-polarimetric and $\pi/4$ mode and found that compact polarimetric mode is efficient for applications dealing with distributed targets like land use classification. However, the HV component cannot be recovered and is submerged in the noise floor rendering this method to be very limited. Raney (2006, 2007a) discusses the usefulness of Stokes’ formalism when
transmission is made at single circular polarisation and reception is made on two linear orthogonal polarisations. Raney (2007b) proposed a decomposition scheme for compact polarimetry data based on the degree of polarisation \( m \) and relative phase \( \delta \) feature space.

Looking at the remarkable advantages of SAR polarimetric technique, India has planned its indigenous SAR sensor with hybrid polarimetric capabilities. However, in India, very little work has been reported on the use of SAR polarimetric technique for target parameter retrieval (Patel et al., 2009). This fact is more relevant in case of exploitation of SAR compact polarimetry and circular polarimetry techniques by Indian scientists (Patel et al., 2008, Singh G., et al., 2010). Hence there is huge potential to explore and exploit PolSAR data for target parameter retrieval, which is a very important application of SAR polarimetric technique.