Chapter 3

Polarimetry

The aim of this chapter is to recall the different formalisms and basic definitions used in polarimetry as well as some fundamental properties of electro-magnetic waves. Polarimetry studies the vector properties of electric fields. In particular polarisation describes how the electric field vector changes direction with time.

3.1 Propagation of Electro-Magnetic Fields

The basic equations describing the propagation of electro-magnetic fields are the Maxwell-equations (e.g. [16]). For isotropic homogeneous media they have the following form:

$$\begin{aligned} div\vec{E} &= \frac{\rho}{\epsilon_0} \\ rot\vec{E} + \frac{\partial\vec{B}}{\partial t} &= 0 \\ div\vec{B} &= 0 \\ c^2 rot\vec{B} &= \frac{\vec{J}}{\epsilon_0} + \frac{\partial\vec{E}}{\partial t} \end{aligned} \tag{3.1}$$

with

$\vec{E}$	the electric field
$\vec{B}$	the magnetic induction
ϵ_0	the dielectric constant in free space
μ_0	the magnetic permeability in free space
ρ	the charge density
c	propagation velocity (speed of light) in free space ($c = 1/\sqrt{\epsilon_0\mu_0}$)
$\vec{J}$	current density of free particles

In free space ($\rho = 0, J = 0$) it follows from the maxwell equations [16] that the electric field must satisfy the wave equation:

$$\nabla^2\vec{E} + \frac{1}{c^2}\frac{\partial^2\vec{E}}{\partial t^2} = 0. \tag{3.2}$$

A plane wave traveling along the z-axis of a reference coordinate system and satisfying eq. 3.2 has only varying components along the x and y axes that are given by the general form:

$$\begin{aligned} E_x(z,t) = & \quad f_x(z-ct) \\ E_y(z,t) = & \quad f_y(z-ct) \end{aligned} . \tag{3.3}$$

Any function of $z-ct$ is thus a solution of the wave equation. In particular a monochromatic plane wave satisfies the equation. It is defined as:

$$\begin{aligned} E_x(z,t) = & \quad a_x cos(kz-\omega t-\delta_x) \\ E_y(z,t) = & \quad a_y cos(kz-\omega t-\delta_y) \end{aligned} , \tag{3.4}$$

where δ_x and δ_y are phase angles and, in order for eq. 3.4 to be of the form of eq. 3.3, we must have that:

$$\omega = ck. \tag{3.5}$$

k is called the wavenumber and ω is the angular frequency of the wave; $\omega = 2\pi\nu$ with ν the frequency of the wave.

3.2 Polarisation

If the electric field satisfies eq. 3.4, the point of the electric field vector describes in general an ellipse. This can be shown by eliminating the $kz - \omega t$ terms in eq. 3.4, which results in:

$$\left(\frac{E_x(z,t)}{a_x}\right)^2 + \left(\frac{E_y(z,t)}{a_y}\right)^2 - 2\frac{E_x(z,t)}{a_x}\frac{E_y(z,t)}{a_y}cos(\delta_x-\delta_y) = sin^2(\delta_x-\delta_y), \tag{3.6}$$

which is indeed the equation of an ellipse. In general a monochromatic plane wave will thus have an elliptical polarisation. Some special cases deserve our attention:

- If $\delta_x - \delta_y = 0 \; or \; \pi$ we get:
$$\frac{E_x}{a_x} = \pm\frac{E_y}{a_y}, \tag{3.7}$$
which means that the direction in which the electric field oscillates is fixed in space. This is called linear polarisation.

- If $\delta_x - \delta_y = \pm\frac{\pi}{2}$ we have an ellipse with its principal axes aligned on the x and y axis of the coordinate system. If $a_x = a_y$ we have circular polarisation.

The polarisation is, by convention, defined to be right-handed if the electric field vector observed as a function of time is rotating in the clockwise direction for an observer looking into the propagation direction. This means that E_y lags behind E_x and therefore:

$$\delta_y - \delta_x > 0 \Leftrightarrow \text{Right Polarisation.} \tag{3.8}$$

In general the electric field vector thus describes an ellipse in a plane perpendicular to the propagation direction (the x,y plane). In figure 3.1 the ellipse described by a general electric field vector is shown. Ψ is called the *orientation angle*, χ is the *ellipticity angle.*

These two angles describe the form of the ellipse completely and thus also the polarisation of the wave.

For linear polarisation $\chi = 0$ while for circular polarisation it reaches its maximal value $\chi = \pm 45°$. The orientation angle can vary between $0°$ and $180°$. If a and b are respectively the long and short semi-axes of the ellipse then $tan(\chi) = \pm b/a$ where the minus-sign denotes right polarisation.

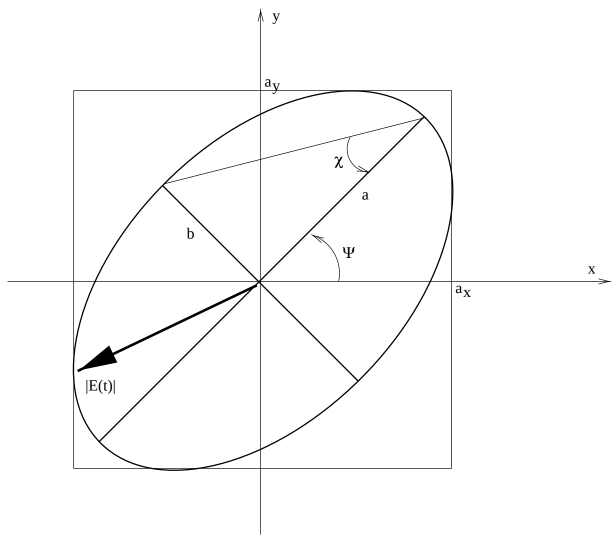

Figure 3.1: Polarisation ellipse

The orientation angle and ellipticity are given by:

$$tan(2\psi) = \frac{2 \mid a_x \mid \mid a_y \mid}{\mid a_x \mid^2 + \mid a_y \mid^2} cos(\delta) \tag{3.9}$$

and

$$sin(2\chi) = \frac{2 \mid a_x \mid \mid a_y \mid}{\mid a_x \mid^2 + \mid a_y \mid^2} sin(\delta), \tag{3.10}$$

with $\delta = \delta_y - \delta_x$.

3.3 The Jones Vector

The plane monochromatic wave in eq. 3.4 can also be written as:

$$\vec{E}(z,t) = Re\left\{\vec{E}_0 exp\left[j(\omega t - kz)\right]\right\}. \tag{3.11}$$

$\vec{E}_0$ is now a complex vector that can be represented as:

$$\vec{E}_0 = \begin{bmatrix} E_{0x} \\ E_{0y} \end{bmatrix} = \begin{bmatrix} a_x e^{-j\delta_x} \\ a_y e^{-j\delta_y} \end{bmatrix}. \tag{3.12}$$

This vector is called the *Jones vector*. Usually it is normalised such that

$$| a_x |^2 + | a_y |^2 = 1. \tag{3.13}$$

The normalised Jones vector describes thus the polarisation state.

3.4 The Stokes Vector

A monochromatic wave is completely defined by its amplitude and its polarisation [17] which can be described either by the parameters $\tau = a_x/a_y, \delta = \delta_x - \delta_y$, by the two characteristic angles of the polarisation ellipse ψ, χ or by the complex Jones vector. The same information can be conveyed by the real *Stokes vector* which is defined as:

$$J = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}, \tag{3.14}$$

where:

$$\begin{array}{lll} I = & | E_{0x} |^2 + | E_{0y} |^2 & = a_x^2 + a_y^2 \\ Q = & | E_{0x} |^2 - | E_{0y} |^2 & = a_x^2 - a_y^2 \\ U = & 2Re(E_{0x}E_{0y}^*) & = 2a_x a_y cos\delta \\ V = & -2Im(E_{0x}E_{0y}^*) & = 2a_x a_y sin\delta \end{array} \tag{3.15}$$

In fact the Stokes vector is the vectorisation, in the basis formed by the Pauli Matrices (see also eq. 3.35), of the outer product of the Jones vector with its transposed conjugate. It is easy to verify from eq. 3.15 that $I^2 = Q^2 + U^2 + V^2$. I is the intensity of the electric field, the three other parameters describe the polarisation.

With respect to the two angles of the polarisation ellipse we have:

$$\begin{array}{l} Q = Icos(2\chi)cos(2\psi) \\ U = Icos(2\chi)sin(2\psi) \\ V = Isin(2\chi) \end{array} \tag{3.16}$$

The parameters Q,U,V define thus a point on a sphere with radius I. It is therefore possible to represent the full set of possible polarisations on a sphere This sphere is called the *Poincaré sphere* and is shown in fig. 3.2.

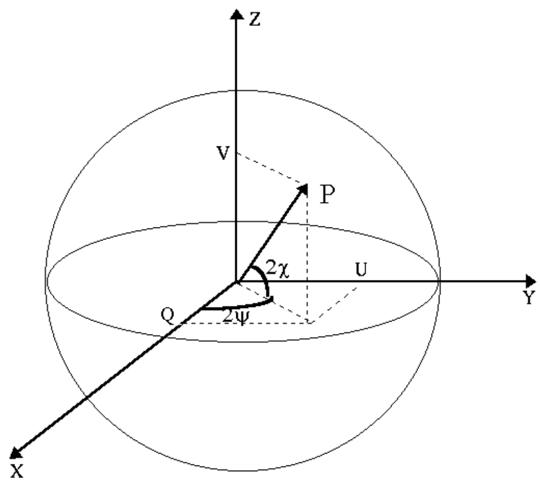

Figure 3.2: Poincaré sphere

The Equator (x,y plane) represents linear polarisation and the north and south pole correspond respectively to right and left circular polarisations. The crossing point of the equator with the positive x-axis represents horizontal linear polarisation while the crossing with the negative x-axis is vertical polarisation. The azimuth angle is thus 2ψ while the elevation angle is 2χ. The radius of the sphere is proportional to the power of the electromagnetic wave I. Using this representation the Q,U,V elements of the Stokes vector are just the x,y,z coordinates of the represented polarisation.

Any polarisation can thus be described by the two angles or by either the Jones or the Stokes vector. In table 3.1 some common polarisations are given with the different notations.

Polarisation	Symbol	$\psi(°)$	$\chi(°)$	Jones Vector	Stokes vector
Horizontal	H	0	0	[1, 0]	[1, 1, 0, 0]
Vertical	V	90	0	[0, 1]	[1,-1, 0, 0]
Linear 45°	45	45	0	$[\frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}}]$	[1, 0, 1, 0]
Right Circular	R	any (say 0)	-45	$[\frac{1}{\sqrt{2}}, \frac{i}{\sqrt{2}}]$	[1, 0, 0,-1]
Left Circular	L	any (say 0)	45	$[\frac{1}{\sqrt{2}}, \frac{-i}{\sqrt{2}}]$	[1, 0, 0, 1]

Table 3.1: Parameters of some common polarisations

linearly polarised wave with orientation angle ψ_0:
$I = E_0^2 \qquad Q = E_0^2 cos(2\psi_0) \qquad U = E_0^2 sin(2\psi_0) \qquad V = 0.$

3.5 Partially Polarised Waves

In the preceding paragraph we have assumed that the electric field vector behaves in a deterministic way characterised by the polarisation. Such a wave is said to be *completely* *polarised.* If the radiation source emits a purely monochromatic wave, that wave is completely polarised. In reality electromagnetic waves are rarely completely polarised. If the source has a finite bandwidth, or if a monochromatic wave travels through a depolarising medium that introduces random defasing between the two orthogonal polarisation states, the wave will no longer be completely polarised. An unpolarised wave is one of which the polarisation state changes in a totally random fashion such that all polarisation states are equally likely at a given instant in time. A partially polarised wave is the more common situation where the polarisation state changes randomly around a certain average state. This corresponds to a cloud of points on the Poincaré sphere.

To characterise the polarisation state the average position of that cloud is determined. In the Stokes formalism this results in:

$$\begin{aligned} I &= \langle \mid E_{0x} \mid^2 \rangle + \langle \mid E_{0y} \mid^2 \rangle \\ Q &= \langle \mid E_{0x} \mid^2 \rangle - \langle \mid E_{0y} \mid^2 \rangle \\ U &= \left\langle 2Re(E_{0x} E_{0y}^*) \right\rangle \\ V &= \left\langle -2Im(E_{0x} E_{0y}^*) \right\rangle \end{aligned} \tag{3.17}$$

We now have: $I^2 \geq Q^2 + U^2 + V^2$, the equality only holding for a completely polarised wave. An unpolarised wave on the other hand has Q=U=V=0. The "polarisation cloud" then covers the complete Poincaré sphere.

A partially polarised wave can be represented as the sum of a fully polarised wave and an unpolarised one.

$$J = \begin{bmatrix} I_p \\ Q \\ U \\ V \end{bmatrix} + \begin{bmatrix} I - I_p \\ 0 \\ 0 \\ 0 \end{bmatrix}. \tag{3.18}$$

The degree of polarisation is defined as:

$$p = \frac{I_p}{I} = \frac{\sqrt{Q^2 + U^2 + V^2}}{I}. \tag{3.19}$$

3.6 The Scattering Matrix

When an object is illuminated by an electro-magnetic wave the wave is scattered by the object. This is illustrated in figure 3.3 where E_t represents the electric field vector of the transmitted wave, E_i the field incident on the scattering object, E_s the scattered field and E_r the field received by the receiving antenna. The scattering, in the general case, changes the polarisation of the wave.

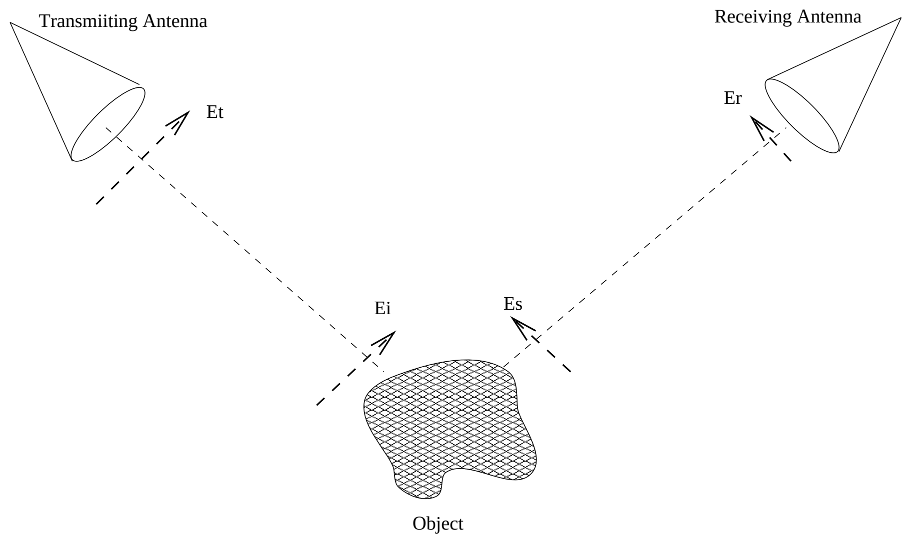

Figure 3.3: Scattering of a wave on an object

This effect can described by the *scattering matrix* **S** that relates the electric field of the incident wave to that of the received wave:

$$\begin{bmatrix} E_h \\ E_v \end{bmatrix}_r = \frac{e^{ikr}}{r}\mathbf{S}\begin{bmatrix} E_h \\ E_v \end{bmatrix}_i = \frac{e^{ikr}}{r}\begin{bmatrix} S_{hh} & S_{hv} \\ S_{vh} & S_{vv} \end{bmatrix}\begin{bmatrix} E_h \\ E_v \end{bmatrix}_i , \qquad (3.20)$$

where r is the distance between the scatterer and the receiving antenna and the assumption is made that this distance is sufficiently large for the scattered wave to be a spherical wave (far field). The elements of the scattering matrix are complex. This means that it contains 7 independent parameters (4 amplitudes and 3 phases as the absolute phase is not important and can not be measured). In radar remote sensing the transmitting and receiving antenna are co-located (or even the same). This is called the mono-static or backscattering configuration. The reciprocity theorem states that for backscattering $S_{hv} = S_{vh}$.

The complex 2x2 matrix in equation 3.20 describes how the scatterer transforms the incident electro-magnetic field. In other words it relates the electric field components of the scattered to that of the illuminating wave. If the scattering matrix is normalised such that $S_{hh}^2 + S_{vv}^2 = 1$ it just describes how the object changes the polarisation of an incoming wave. The scattering matrix is compatible with the Jones vector notation. The matrix that describes the polarisation change in the Stokes vector notation is called the Müller matrix (sometimes called the Stokes matrix), it is a 4x4 real matrix that will not be discussed here.

3.6.1 Scattering Matrices for Elementary Targets

Scattering by a smooth dielectric surface

If a plane monochromatic electro-magnetic wave is normally incident on a smooth surface with dielectric constant ϵ the scattering matrix is:

$$[S] = \frac{1-\sqrt{\epsilon}}{1+\sqrt{\epsilon}} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}. \tag{3.21}$$

This means the backscattering will be maximal for all linear polarisations ($\chi = 0$) and independent of the polarisation orientation angle (ψ). This type of signature can be expected when specular reflections occur. This is for example the case for a part of the ocean waves under specific incidence angles or for roofs of buildings perpendicular to the local viewing direction of the radar.

More generally, for a non-normal incidence, the specular reflection on a flat surface is described by the Fresnel equations. The reflection coefficient is different for horizontal or vertical polarisation, or more precisely, when the electric field is parallel to the incidence plane or perpendicular to that direction. The Fresnel reflection coefficients are:

$$R_{//}(\epsilon,\theta) = \frac{cos\theta - \sqrt{\xi - sin^2\theta}}{cos\theta + \sqrt{\xi - sin^2\theta}}, \tag{3.22}$$

$$R_{\perp}(\epsilon,\theta) = \frac{\xi cos\theta - \sqrt{\xi - sin^2\theta}}{\xi cos\theta + \sqrt{\xi - sin^2\theta}}, \tag{3.23}$$

with θ the (local) incidence angle and ξ the relative index of refraction:

$$\xi = \frac{\epsilon_2 \mu_2}{\epsilon_1 \mu_1}. \tag{3.24}$$

The corresponding scattering matrix is:

$$[S] = \begin{bmatrix} R_{//} & 0 \\ 0 & -R_{\perp} \end{bmatrix} \tag{3.25}$$

The minus sign for the perpendicular component polarisation is a result of the geometric convention that is used in backscattering , the *BSA (Backward Scattering Alignement)* convention[17, 18]. In the BSA-convention the coordinate system changes from right-handed to left-handed when the wave is scattered. This results in an inversion of the lower row of the scattering matrix (i.e. the "vertical direction" changes its sign for the scattered wave). This doesn't seem very important but it has to be taken into account when applying results of (forward) scattering theory to backscattering problems.

If the wave is traveling in free space or air than $\mu_1 = \mu_0$ and $\epsilon_1 = \epsilon_0$. For materials that are not ferro-magnetic $\mu_2 = \mu_0$.

Scattering by a dihedral corner reflector

A wave scattered from a dihedral corner reflector will undergo two reflections and return in the direction from which it came (fig 3.4).

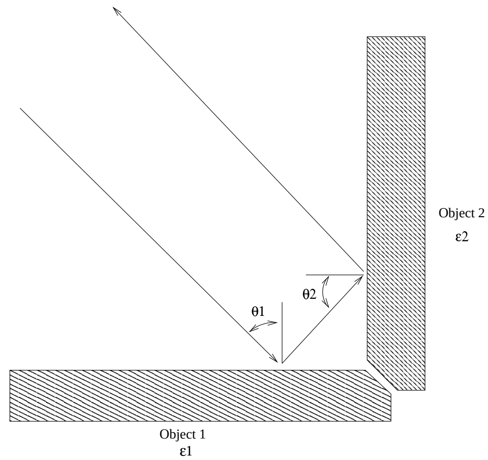

Figure 3.4: Scattering geometry for a dihedral reflector

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This backscattering geometry may be represented by the scattering matrix:

$$[S] = \begin{bmatrix} R_h(\xi_1,\theta_1)R_h(\xi_2,\theta 2) & 0 \\ 0 & -R_v(\xi_1,\theta_1)R_v(\xi_2,\theta 2) \end{bmatrix}, \tag{3.26}$$

where R_h and R_v are the Fresnel reflection coefficients for horizontal and vertical polarisation respectively. We thus assume the two surfaces of the dihedral to be relatively flat. This type of scattering can be found in villages as the so-called double-bounce scattering between the ground and the wall of a building or sometimes in forests between the ground and a tree trunk.

Dihedral corner reflectors are often used for radar calibration. In that case they are made of metal. This results in a scattering matrix of the form:

$$[S] = \sqrt{\sigma_D}\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}. \tag{3.27}$$

The double reflection thus results in a reversal of the vertical polarisation while the horizontal polarisation component remains unchanged.

This is the case where the reflector is placed with the intersection of its sides in the x,y-plane of the incident wave, i.e. perpendicular to the propagation direction of the wave. When the dihedral is rotated over an angle θ around the boresight direction we get [17, 19]:

$$[S] = \sqrt{\sigma_D}\begin{bmatrix} cos(2\theta) & sin(2\theta) \\ sin(2\theta) & -cos(2\theta) \end{bmatrix}. \tag{3.28}$$

In particular, when a dihedral is turned over 45^o it has the following scattering matrix:

$$[S] = \sqrt{\sigma_D}\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}, \tag{3.29}$$

which means that it will completely cross-polarise an incident linearly polarised wave (i.e. it produces a 90^o phase shift). Such corner reflectors are used for polarimetric calibration of a SAR system. σ_D is the radar scattering cross-section of a dihedral [19]:

$$\sigma_D = 8\pi \frac{a^2 b^2}{\lambda^2}, \tag{3.30}$$

with a and b the width and height of the rectangular plates of the corner reflector.

Scattering by a trihedral corner reflector

Trihedrals are also used as radar calibration objects. The scattering matrix of such a (metallic) corner reflector is:

$$[S] = \sqrt{\sigma_T} \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}. \tag{3.31}$$

A trihedral will thus introduce a 180^o phase shift, it inverses all linear polarisations. A trihedral corner reflector can have square or triangular sides. Their radar cross-sections are respectively [19]:

$$\sigma_{T,square} = 12\pi \tfrac{L^4}{\lambda^2} \quad \sigma_{T,triangle} = 4\pi \tfrac{L^4}{\lambda^2} \ . \tag{3.32}$$

3.6.2 Vectorisation of the Scattering Matrix

In the previous section elementary deterministic scatterers were discussed. The scattering behaviour of determistic scatterers can be described by a single constant scattering matrix S. In remote sensing applications the assumption of determistic scatterers is not valid. The signal received by the SAR system for a single resolution cell is composed of contributions of many spatially distributed scattering centres. Each of these centres is characterised by an individual scattering matrix S_i and the measured S matrix is a coherent superposition of these individual scattering matrices.

It is possible to write any scattering matrix as a linear combination of 4 orthonormal 2×2 basis matrices. The coefficients of this linear combination form a complex vector $\overrightarrow{k}$, called a target vector. It is thus possible to vectorise the scattering matrix in a given base of elementary matrices Ψ.

$$[S] = \sum_{i=1}^{4} k_i \, [\Psi_i] \, . \tag{3.33}$$

Several different basis sets have been used. Two important examples [20] are:

$$\Psi_L : \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}, \tag{3.34}$$

$$\Psi_P : \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}. \tag{3.35}$$

The set of basis matrices Ψ_P are called the Pauli (spin) matrices. Comparing them with the scattering matrices for elementary targets presented in section 3.6.1 it turns out that the first three Pauli matrices correspond respectively to the scattering matrix of a flat surface, a dihedral aligned in the x,y plane and a dihedral tilted by 45^o. The fourth one is physically impossible for backscattering (it would make $S_{hv} \neq S_{vh}$).

The target vectors have the following explicit form:

$$k_L = [S_{hh} \quad S_{hv} \quad S_{vh} \quad S_{vv}]^t \ , \tag{3.36}$$

and

$$k_P = [S_{hh} + S_{vv} \quad S_{hh} - S_{vv} \quad S_{hv} + S_{vh} \quad S_{hv} - S_{vh}]^t. \ . \tag{3.37}$$

For the backscattering case $S_{hv} = S_{vh}$ such that only three basis vectors are necessary. For Ψ_L the second or third can be dropped, for Ψ_P the last is dropped because its coefficient will always be zero. The outer product of the k_L and k_P vectors with their adjoint vector yields respectively the polarimetric *covariance matrix [C]* and the polarimetric *coherency matrix [T]* [1]:

$$[C] = < k_L.k_L^{*t} >= \begin{bmatrix} <\mid S_{hh} \mid^2> & < S_{hh}S_{hv}^* > & < S_{hh}S_{vv}^* > \\ < S_{hv}S_{hh}^* > & <\mid S_{hv} \mid^2> & < S_{hv}S_{vv}^* > \\ < S_{vv}S_{hh}^* > & < S_{vv}S_{hv}^* > & <\mid S_{vv} \mid^2> \end{bmatrix}, \tag{3.38}$$

$$[T] = < k_P.k_P^{*t} >= \begin{bmatrix} <\mid S_{hh}+S_{vv} \mid^2> & < (S_{hh}+S_{vv})(S_{hh}-S_{vv})^* > & 2 < (S_{hh}+S_{vv})S_{hv}^* > \\ < (S_{hh}-S_{vv})(S_{hh}+S_{vv})^* > & <\mid S_{hh}+S_{vv} \mid^2> & 2 < (S_{hh}-S_{vv})S_{hv}^* > \\ 2 < S_{hv}(S_{hh}-S_{vv})^* > & 2 < S_{hv}(S_{hh}-S_{vv})^* > & 4 < S_{hv}S_{hv}^* > \end{bmatrix}. \tag{3.39}$$

The $<>$ denote spatial ensemble averaging which assumes (local) homogeneity of the random scattering medium.

3.7 Polarimetric Radar Data

In remote sensing, an *horizontally polarised wave* is defined as a wave for which the electric field is horizontal (usually parallel to the observed scene). A vertically polarised wave is one for which the electric field vector is perpendicular to that direction. Most radars either emit a horizontally or a vertically polarised wave and measure the returned signal according to either of these two polarisation directions. The value of a pixel in the image is thus proportional to the corresponding element of the scattering matrix averaged over the area on the ground corresponding to that pixel. If the radar is calibrated the value of a pixel is equal to the element of the scattering matrix (averaged over the area corresponding to that pixel).

Conventional imaging radars operate with a single fixed-polarisation antenna for both transmission and reception. In this way a single scattering coefficient is measured for each resolution element in the image. This means that only a single element of the scattering

[1]Note that the definition of the coherency matrix is different from the definiton of optical coherence[21, 22]

matrix is measured and that any information about the surface contained in the polarisation properties of the reflected signals is lost. To retain all the information in the scattered wave the complete polarisation properties of the scattered wave must be measured.

A polarimetric radar has the possibility to send and receive both horizontally and vertically polarised radar waves. It alternatively sends horizontal polarisation and receives both vertical and horizontal polarisation and then, in the next pulse, it sends vertical polarisation and again measures the return for both polarisations. A polarimetric radar is thus capable of measuring the complete scattering matrix. The corresponding image set can have different formats [14]. The images we used were delivered in the *complex scattering matrix format*. This format consists of four (complex) images, corresponding to the four elements of the scattering matrix: $S_{HH}, S_{HV}, S_{VH}, S_{VV}$ two of which (i.e. the image of S_{HV}, S_{VH}) are identical.

3.8 Description of the Test Images

For the main part of this project an L-band polarimetric image of the E-SAR system of DLR (the German Aerospace Center) was used. It is an image of the airfield of Oberpfaffenhofen covering an area of approximately 2 $km \times 5$ km. Its main characteristics are listed in table 3.2 in the column labeled "Image 1". Near the end of the project we also received from DLR a set of two other L-band polarimetric images. These are both dual-pass interferometric images. The region on the image is smaller than the region covered by the first image (about 2.5 $km \times 2.5$ km).

Most of the results shown in this thesis are based on image 1. Image 2 will be used in the section describing the decomposition method of Cloude and Pottier (sect. 6.2.3) in order to show how the use of the interferometric coherence increases the results of the obtained image classification.

All processing described in this thesis was performed on the single-look slant-range images. Single-look images provide the highest spatial resolution at the expense of containing also the maximum strength of speckle.

Parameter	Units	Image 1	Image 2	Image 3
Acquistion Date		06/04/99	20/07/99	20/07/99
Acquisition Time		12h26	10h25	10h50
Polarimetric		Yes	Yes	Yes
Interferometric		No	Yes	Yes
Azimuth Pixel Spacing	[m]	0.467145	0.879152	0.879152
Azimuth Resolution	[m]	1.200	3	3
Range Pixel Spacing	[m]	1.49854	1.49854	1.49854
Range Resolution	[m]	1.49854	1.49854	1.49854
Image Width (range dir.)	[pixels]	1280	1540	1540
Image Height (azimuth dir.)	[pixels]	10350	2816	2816
Alt. above Mean Sea Level	[m]	3791.72	3872.33	3873.59
Average Terrain Elevation	[m]	580	625	625
Slant Range, Proc. Swath Start	[m]	3544	3584	3585
Slant Range, Proc. Swath End	[m]	5918	5974	5974
Platform Heading	[^{o}]	130.632	133.94436	43.550
GPS Longitude	[^{o}]	-	11.224686	11.283728
GPS Latitude	[^{o}]	-	48.073028	48.049798

Table 3.2: Main characteristics of the used E-SAR images

In figs. 3.5..3.7 the three images are shown. For the display, for each of the images, the logarithm of the intensity was linearly rescaled to the same range for all three polarisations. Then a color composite was made of the three components (HH:red, VV:green and HV:blue). Note that this is just one of many possible ways to display a polarimetric SAR image and that none of them is representative for the full information content of such images. Note also that the size of the image was rescaled for display purposes, in particular the width/height ratio of the original image (as given in the table) was not preserved.

As a reference, part of a topographic map corresponding to the area around the airfield of Oberpfaffenhofen is shown in fig. 3.8.

Figure 3.5: Test image 1: polarimetric L-Band image of the Oberpfaffenhofen airfield acquired by the E-SAR system on 06/04/1999 (©DLR).

Figure 3.6: Test image 2: dual-pass interferometric polarimetric L-Band image of the Oberpfaffenhofen airfield acquired by the E-SAR system on 20/07/1999 (©DLR).

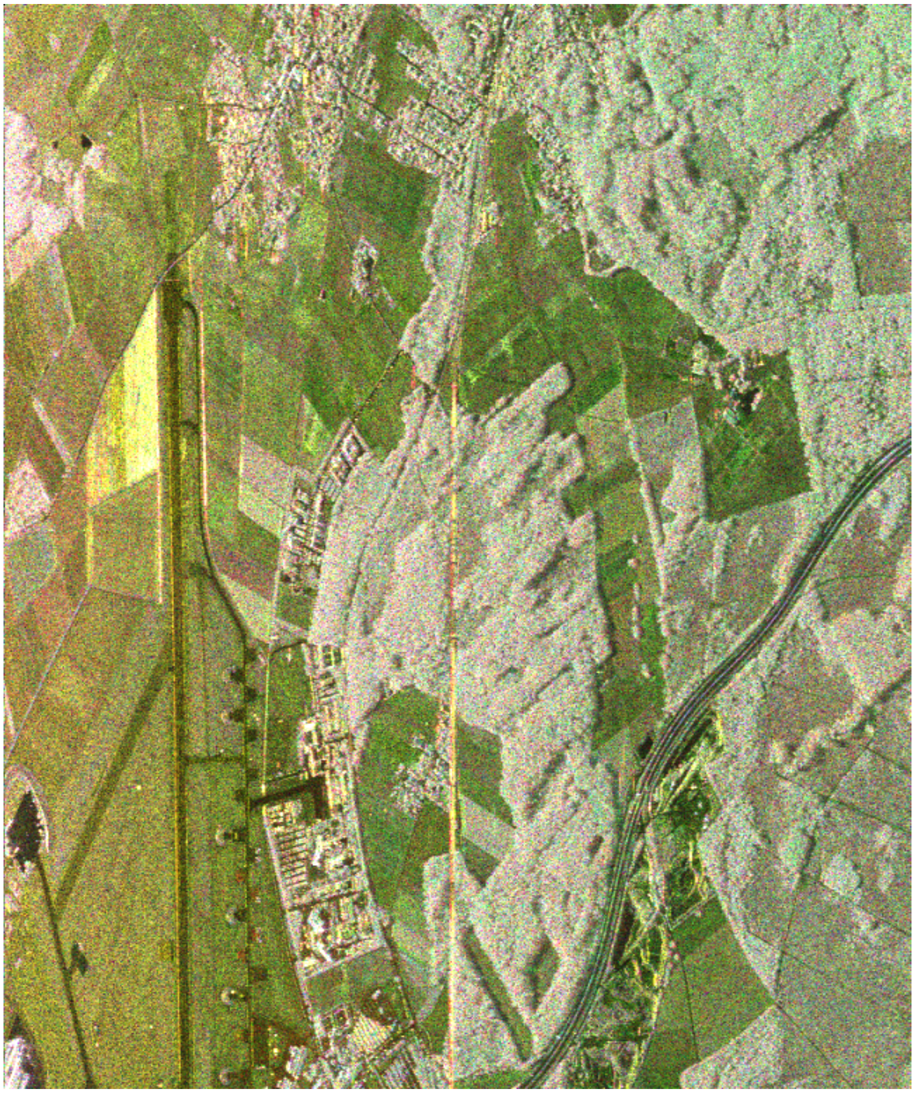

Figure 3.7: Test image 3: dual-pass interferometric polarimetric L-Band image of the Oberpfaffenhofen airfield acquired by the E-SAR system on 20/07/1999 (©DLR).

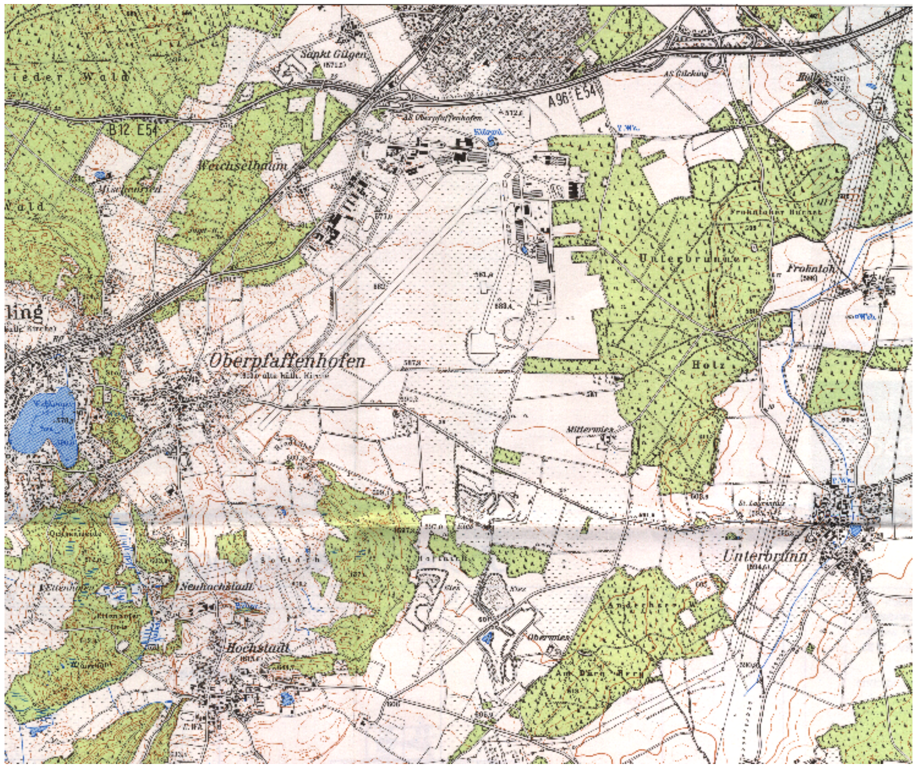

Figure 3.8: Topographic map of the area around Oberpfaffenhofen airfield (©Bayerishes Landesvermessungsamt).

3.9 Lessons Learned

A calibrated polarimetric SAR sensor provides the four elements of the complex scattering matrix. The scattering matrix thus represents all the polarimetric information delivered by the SAR system.

The same information can be represented under the form of the polarimetric covariance matrix or the polarimetric coherency matrix.

Different kinds of scattering result in different relations between the elements of the scattering matrix. It is therefore possible to derive information about the type of scattering by interpretation of the scattering matrix (or the covariance or coherency matrices). By relating the type of scattering to different possible kinds of land cover, it should thus be possible to develop an image classification method. Such an approach is followed by "polarimetric decompositon algorithm". Some of the existing polarimetric decomposition methods will be discussed in chapter 6.