Fully Polarimetric Radiometer System for Airborne Remote Sensing

Janne Lahtinen

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Ex minimis seminibus nascuntur ingentia

Lucius Annaeus Seneca jr.
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Preface

The work presented in this thesis was carried out in the Laboratory of Space Technology at Helsinki University of Technology (HUT) in Espoo, Finland, during 1996-2002 and in the Environmental Technology Laboratory of the U.S. National Oceanic and Atmospheric Administration (NOAA) in Boulder, Colorado, USA, during spring 1999. The thesis was finished while I was working for the European Space Agency’s European Space Research and Technology Centre (ESTEC) in Noordwijk, the Netherlands. All the papers presented in this thesis are closely related to the National Technology Agency of Finland’s (Tekes) project Novel microwave radiometer technologies in the remote sensing of the environment.

Professor Martti Hallikainen is acknowledged for providing me with the opportunity to carry out this work and for being my supervisor. I am grateful to dozens of colleagues at HUT, NOAA, ESTEC, and other institutes for the help they provided during the work. In particular, I thank the following individuals: Olli Koistinen, Irja Kurki, Ilkka Mononen, Jörgen Pihlflyckt, Jaan Praks, Kimmo Rautiainen, Markku Roschier, Pekka Rummukainen, Simo Tauriainen, and Heikki Valmu. Kimmo Rautiainen is also acknowledged for his poetry and limping jokes. Furthermore, I am indebted to Dr. Albin J. Gasiewski and Prof. Jouni Pulliainen for always having time for my questions and showing me what science is about. The pre-examiners professors Erkki Salonen and Christopher S. Ruf are thanked for constructive criticism.

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Finally, I thank my friends, parents, and parents-in-law for encouragement. My deepest gratitude, however, belongs to my wife Ulrike, for supporting me during the difficult periods.

Haarlem, the Netherlands, October 11, 2003

Janne Lahtinen
Abstract

As a result of the increasing interest in polarimetric microwave radiometer measurements, a fully polarimetric radiometer system was developed and thoroughly tested in this work. The system is primarily designed for airborne remote sensing; however, ground-based and laboratory measurements are possible as well. The feasibility of the system for remote sensing was demonstrated in laboratory measurements and in an airborne experiment. The system comprises a polarimetric radiometer at 36.5 GHz (the Fully Polarimetric Radiometer) and a passive calibration standard (the Fully Polarimetric Calibration Standard).

This work is the first successful demonstration of a polarimetric remote sensing radiometer that is based on analog direct cross-correlating architecture; analog multipliers were used as correlating elements. Compared to other possible polarimetric radiometer topologies, the applied solution possesses several advantages, e.g., the simple structure of both the receiver and the correlator, which is beneficial in terms of reliability, costs, mass, size, and power consumption.

A novel fully polarimetric end-to-end calibration technique was developed. The theoretical background of the technique is thoroughly studied, the mathematics necessary to determine the a priori Stokes vectors and error analysis are derived, and a calibration matrix inversion technique is presented. Using the principles presented, fully polarimetric calibration standards were developed at 10.6 GHz and 36.5 GHz and their function demonstrated. The uncertainties associated with the practical implementation of fully polarimetric calibration standards for wind vector remote sensing are discussed.

Using the developed radiometer system, an airborne experiment was conducted over the Gulf of Finland. Polarimetric dataset obtained for a semi-enclosed sea composed of brackish water is presented. The results suggest that the relationship between the wind vector and the Stokes parameters may vary locally.

Keywords: Calibration, correlators, polarimetry, radiometers, remote sensing, wind, wire grids
# List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>A/D</td>
<td>Analog-to-Digital</td>
</tr>
<tr>
<td>ASD</td>
<td>Allan Standard Deviation</td>
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<tr>
<td>ECL</td>
<td>Emitter Coupled Logic</td>
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<tr>
<td>EMIRAD</td>
<td>Electromagnetics Institute Radiometer</td>
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<td>ESMR</td>
<td>Electrically Scanning Microwave Radiometer</td>
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<tr>
<td>ETL</td>
<td>Environmental Technology Laboratory</td>
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<td>FPCS</td>
<td>Fully Polarimetric Calibration Standard</td>
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<tr>
<td>FPoR</td>
<td>Fully Polarimetric Radiometer</td>
</tr>
<tr>
<td>HUT</td>
<td>Helsinki University of Technology</td>
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<tr>
<td>HUTRAD</td>
<td>Helsinki University of Technology Radiometer</td>
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<tr>
<td>IF</td>
<td>Intermediate Frequency</td>
</tr>
<tr>
<td>IKI</td>
<td>Space Research Institute</td>
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<tr>
<td>IPO</td>
<td>Integrated Program Office</td>
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<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
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<tr>
<td>KAPOL</td>
<td>Ka Band Polarimeter</td>
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<tr>
<td>LF</td>
<td>Low Frequency</td>
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<tr>
<td>MARSS</td>
<td>Microwave Airborne Radiometer Scanning System</td>
</tr>
<tr>
<td>NAMR</td>
<td>Nadir-looking Airborne Multichannel Radiometer</td>
</tr>
<tr>
<td>NOAA</td>
<td>U.S. National Oceanic and Atmospheric Administration</td>
</tr>
<tr>
<td>NPOESS</td>
<td>U.S. National Polar-Orbiting Environmental Satellite System</td>
</tr>
<tr>
<td>PSR</td>
<td>Polarimetric Scanning Radiometer</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>SSB</td>
<td>Single Side-Band</td>
</tr>
<tr>
<td>SSM/I</td>
<td>Special Sensor Microwave Imager</td>
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List of Symbols

$B_{bb}$ brightness of a blackbody

$B_n$ equivalent predetection noise bandwidth

$\bar{C}_{b,0}$ brightness data matrix

$\bar{C}_0$ Stokes vector column matrix

$D_3$ degradation factor of the radiometer channel that measures the third Stokes parameter

$D_4$ degradation factor of the radiometer channel that measures the fourth Stokes parameter

$\overline{E}(t)$ electric field vector as a function of time

$\overline{E}_R(t)$ electric field vector as a function of time, generated by the thermal emission of a retardation plate

$E_{R,h}(t)$ electric field for horizontal polarization as a function of time, generated by the thermal emission of a retardation plate

$E_{R,v}(t)$ electric field for vertical polarization as a function of time, generated by the thermal emission of a retardation plate

$\overline{E}_{R,x}(t)$ electric field vector for the $x$-direction as a function of time, generated by the thermal emission of a retardation plate

$E_{R,x0}(t)$ amplitude of an electric field for the $x$-direction as a function of time, generated by the thermal emission of a retardation plate

$\overline{E}_{R,y}(t)$ electric field vector for the $y$-direction as a function of time, generated by the thermal emission of a retardation plate

$E_{R,y0}(t)$ amplitude of an electric field for the $y$-direction as a function of time, generated by the thermal emission of a retardation plate

$E_{R0||}$ amplitude of an electric field in parallel with the slow axis of a retardation plate, generated by the thermal emission of the plate

$E_{R0,\perp}$ amplitude of an electric field perpendicular to the slow axis of a retardation plate, generated by the thermal emission of the plate

$E_h$ electric field for horizontal polarization

$E_v$ electric field for vertical polarization
\( \overline{E}_x(t) \) electric field vector for the \( x \)-direction as a function of time

\( E_x'(t) \) electric field for the \( x \)-direction as a function of time after passing a retardation plate

\( E_{x0} \) amplitude of an electric field for the \( x \)-direction

\( E_{x0}(t) \) amplitude of an electric field for the \( x \)-direction as a function of time

\( \overline{E}_y(t) \) electric field vector for the \( y \)-direction as a function of time

\( E_y'(t) \) electric field for the \( y \)-direction as a function of time after passing a retardation plate

\( E_{y0} \) amplitude of an electric field for the \( y \)-direction

\( E_{y0}(t) \) amplitude of an electric field for the \( y \)-direction as a function of time

\( E_{||}(t) \) electric field as a function of time after passing a retardation plate, in parallel with the slow axis of the plate

\( E_\perp(t) \) electric field as a function of time after passing a retardation plate, perpendicular to the slow axis of the plate

\( I \) the first Stokes parameter in brightness temperature

\( K \) factor for radiometer configuration

\( L_{||} \) ohmic power losses of a polarizing grid in parallel with grid wires

\( L_\perp \) ohmic power losses of a polarizing grid perpendicular to grid wires

\( M \) the number of applied brightness temperature scenes in calibration

\( T_B \) brightness temperature

\( \overline{T}_B \) Stokes vector

\( T_{B}(\theta,\phi) \) brightness temperature with directional dependency \( (\theta,\phi) \)

\( T_{COLD} \) brightness temperature of a hot blackbody target

\( T_G \) physical temperature of a polarizing grid

\( T_{HOT} \) brightness temperature of a hot blackbody target

\( T_P \) physical temperature

\( T_{P,R} \) physical temperature of a phase retardation plate

\( \overline{T}_R \) Stokes vector of a phase retardation plate

\( T_{R,h} \) brightness temperature of a retardation plate for horizontal polarization

\( T_{R,v} \) brightness temperature of a retardation plate for vertical polarization

\( T_{R,3} \) third Stokes parameter of a retardation plate
$T_{R,4}$ fourth Stokes parameter of a retardation plate

$T_{R,||}$ brightness temperature of a retardation plate in parallel with the slow axis of the plate

$T_{R,\perp}$ brightness temperature of a retardation plate perpendicular to the slow axis of the plate

$T_{SYS}$ system noise temperature of a radiometer channel

$\bar{T}_T$ tri-polarimetric Stokes vector

$T_{cl}$ brightness temperature for left-hand circular polarization

$T_{cr}$ brightness temperature for right-hand circular polarization

$T_h$ brightness temperature for horizontal polarization, also called the second modified Stokes parameter in brightness temperature

$T_{h0}$ the mean brightness temperature of the sea for horizontal polarization over a full circle of azimuth

$T_v$ brightness temperature for vertical polarization, also called the first modified Stokes parameter in brightness temperature

$T_{v0}$ the mean brightness temperature of the sea for vertical polarization over a full circle of azimuth

$T_3$ third Stokes parameter in brightness temperature

$T_4$ fourth Stokes parameter in brightness temperature

$T_{45}$ brightness temperature for $+45^\circ$ linear polarization

$T_{-45}$ brightness temperature for $-45^\circ$ linear polarization

$U$ third Stokes parameter in brightness temperature

$V$ fourth Stokes parameter in brightness temperature

$Q$ second Stokes parameter in brightness temperature

$Q_c$ degradation factor of a correlator due to quantization

$a_{h1}$ first-order harmonic coefficient for the brightness temperature of the sea at horizontal polarization

$a_{h2}$ second-order harmonic coefficient for the brightness temperature of the sea at horizontal polarization

$a_{v1}$ first-order harmonic coefficient for the brightness temperature of the sea at vertical polarization
second-order harmonic coefficient for the brightness temperature of the sea at vertical polarization

first-order harmonic coefficient for the third Stokes parameter of the sea

second-order harmonic coefficient for the third Stokes parameter of the sea

first-order harmonic coefficient for the fourth Stokes parameter of the sea

second-order harmonic coefficient for the fourth Stokes parameter of the sea

e(θ,φ) emissivity with directional dependency (θ,φ)

\( \bar{g} \) gain estimate matrix of a polarimetric radiometer

\( g_{hh} \) the gain parameter of the horizontal channel of a radiometer

\( g_{hv} \) the gain parameter of a radiometer describing the coupling from the vertical to the horizontal channel

\( g_{h3} \) the gain parameter of a radiometer describing the coupling from the channel measuring the third Stokes parameter to the horizontal channel

\( g_{h4} \) the gain parameter of a radiometer describing the coupling from the channel measuring the fourth Stokes parameter to the horizontal channel

\( g_{vv} \) the gain parameter of the vertical channel of a radiometer

\( g_{vh} \) the gain parameter of a radiometer describing the coupling from the horizontal to the vertical channel

\( g_{v3} \) the gain parameter of a radiometer describing the coupling from the channel measuring the third Stokes parameter to the vertical channel

\( g_{v4} \) the gain parameter of a radiometer describing the coupling from the channel measuring the fourth Stokes parameter to the vertical channel

\( g_{33} \) the gain parameter of a radiometer channel that measures the third Stokes parameter

\( g_{3v} \) the gain parameter of a radiometer describing the coupling from the vertical channel to the channel that measures the third Stokes parameter

\( g_{3h} \) the gain parameter of a radiometer describing the coupling from the horizontal channel to the channel that measures the third Stokes parameter

\( g_{34} \) the gain parameter of a radiometer describing the coupling from the channel that measures the fourth Stokes parameter to the channel measuring the third Stokes parameter
\( g_{44} \) the gain parameter of a radiometer channel that measures the fourth Stokes parameter
\( g_{4v} \) the gain parameter of a radiometer describing the coupling from the vertical channel to the channel that measures the fourth Stokes parameter
\( g_{4h} \) the gain parameter of a radiometer describing the coupling from the horizontal channel to the channel that measures the fourth Stokes parameter
\( g_{43} \) the gain parameter of a radiometer describing the coupling from the channel that measures the third Stokes parameter to the channel measuring the fourth Stokes parameter
\( k_B \) Boltzmann’s constant (= 1.38×10\(^{-23}\) J·K\(^{-1}\))
\( l_{||} \) loss of a phase retardation plate in parallel with the slow axis
\( l_{\perp} \) loss of a phase retardation plate perpendicular to the slow axis
\( \bar{n} \) random noise of a radiometer referred to video outputs
\( \bar{o} \) offset estimate vector of a polarimetric radiometer
\( o_h \) the offset parameter of the horizontal channel of a radiometer
\( o_v \) the offset parameter of the vertical channel of a radiometer
\( o_3 \) the offset parameter of the radiometer channel that measures the third Stokes parameter
\( o_4 \) the offset parameter of the radiometer channel that measures the third Stokes parameter
\( r_c \) radiometer signal output matrix in calibration
\( \bar{r} \) video output response vector of a radiometer
\( r_h \) video output response of the horizontal channel of a radiometer
\( r_v \) video output response of the vertical channel of a radiometer
\( r_3 \) video output response of the radiometer channel measuring the third Stokes parameter
\( r_4 \) video output response of the radiometer channel measuring the fourth Stokes parameter
\( \eta_{||} \) power reflection coefficient of a polarizing grid in parallel with grid wires
\( \eta_{\perp} \) power reflection coefficient of a polarizing grid perpendicular to grid wires
\( t \) time
$t_{||}$ power transmission coefficient of a polarizing grid in parallel with grid wires

$t_{\perp}$ power transmission coefficient of a polarizing grid perpendicular to grid wires

$\mathbf{u}_x$ unit vector for the $x$-direction

$\mathbf{u}_y$ unit vector for the $y$-direction

$\Delta G/G_0$ normalized root-mean-square fluctuations of radiometer system gain

$\Delta \mathbf{T}_B$ Stokes uncertainty matrix of a scene

$\Delta \mathbf{T}_C$ Stokes uncertainty matrix in calibration

$\Delta T_h$ radiometric resolution of the horizontal channel of a radiometer

$\Delta T_v$ radiometric resolution of the vertical channel of a radiometer

$\Delta T_3$ radiometric resolution of the radiometer channel that measures the third Stokes parameter

$\Delta T_4$ radiometric resolution of the radiometer channel that measures the fourth Stokes parameter

$\Delta f$ bandwidth

$\zeta$ relative phase shift between the fast and slow axes of a biaxial phase retardation plate

$\eta$ wave impedance of a medium

$\theta$ rotation angle of a linearly polarized calibration standard

$(\theta, \phi)$ angular variables in a spherical coordinate system

$\lambda$ wavelength

$\tau$ integration time

$\varphi$ rotation angle of a biaxial phase retardation plate

$\phi$ phase difference between electromagnetic radiation in the $y$- and $x$-axes

$\phi(t)$ phase difference between electromagnetic radiation in the $y$- and $x$-axes as a function of time

$\phi_w$ relative azimuth angle to wind

$\omega$ radian frequency
List of Appended Papers

This thesis is based on the work contained in the following publications, hereafter referred to as publications [P1] to [P5]:


In publication [P1], the design work to upgrade the NOAA linearly polarized calibration standard into a fully polarimetric standard was carried out by J. Lahtinen. The construction of the standard and the design of the calibration experiment were carried out by J. Lahtinen with advisement from Dr. A. J. Gasiewski. The experimental setup was prepared by J. Lahtinen and Dr. M. Klein; Drs. Gasiewski and Klein were responsible for providing the PSR instrument. The actual calibration experiment was
conducted by J. Lahtinen and Prof. I. Corbella. The processing of the data was conducted by J. Lahtinen with some assistance from Prof. I. Corbella. The manuscript was outlined jointly by J. Lahtinen and Dr. Gasiewski, and prepared by J. Lahtinen with editorial assistance from Dr. Gasiewski.

In publications [P2] and [P3] the research work was carried out by J. Lahtinen, who acted alone and also prepared the manuscripts.

Publication [P4] was initiated by O. Koistinen, who also designed the setup to measure the phase and amplitude responses of the correlators. The mixer based correlator was designed, constructed, and tested by O. Koistinen, the analog multiplier-based correlator by J. Lahtinen. The manuscript was prepared in close cooperation between O. Koistinen and J. Lahtinen. O. Koistinen had the main responsibility for Section III.A, the discussion on the measurement methods in Section IV, and the general conclusions in Section V. Furthermore, the description of the design, the description of the measurement results, and the conclusions with regard to the mixer-based correlator are also mainly contributed by him. J. Lahtinen had the chief responsibility for Section II. In addition, the description of the design, the description of the measurement results, and the conclusions with regard to the analog multiplier-based correlator are also mainly contributed by him.

In publication [P5], the RF system, IF system, and correlator system of the receiver were developed by J. Lahtinen; the LF electronics system was developed by I. Mononen on the basis of a design by J. Pihlflyckt. The mechanical support structure of the radiometer was designed by Dr. M. Kemppinen, the software was developed by J. Pihlflyckt, and the temperature stabilization system by J. Pihlflyckt, with some help from I. Mononen. With regard to the associated subsystems of the HUTRAD, the Power and Control Unit was developed jointly by J. Pihlflyckt and I. Mononen and the Operator Interface Assembly by J. Pihlflyckt. The laboratory experiments were conducted and the data were analyzed by J. Lahtinen. The airborne experiment was planned and conducted in close cooperation with J. Lahtinen and S. Tauriainen; the data were analyzed by J. Lahtinen. The manuscript was prepared by J. Lahtinen.
The development of the HUT polarimetric radiometer system was initiated by Prof. M. Hallikainen, who also acted as scientific advisor and provided editorial assistance in preparing publications [P2]-[P5].
1 Introduction

In situ measurements are often expensive or impractical as a means of acquiring information on the properties of land, sea, and atmosphere. Therefore, several airborne and spaceborne remote sensing techniques have been developed; large areas can be covered quickly and in a cost-efficient way, which is important in, for instance, the monitoring of global processes. Based on sensor frequency, remote sensing is divided into two main fields: optical remote sensing, which covers wavelengths from approximately 0.3 to 14 µm, and microwave remote sensing, which covers frequencies from approximately 300 MHz to 300 GHz (this frequency range equals the wavelengths between 1 mm and 1 m) [Lillesand and Kiefer, 2000]. In addition, remote sensing techniques can be either active or passive. For example, radar is an active microwave instrument, whereas a photographic camera without a flashlight is a passive optical instrument. Passive microwave instruments are called microwave radiometers. For the sake of simplicity, the term radiometer is used for microwave radiometer in this work.

A radiometer is a sensitive receiver that measures radiated electromagnetic power; in remote sensing, this power is, in most cases, noise-like thermal radiation. Microwave radiometry has several benefits compared to optical remote sensing; the measurements are independent of lighting conditions and remain relatively undisturbed by clouds, fog, and light rain. Furthermore, penetration depth increases with increasing wavelength and microwaves therefore also provide sub-surface information about target characteristics. Compared to radar, radiometers are cost-effective and require less electrical power, which is important in spaceborne applications. The applications of airborne and/or spaceborne radiometers include, for instance, the determination of atmospheric parameters (e.g., [Rosenkranz, 2001]) and snow water equivalent (e.g., [Pulliainen et al., 1999]), the classification of sea ice types (e.g., [Kurvonen and Hallikainen, 1996]), and the retrieval of forest stem volume (e.g., [Grandell et al., 1998]) and near-surface wind speed in oceanic regions (e.g., [Goodberlet et al., 1989]).

The use of microwave radiometers for remote sensing dates back to the 1940s; the first measurements were most probably those of Dicke et al. [1946] on atmosphere. About a decade later, Straiton et al. [1958] made measurements on several terrestrial materials (water, wood, metal, grass, asphalt, gravel, and asbestos); this seems to have
been the first attempt to measure Earth’s surface by means of radiometers. A major step forward, however, was the development of the first airborne and spaceborne instruments in the 1960s, (e.g., [Hach, 1968; Nordberg et al., 1969; Gurvich and Demin, 1970; Hoover and Moore, 1971]); the first imaging radiometer on Earth orbit was ESMR in 1972 [Kramer, 1996]. After these pioneering steps, several spaceborne systems have been developed. For example, the series of SSM/I instruments has provided continuous data since 1987 [Hollinger et al., 1990]. Furthermore, numerous airborne systems have been developed for different applications, e.g., EMIRAD in the 1970s [Skou, 1989], MARSS in the 1980s [Kramer, 1996], and HUTRAD in the 1990s [Hallikainen et al., 1998]).

Until recently, remote sensing radiometers were mostly used to detect thermal emission at vertical and/or horizontal polarizations. As discussed in Section 3.4, however, supplementary information on quite a few targets can be obtained by determining the polarization characteristics of the emission. Radio astronomy has taken advantage of such polarimetric microwave measurements since as long ago as the end of the 1950s [Mayer et al., 1957; Akabane, 1958]. During the last decade the remote sensing community too has adopted the polarimetric technique; the first polarimetric radiometers for ground-based and airborne measurements were completed in early 1990s [Dzura et al., 1992; Gasiewski and Kunkee, 1993; Yueh et al. 1995]. The applicability of polarimetric radiometry is due to the linearly and/or circularly polarized thermal emission component of certain targets, e.g., periodic surfaces. Currently, the measurement of maritime wind vectors is one of the most promising applications (e.g., [Yueh et al., 1999; Piepmeier and Gasiewski, 2001a; Laursen and Skou, 2001]); global wind vector measurement from space would give valuable information for many meteorological, climatological, and oceanographic studies. The feasibility of radiometers for maritime wind measurements is based on the modulation of sea emissivity by wave height and orientation, which in turn is related to near-surface wind speed and direction. Besides spaceborne measurements, airborne measurements are needed for the calibration and validation of spaceborne instruments, for the development of retrieval algorithms, and for the production of regional high-resolution maps. It should be noted that global wind vector maps can also be retrieved using spaceborne microwave scatterometers, as demonstrated by Jones et al. [1982]. However, scatterometers require significant electric power and complex on-board
signal processing hardware (e.g., [Naderi et al., 1991]) and the use of radiometers would thus provide significant benefits in terms of system complexity and costs. Furthermore, the wind vectors retrieved from scatterometer data suffer from directional ambiguities (e.g., [Figa and Stoffelen, 2000]), which, at least in theory, could be avoided using polarimetric radiometers. The spatial resolution of spaceborne scatterometers and radiometers is, however, in the same range [Grandell, 2000].

A polarimetric radiometer (also called a polarimeter) can be constructed using various receiver architectures, each solution having its own benefits and weaknesses. During recent years several tri-polarimetric and fully polarimetric airborne radiometers have been developed to measure, respectively, three or all four of the so-called Stokes parameters at a time. In the current stage of research, however, the feasibility for remote sensing applications of all the potential receiver architectures has not yet been demonstrated; this would be required to compare the trade-offs associated with different techniques. Furthermore, relatively little has been published on the calibration of polarimetric radiometers. A fundamental work in this area is the study by Gasiewski and Kunkee [1993], which introduced a linearly polarized standard to calibrate the first three Stokes parameters. However, the study did not address the calibration of the fourth Stokes parameter.

The main objectives of this study were: first, the development and demonstration of an airborne fully polarimetric radiometer at 36.5 GHz using the analog direct cross-correlation technique; second, the development of an accurate calibration method for fully polarimetric radiometers in general, and third, the development and demonstration of a calibration standard for the developed fully polarimetric radiometer.
2 Theoretical Background

2.1 Brightness Temperature and Stokes Parameters

All physical objects emit thermal radiation in the form of electromagnetic waves. Under thermal equilibrium the physical temperature of an object is constant, which means that the object radiates and absorbs energy at the same rate. A good absorber is thus a good radiator and vice versa. A perfect absorber is called a blackbody, and it follows that it is a perfect radiator as well. Planck’s radiation law gives the brightness of a blackbody, but at microwave frequencies the linear Rayleigh-Jeans law gives an applicable estimation \[ Ulaby et al., 1981 \]:

\[
B_{bb} = \frac{2k_B T_p}{\lambda^2} \Delta f, \tag{1}
\]

where \( k_B \) is Boltzmann’s constant, \( T_p \) is the physical temperature, \( \lambda \) is the wavelength, and \( \Delta f \) is the bandwidth. Although good approximations can be manufactured for a limited frequency range, no perfect blackbodies exist in practice: a physical object radiates less than a blackbody at the same physical temperature. The emissivity \( e(\theta, \phi) \) of an object, which is dependent on the angular variables \( \theta \) and \( \phi \), is defined as the ratio between the brightness of the object and that of a blackbody at the same physical temperature. In passive microwave remote sensing the observed power is expressed as brightness temperature \( T_b(\theta, \phi) \) (in Kelvin), which is the product of the emissivity of a target and its physical temperature \[ Ulaby et al., 1981 \]:

\[
T_b(\theta, \phi) = e(\theta, \phi) \cdot T_p \tag{2}
\]

The polarization of electromagnetic radiation can be completely described by four parameters. In remote sensing it is common to apply the so-called modified Stokes parameters \[ Tsang et al., 1985 \]. The first and second parameters represent, respectively, the root-mean-square (rms) flux density within vertical and horizontal polarizations (henceforth called orthogonal polarizations). The third and fourth parameters represent the complex coherence between the first two parameters.
representing, respectively, the linearly and circularly polarized components of the flux density. Considering the compatibility of the terminology with microwave radiometry in general, however, it is convenient to describe the parameters as modified Stokes parameters in brightness temperature. Since this term is somewhat lengthy, the term \textit{Stokes parameters} is used henceforth in this work for \textit{modified Stokes parameters in brightness temperature} unless otherwise indicated. Similarly, the term \textit{Stokes vector} is used for \textit{modified Stokes vector in brightness temperature}.

The Stokes vector is the vector-valued representation of the Stokes parameters. Under the Rayleigh-Jeans approximation the polarimetric characteristics of the full Stokes vector can be represented by (e.g., [Yueh et al., 1999]):

$$
\bar{T}_b = \begin{bmatrix} T_v \\ T_h \\ T_3 \\ T_4 \end{bmatrix} = \begin{bmatrix} T_v \\ T_h \\ T_{45} - T_{-45} \\ T_{cl} - T_{cr} \end{bmatrix} = \frac{\lambda^2}{k_h \cdot \eta} \begin{bmatrix} \langle |E_v|^2 \rangle \\ \langle |E_h|^2 \rangle \\ 2 \cdot \text{Re}\langle E_v E_h^* \rangle \\ 2 \cdot \text{Im}\langle E_v E_h^* \rangle \end{bmatrix}, \quad (3)
$$

where \(T\) is the brightness temperature, \(\eta\) the wave impedance of the medium, and \(E\) the electric field per unit bandwidth (V·m⁻¹·Hz⁻¹/²). The subscripts \(v, h, 3,\) and \(4\) refer, respectively, to the first, second, third, and fourth Stokes parameters, and subscripts \(45, -45, cl,\) and \(cr\) refer to \(+45^\circ\) linear, \(-45^\circ\) linear, left-handed, and right-handed circularly polarized brightness temperatures, respectively. Note that some research groups in the remote sensing community also use the “unmodified” Stokes parameters (in brightness temperature), traditionally applied in radio astronomy. In this case, the full Stokes vector is represented by (e.g., [Skou et al., 1999]):

$$
\bar{T}_b = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} T_v + T_h \\ T_v - T_h \\ T_{45} - T_{-45} \\ T_{cl} - T_{cr} \end{bmatrix} = \frac{\lambda^2}{k_h \cdot \eta} \begin{bmatrix} \langle |E_v|^2 \rangle + \langle |E_h|^2 \rangle \\ \langle |E_v|^2 \rangle - \langle |E_h|^2 \rangle \\ 2 \cdot \text{Re}\langle E_v E_h^* \rangle \\ 2 \cdot \text{Im}\langle E_v E_h^* \rangle \end{bmatrix}, \quad (4)
$$
As can be seen in Eq. (3) (and in Eq. (4)), there are two equivalent definitions for the third and fourth Stokes parameters. Accordingly, the different receiver architectures of polarimetric radiometers fall into two main categories: polarization combining radiometers (also called adding polarimetric radiometers) and correlating polarimetric radiometers. Polarization combining radiometers (e.g., \cite{Yueh1995}) require the incoherent detection of at least four principal polarizations along with post-detection differencing. Correlating polarimeters (e.g., \cite{Piepmeier2001b}), on the other hand, require coherent cross-correlation of the signals at two orthogonal polarizations. The correlation can be performed using an adding analog cross-correlator or a direct correlating analog or digital cross-correlator.

### 2.2 Calibration and Absolute Accuracy

The relationship between the response of a radiometer and the input signal is manifested by calibration. A widely used calibration technique, two-point calibration, is based on the measurement of two distinct power levels \cite{Ulaby1981}. This calibration technique makes possible the retrieval of any antenna temperature, provided that the radiometer is sufficiently linear, the antenna losses are accounted for, and there is no significant cross-talk (signal leakage) between the channels of the radiometer. The relationship between the radiometer response and the brightness temperature of the scene (weighted over the antenna pattern) can now be expressed by a simple linear model \cite{Ulaby1981}; using a matrix representation and including the instrument random noise, this relationship is, for a two-channel (vertical and horizontal polarizations) radiometer:

\[
\mathbf{r} = \begin{bmatrix} r_v \\ r_h \end{bmatrix} = \begin{bmatrix} g_{vv} & 0 \\ 0 & g_{hh} \end{bmatrix} \begin{bmatrix} T_v \\ T_h \end{bmatrix} + \begin{bmatrix} o_v \\ o_h \end{bmatrix} + \mathbf{n} = \mathbf{g} \mathbf{T} + \mathbf{o} + \mathbf{n},
\]

where \( \mathbf{r} \) is the video output response vector, \( \mathbf{g} \) and \( \mathbf{o} \) consist of the radiometer gain and offset parameters, and \( \mathbf{n} \) is the instrument random noise referred to the video outputs. The aforementioned requirements for the application of Eq. (5) are justified in general, provided that the receiver is well designed and an end-to-end calibration is applied. The effect of interchannel cross-talk, however, can be noticeable and should be...
considered for certain brightness temperature scenes and/or when very high calibration accuracy is required [P1]. With regard to polarimetric radiometry, the level of the orthogonal signals of natural remote sensing targets is typically at least one or two orders of magnitude higher than the level of the polarized signals. The interchannel cross-talk may thus generate a strong response in the channels that measure the third and fourth Stokes parameters. In addition, the cross-talk between the orthogonal channels (i.e., the channels that measure the thermal emission at vertical and horizontal polarizations) may also generate significant error terms, e.g., in maritime wind vector measurements, as the brightness temperatures of orthogonal polarizations have a high contrast. Although often neglected in conventional radiometric measurements, the cross-talk has thus to be accounted for in polarimetric radiometry due to its potentially dramatic influence.

The relationship between the brightness temperature scene and the response of a fully polarimetric radiometer can be expressed as [P1]:

\[
\begin{bmatrix}
    r_v \\
    r_h \\
    r_3 \\
    r_4
\end{bmatrix}
= \begin{bmatrix}
g_{vv} & g_{vh} & g_{v3} & g_{v4} \\
g_{hv} & g_{hh} & g_{h3} & g_{h4} \\
g_{3v} & g_{3h} & g_{33} & g_{34} \\
g_{4v} & g_{4h} & g_{43} & g_{44}
\end{bmatrix}
\begin{bmatrix}
T_v \\
T_h \\
T_3 \\
T_4
\end{bmatrix}
+ \begin{bmatrix}
o_v \\
o_h \\
o_3 \\
o_4
\end{bmatrix}
+ n = gT_b + + n. \tag{6}
\]

The off-diagonal elements of \( g \) represent interchannel cross-talk, generated by the non-idealities of the radiometer [P1]. A fully polarimetric calibration is based on a set of reference Stokes vectors that are presented to the antenna or injected into receiver chains. In order to determine the unknown gain and offset elements in Eq. (6), the set of reference vectors must fulfill two requirements: first, the observed brightness temperatures must be capable of being determined \textit{a priori} with adequate precision and second, the number of observed linearly independent Stokes vectors must be greater than or equal to the number of gain/offset unknowns for each channel [P1]. In the fully polarimetric case the minimum number of linearly independent reference Stokes vectors is five, assuming that no unknown gain or offset parameters can be predetermined and held fixed by other methods [P1]. Note that depending on the applied receiver architecture, the applicable calibration interval of a radiometer may be limited by the stability of its gain and offset terms, although some efforts have been
made to compensate for the variations that are generated by temperature fluctuations [Skou, 1989; de Maagt et al., 1992].

Since the polarized brightness temperature components of natural targets are typically only a few Kelvin, e.g., in the detection of maritime wind vectors, stringent requirements are set for the absolute accuracy of the polarimetric measurements [Piepmeier, 1999], [P1]. Calibration and the associated uncertainties play an important role with regard to the absolute accuracy of a radiometer. Besides calibration errors, however, several other factors can degrade the accuracy. Since some of them are dependent on the configuration of the equipment, it is difficult to give a complete list of all factors. When estimating the absolute accuracy of radiometer data, however, at least the following aspects should be considered, insofar as they are relevant to the radiometer configuration under study: calibration uncertainties (including cross-talk between channels), the instabilities of the receiver, the non-idealities of the antenna beam, stray radiation from outside the target (e.g., from anthropogenic sources and reflections from the platform structure), fluctuations in the physical temperature of the antenna, variations in antenna reflector losses over time, the non-linearity of the receiver, errors in compensating for polarization mixing and variations of the angle of incidence of the antenna beam (due platform motion), and scanning geometry.

2.3 Radiometric Resolution

Besides absolute accuracy, radiometric resolution (often called radiometric sensitivity) is another important parameter in remote sensing radiometry. Radiometric resolution is the measure of the signal-to-noise ratio of a radiometer; it equals the smallest change in antenna temperature that is detectable by the receiver. The radiometric resolution of the orthogonal channels of a total power radiometer is [Tiuri, 1964]:

\[
\Delta T_{v/h} = T_{\text{SYS,v/h}} \cdot \left( \frac{1}{B_n \cdot \Delta \tau} + \left( \frac{\Delta G}{G_0} \right)^2 \right)^{-1},
\]

(7)

\(^1\) The term radiometric sensitivity is somewhat misleading considering the definition of sensitivity in general [ISO, 1993].
where $T_{\text{SYS},v}$ and $T_{\text{SYS},h}$ are the system noise temperatures of the vertical and horizontal channels, respectively, $B_n$ is the equivalent predetection noise bandwidth of a channel, $\tau$ is the postdetection integration time, and $\Delta G/G_0$ represents the normalized rms fluctuations of system gain. The system noise temperature is the sum of the antenna temperature and receiver noise temperature. Note that in practice a total power radiometer requires periodic calibration to suppress gain variations, which degrades the radiometric resolution [Hersmann and Poe, 1981]. If the gain variations are not accounted for, the theoretical radiometric resolution of a Dicke radiometer [Dicke, 1946], which employs continuous switching between the antenna and a reference load, is degraded by a factor of two compared to a total power radiometer [Tiuri, 1964]². On the other hand, the Dicke-configuration removes the effect of receiver noise fluctuations and greatly reduces the effect of gain variations; the calibration interval can thus be increased. The theoretical radiometric resolution of balanced Dicke radiometers (also called noise injection radiometers) is approximately equal to that of a standard Dicke radiometer; the effect of both gain and receiver noise fluctuations, however, is now completely cancelled [Tiuri, 1964]. Note that since many RF components have non-negligible temperature coefficients associated with them, the physical temperature of a total power or a standard Dicke-receiver should be stable between two consecutive calibrations in order to minimize $\Delta G/G_0$.

Since the polarized signals of natural targets are small, typically less than 5 K, (e.g., [Yueh et al., 1999; Camps et al., 2000; Piepmeier and Gasiewski, 2001a]), the importance of radiometric resolution is actually emphasized in polarimetric remote sensing radiometry. Considering first the polarization combining radiometer architecture, the radiometric resolution of the measured third and fourth Stokes parameters is, in the case of a total power radiometer:

$$\Delta T_{3/4} = \left[ (T_{\text{SYS},1}^2 + T_{\text{SYS},2}^2) \right]^{1/2} \left. \frac{1}{B_n \cdot \tau} + \left( \frac{\Delta G}{G_0} \right)^2 \right]^{1/2},$$  

(8)

² Note that this is exactly true only if the physical temperature of the reference load equals the antenna temperature.
where $T_{SYS,1}$ and $T_{SYS,2}$ are the system noise temperatures of the channels that measure $+45^\circ$ and $-45^\circ$ linear polarizations (or left-hand circular and right-hand circular polarizations) to determine the third (or the fourth) Stokes parameter. It is assumed that the equivalent predetection noise bandwidth and the gain fluctuations of the two channels are identical (but the gain fluctuations statistically independent of each other) and distinct radiometer channels are dedicated for the measurement of different polarizations, i.e., the third and fourth Stokes parameters are not obtained by the time multiplexing of a single channel. If a single-channel radiometer with time multiplexing is applied, the theoretical radiometric resolution is degraded as a consequence of reduced effective integration time. The gain fluctuations, however, are also reduced [Skou et al., 1999].

The radiometric resolution of the polarimetric channels (i.e., the channels measuring $T_3$ and $T_4$) of a direct cross-correlating radiometer can be determined by applying the signal-to-noise ratio of a single baseline in an aperture synthesis radiometer. When the orthogonal signals are cross-correlated, the correlation is degraded by the differences of the propagation time through the distinct channels and the differences of transfer functions of the pass-bands [Thompson and D’Addario, 1982]. Although the degradation of the correlation can be compensated for in calibration, there is an irrecoverable loss in the radiometric resolution. In determining the radiometric resolution, the following assumptions are made: the polarized brightness temperature component of the scene is small, which is a reasonable assumption for most remote sensing targets, and the propagation time difference of the two signals is very small compared to the correlation length of the channels (which equals approximately the inverse of the bandwidth). Applying the formulations given in [Hagen and Farley 1973; Thompson and D’Addario 1982] and [P4], the radiometric resolution of the measured third and fourth Stokes parameters can be written as:

$$\Delta T_{3/4} = \frac{K}{D_{3/4}} \cdot \sqrt{\frac{2 \cdot Q_c \cdot T_{SYS,a} \cdot T_{SYS,b}}{\Delta f \cdot \tau}},$$

(9)

where $D_{3/4}$ is the degradation factor generated by the non-ideal amplitude and phase responses of the receiver chains and the correlator and $\Delta f$ is the pass-band bandwidth.

Note that $\Delta f$ equals the equivalent noise bandwidth $B_n$ only if the pass-band is
rectangular. The factor $Q_c$ stands for the degradation due to the quantization of digital cross-correlators; $Q_c$ is unity for analog correlators. The factor $K$ stands for the different radiometer architectures; it is unity for total power radiometers and two for Dicke and noise injection radiometers.

If the system noise temperatures and transfer functions of distinct radiometer channels are equal and an analog cross-correlator is applied, the radiometric resolution defined by Eq. (9) is similar to that defined by Eq. (8). Unlike in the case of the polarization combining radiometer, however, the gain variations will not affect the radiometric resolution of the polarimetric channels of a direct cross-correlating polarimeter, provided that the correlated signals are low compared to the system noise temperatures and the gain fluctuations are not correlated, e.g., due to temperature drift. Note that if the phase differences of the transfer functions are small prior to correlation, the signal propagation times are well balanced, and the gain variations of the orthogonal channels are insignificant, Eq. (9) becomes $\Delta T_{3/4} \approx (2 \cdot \Delta T_v \cdot \Delta T_h)^{1/2}$.

In order to detect $T_4$, the orthogonal signals have to be correlated in quadrature (i.e., the relative phase of the other signal is delayed by 90° prior to correlation, see Eq. (3)). Considering a superheterodyne receiver, which is a practical solution for receivers operating at microwave frequencies, the required 90° phase shift can be generated either in the radio frequency (RF) section or intermediate frequency (IF) section of the receiver. Phase shift in the RF section is associated with a potentially significant increase in system complexity, whereas phase shift in the IF section requires single side-band (SSB) receiver topology. Otherwise, the upper and lower sidebands would cancel each other upon detection.
3 Advances in Polarimetric Radiometry

3.1 General

Since the beginning of the 1990s, much theoretical and experimental work has been published in the area of polarimetric microwave radiometry. Early theoretical studies [Tsang, 1991; Veysoglu et al., 1991] and laboratory and airborne measurements [NgHiem et al., 1991; Dzura et al., 1992] indicated that a non-zero third Stokes parameter could be generated by periodic surfaces. The phenomenon was further investigated by measuring artificially generated water waves (e.g., [Yueh et al., 1994; Gasiewski and Kunkee, 1994]) and conducting airborne experiments (e.g., [Yueh et al., 1999]). By now, it has been demonstrated that the measurement of the first three Stokes parameters enables the determination of maritime wind vectors, i.e., both wind speed and direction [Piepmeier and Gasiewski, 2001a; Laursen and Skou, 2001]. The fourth Stokes parameter is also potentially useful for this purpose [Chang et al., 1997; Yueh et al., 1997; Laursen and Skou, 2001], having the additional benefit of not being affected by Faraday rotation, which could disturb spaceborne polarimetric measurements at low frequencies [Yueh, 2000]. So far, research on polarimetric radiometry has concentrated on the retrieval of wind vectors in sea areas. However, there are also other applications, for example, the determination of the orientation distribution of hydrometeors [Kutuza et al., 1998; Hornbostel et al., 1999; Camps et al., 2000] and the vertical sounding of the mesosphere [Lipton, 2002]. Additionally, the third Stokes parameter can be used to compensate for the polarization coupling in mechanically scanned imaging radiometers [Gasiewski and Kunkee, 1993] and to compensate for the polarization coupling resulting from platform motion [P5]. Furthermore, the third and fourth Stokes parameters could be used for interference detection, as man-made radio frequency signals are often linearly or circularly polarized.

3.2 Radiometers

Although some of the early polarimetric experiments were conducted by physically rotating a conventional ground-based radiometer [NgHiem et al., 1991; Yueh et al., 1994], dedicated polarimetric radiometers are preferred in accurate measurements. The first polarimetric radiometer was developed in the late 1980s and early 1990s by Space
Research Institute (IKI) in the former Soviet Union [Dzura et al., 1992]; it was soon followed by another airborne instrument, WINDRAD, which was developed by Jet Propulsion Laboratory, USA [Yueh et al., 1995]. Both these instruments were profiling, i.e., they produced one-dimensional data. The first imaging polarimetric radiometers, on the other hand, were developed by the Technical University of Denmark [Skou et al., 1999] and the Georgia Institute of Technology, USA [Piepmeier, 1999]. Besides these instruments, a few other polarimetric radiometers have been developed in Russia, USA, and Europe.

When designing a polarimetric radiometer, there are several possible receiver configurations. In the following section, various receiver realizations are discussed with regard to differences in detecting the third and/or fourth Stokes parameters. For the sake of completeness, some receivers developed for polarimetric radio astronomy measurements are also included.

As discussed in Section 2.1, there are two fundamentally different ways to detect the full Stokes vector. On the basis of either incoherent or coherent detection, several distinct polarimetric receiver architectures have been documented in the literature for both remote sensing and radio astronomy. The incoherent topologies include (A) the rotation of a quasi-optical device, such as a phase shifter [Salonen, 1986] or polarizing grid [Söllner, 1998] in front of the antenna of a conventional radiometer, (B) the use of a phase modulator between the antenna and a conventional receiver [Akabane, 1958], and the direct measurement of the principal polarizations by (C) time multiplexing [Yueh et al., 1995], (D) parallel channels [St.Germain and Gaiser, 2000], or (E) a polarization combining network [Bobak et al., 2001]. The coherent topologies, on the other hand, include the measurement of vertical and horizontal polarizations and their complex correlations using (F) the adding technique [Gasiewski and Kunkee, 1993] or (G) direct cross-correlation [Skou et al., 1999].

So far, none of the aforementioned polarimetric receiver topologies has proven to be superior; the optimum topology may vary for different applications and user requirements. With regard to airborne and spaceborne remote sensing, however, the following aspects should be considered. Options (A), (B), and (C) have the potential to be constructed using a single channel receiver, which is beneficial in terms of power consumption, size, weight, system complexity, and costs. However, these options apply time multiplexing in detecting the Stokes parameters (i.e., the individual principal
polarizations are measured one after another), which leads to a low duty cycle and thus a significant (up to 145%) degradation of the radiometric resolution. In principle, the low duty cycle could be compensated for by increased integration time; in practice, however, operational radiometers on board fast-moving platforms, such as satellites and airplanes, have a limited dwell time. Furthermore, the use of moving mechanical components in options (A) and (B) is impractical for airborne and spaceborne instruments. Using options (D)-(G), on the other hand, all the Stokes parameters can be measured simultaneously, which improves the radiometric resolution. Options (E) and (F), however, may lead to high polarization cross-talk values unless the summing networks are very well balanced, which may be difficult.

Because of the reasons discussed above, options (D) and (G) are strong candidates for airborne and spaceborne remote sensing polarimetry. If these two options are compared with each other and fully polarimetric receivers are assumed, option (G) has only two parallel channels compared to the six channels of option (D). This makes a significant difference in terms of power consumption, size, weight, system complexity, and cost. Furthermore, as discussed in Section 2.3, option (G) is less sensitive to the gain variations of the receiver, providing better practical radiometric resolution in total power and Dicke configurations (when observing a typical remote sensing target). An additional benefit of option (G) is that only one dual-polarized antenna or feedhorn is required. This is not the case for option (D); multiple antennas or antenna feedhorns can lead to footprint misalignment between different polarizations. Nonetheless, option (G) requires a cross-correlator, which may increase system complexity and power consumption and set bandwidth limitations.

The greatest advantage of option (D) is that an external end-to-end calibration of the radiometer can be accomplished using conventional calibration standards. Option (G), on the other hand, generally requires the generation of polarized reference signals, which cannot be achieved using conventional blackbody calibration standards. Some other methods of calibrating correlating polarimetric radiometers, however, have been presented in the literature (see Section 3.3). Compared to option (G), an additional benefit of option (D) is improved tolerance against errors in calibrating the polarization cross-talk terms [Ruf, 1998].

A direct cross-correlating polarimetric radiometer can be built using both analog and digital correlators. Few instruments based on digital topology have been presented
in the literature [Skou et al., 1999; Piepmeier and Gasiewski, 2001b]. Distinguished by the number of quantization levels, there is a variety of potential digital correlator types, the two- and three-level quantization approaches being probably the most suitable for correlating radiometry [Søbjærg, 1996]. The merits of digital cross-correlators include some or complete insensitivity to gain fluctuations of the receiver for the three- and two-level quantization schemes, respectively. Furthermore, a negligible cross-coupling between different Stokes parameters can be achieved [Piepmeier and Gasiewski, 2001b]. In addition, it has been suggested that a carefully constructed digital polarimeter with more than two-level quantization could be sufficiently calibrated using only unpolarized calibration scenes [Piepmeier and Gasiewski, 2001b]. This, however, sets stringent requirements for the parameters of A/D converters. Otherwise, offset errors and the errors generated by A/D conversion hysteresis may be significant [Søbjærg, 1996; Laursen, 1999; Piepmeier and Gasiewski, 2001b]. The offset errors could be considerably reduced using the phase-switching technique, though [Skou et al., 1999]. On the other hand, the digital cross-correlators of the first generation used ECL (Emitter Coupled Logic) electronics and used to be bulky and to consume a great deal of power (∼100 W) [Piepmeier, 1999]. Therefore, considering size, complexity, and power consumption, analog cross-correlators have had a clear advantage until recently. With present-day technology, however, it should be possible to make digital correlators which consume less power (< 5 W for the 250 MHz bandwidth) [Piepmeier et al., 2000].

If analog cross-correlators are compared with digital ones, the advantages of analog correlators include the improved radiometric resolution (up to 1.57 times) of the correlated channels [Hagen and Farley, 1973]. Furthermore, analog correlators can be built to be very small and consume little power. Mixer-based cross-correlators have been developed for wide-band interferometric radio astronomy [Padin, 1994] and analog multiplier-based cross-correlators have been used in two-dimensional aperture synthesis demonstration [Laursen and Skou, 1998]. Furthermore, in [Laursen and Skou, 1997] it was briefly mentioned that analog multiplier-based cross-correlators were used to verify the function of the digital cross-correlator of a polarimetric radiometer. Prior to the current work, however, the use of analog direct cross-correlating architecture has not been demonstrated in polarimetric remote sensing radiometry.
To gain an overview of the polarimetric radiometers that have been developed for airborne remote sensing, the instruments described in the literature are listed in Table 1. For comparison, the first spaceborne polarimetric radiometer, WindSat, which was launched in January 2003 on board the U.S. Air Force’s Coriolis satellite, is also included. Some of the main characteristics of the radiometers are also given. It can be seen that no receiver architecture is clearly the most popular in detecting $T_3$ and/or $T_4$; intensive research into polarimetric radiometry started only about a decade ago and the benefits and limitations of different architectures are still under study. Additionally, a variety of frequencies ranging from 1.4 GHz to 89 GHz have been applied. At the moment the most popular frequency range seems to be at around 35 GHz.
<table>
<thead>
<tr>
<th>Instrument/ Developer</th>
<th>Polarimetric Channels</th>
<th>Frequency (GHz)</th>
<th>Detection of Polarized Signals</th>
<th>Basic Architecture</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPoR/ Helsinki Univ. Tech.</td>
<td>$T_3$ and $T_4$</td>
<td>36.5</td>
<td>Coherent, direct analog correlation</td>
<td>Dicke</td>
<td>[Lahtinen and Hallikainen, 1997]</td>
</tr>
<tr>
<td>PSR-A/ U.S. Nat. Oceanic and Atmospheric Administr.</td>
<td>$T_3$ and $T_4$</td>
<td>10.7; 18.7</td>
<td>Coherent, adding analog correlation</td>
<td>Total power</td>
<td>[NOAA/ETL, 2003]</td>
</tr>
<tr>
<td>PSR-CX/ U.S. Nat. Oceanic and Atmospheric Administr.</td>
<td>$T_3$ and $T_4$</td>
<td>6.92, 10.7</td>
<td>Coherent, adding analog correlation</td>
<td>Total power</td>
<td>[Jackson et al., 2003; Gasiewski, 2003]</td>
</tr>
<tr>
<td>EMIRAD/ Technical University of Denmark</td>
<td>$T_3$ and $T_4$</td>
<td>1.4; 16; 34</td>
<td>Coherent, digital direct correlation</td>
<td>Dicke</td>
<td>[Skou et al., 1999; Rotbøll et al., 2001]</td>
</tr>
<tr>
<td>WindSat/ Naval Research Laboratory (USA)</td>
<td>$T_3$ and $T_4$</td>
<td>10.7; 18.7; 37.0</td>
<td>Incoherent, parallel channels</td>
<td>Total power</td>
<td>[Gaiser, 1999]</td>
</tr>
<tr>
<td>WINDRAD/ Jet Propulsion Laboratory (USA)</td>
<td>$T_3$ or $T_4$</td>
<td>19.35</td>
<td>Incoherent, time multiplexing</td>
<td>Dicke</td>
<td>[Yueh et al., 1997]</td>
</tr>
<tr>
<td>PSR-D/ Georgia Institute of Technology (USA)</td>
<td>$T_3$</td>
<td>10.7; 37</td>
<td>Coherent, digital direct correlation</td>
<td>Total power</td>
<td>[Piepmeier, 1999]</td>
</tr>
<tr>
<td>KAPOL/ Space Research Institute (Russia)</td>
<td>$T_3$</td>
<td>37</td>
<td>Incoherent, time multiplexing</td>
<td>Dicke</td>
<td>[Dzura et al., 1992]</td>
</tr>
<tr>
<td>NAMR/ Space Research Institute (Russia)</td>
<td>$T_3$</td>
<td>20; 37</td>
<td>Incoherent, time multiplexing</td>
<td>Dicke</td>
<td>[Kuzmin and Pospelov, 1999]</td>
</tr>
</tbody>
</table>
3.3 Calibration

Many remote sensing applications require high absolute data accuracy and the calibration of the instrument(s) is thus an important issue. To calibrate a microwave radiometer, both internal and external methods can be used. Internal calibration applies embedded sources to inject reference noise into the RF chain (e.g., [Corbella et al., 2002]). External calibration, on the other hand, takes advantage of reference(s) that lie outside the receiver. Reference noise can be injected into the RF chain [Stelzried, 1965] or the antenna can be illuminated with exactly-known brightness temperature scenes. The latter method is widely used in remote sensing as it provides an end-to-end calibration, i.e., the calibration of the whole radiometer as a unit. A useful end-to-end calibration technique is atmospheric tipping calibration (e.g., [Han and Westwater, 2000]). Probably the most widely used technique, however, is a two-point calibration with reference blackbody standards (also called targets or loads) at different physical temperatures. The use of physical temperatures that encompass the whole range of the observed brightness temperatures is preferable. The use of microwave absorbers at ambient and at boiling nitrogen temperatures [Hardy, 1973] is a common practice in Earth remote sensing; sophisticated helium-cooled targets [Bensaloun et al., 1992] are justified for the measurement of the cosmic microwave background and possibly the atmosphere. Furthermore, since the application of cryogenic cooling is sometimes impractical, targets that are heated above the ambient temperature have also been developed (e.g., [Goldsmith et al., 1979; Piepmeier and Gasiewski, 2001b]).

Conventional calibration methods generate only unpolarized signals, i.e., no orientation of electromagnetic radiation is more probable than another. Furthermore, polarimetric radiometers will generally exhibit some sensitivity in each channel to all four Stokes parameters, as expressed by Eq. (6). Therefore, other methods are required to calibrate correlating polarimetric radiometers. For complete calibration, i.e., to retrieve the cross-talk terms too, more than two linearly independent input stimuli are required. Note that although the conventional two-point method is sufficient for the calibration of incoherent polarimetric radiometers, the level of possible polarization cross-talk remains unknown. Cross-talk can be caused by, for example, the misalignment of the polarization frame of multiple antennas or antenna feeds.
A linearly polarized standard to calibrate a radiometer that measures the first three
Stokes parameters was introduced by Gasiewski and Kunkee [1993]. The standard
comprises a blackbody target at ambient (cold target) and ~40 K elevated temperature
(hot target) and a polarization splitting wire grid. A schematic diagram of the target is
presented in Fig. 1. A modification of this standard, applying blackbody targets at
ambient and boiling nitrogen temperatures, was briefly described in [Piepmeier and
Gasiewski, 2001b]. Along with a conventional unpolarized blackbody target, the
linearly polarized standard enables the first three Stokes parameters ($T_v$, $T_h$, and $T_3$), but
not the fourth Stokes parameter, to be generated and calibrated.

Another polarimetric calibration method was described in [Laursen, 1999; Skou et
al., 1999]: The two receiver chains of a correlating polarimetric radiometer are fed with
a common internal active noise source. The level of the injected noise is measured by
the orthogonal channels, which in turn are calibrated using conventional hot and cold
blackbody targets. The phase coherence between the orthogonal channels is calibrated
using an external active noise source, the signal of which is divided (and attenuated)
and connected to the inputs of the radiometer. The greatest advantage of this calibration
method is its simplicity; only basic microwave components are required. However, the
method has some drawbacks, too; with the exception of $g_{vv}$ and $g_{hh}$ terms and $\bar{o}$ in Eq.
(6), the influence of the antenna is not accounted for. Furthermore, most of the

![Schematic diagram of the linearly polarized calibration standard](image_url)

**Figure 1.** Schematic diagram of the linearly polarized calibration standard [Gasiewski
and Kunkee, 1993].
unknown cross-talk parameters are not retrieved. In addition, some uncertainty is introduced by the imperfect modeling of the component parameters of the active external reference.

Prior to the current work, there have been no reliable means to perform end-to-end fully polarimetric calibrations, i.e., to determine all unknown gain and offset terms in Eq. (6). Since polarization-combining radiometers can be calibrated — at least to some extent — using conventional calibration techniques, the lack of a reliable calibration method has been especially disadvantageous for correlating fully polarimetric radiometers. In particular, the applicability of analog cross-correlators for fully polarimetric radiometers has been questionable; although not thoroughly demonstrated, the results presented in [Piepmeier and Gasiewski, 2001b] suggest that a direct correlating polarimetric radiometer with a well-designed digital three-level cross-correlator could be calibrated using only conventional calibration targets.

### 3.4 Measurements and Applications

Interest in polarimetric radiometry originates from the theoretical and experimental work conducted in IKI in the former Soviet Union during the late 1970s and 1980s. It was found out that the brightness temperature of a perturbed sea is modulated by the relative wind direction [Bespalova et al., 1981; Bespalova et al., 1982]. While the applicability of microwave brightness temperature measurements was already known for the purpose of determining maritime wind speeds (e.g., [Hollinger, 1971]), this new discovery showed that the retrieval of both wind speed and direction (i.e., wind vector) is possible in sea areas [Irisov et al., 1991; Wentz, 1992].

The option to use the third and possibly the fourth Stokes parameter to improve the retrieval of wind vectors and some other geophysical parameters ignited interest in polarimetric radiometer measurements at the beginning of the 1990s. The pioneering work conducted in the IKI led to the development of the first airborne polarimetric radiometer and the first airborne measurements [Dzura et al., 1992]. Furthermore, new theoretical [Tsang, 1991; Veysoglu et al., 1991] and experimental works [Nghiem et al., 1991] were published on this field. Hitherto, the determination of wind vectors in sea areas has received the most intensive attention of all the potential applications of polarimetric radiometry. Besides numerous theoretical studies and laboratory
experiments (e.g., [Johnson et al., 1993; Yueh et al., 1994; Gasiewski and Kunkee, 1994]), some ground-based in-field experiments have been conducted (e.g., [Frasier et al., 2001]) to elucidate the capability of polarimetric radiometry for maritime wind vector retrieval. Furthermore, several research groups in the United States of America [Yueh et al., 1995; Chang et al., 1997; Piepmeier and Gasiewski, 2001a], Russia [Kuzmin and Pospelov, 1999], Denmark [Laursen and Skou, 2001], and Finland [Lahtinen et al., 2001] have conducted airborne measurements. Up till now, the retrieval of one- and two-dimensional wind vector maps has been demonstrated [Piepmeier and Gasiewski, 2001a; Laursen and Skou, 2001]. Furthermore, models for the association between the Stokes parameters and the wind vectors have been presented for some frequencies and incidence angles [Yueh et al., 1999; Piepmeier and Gasiewski, 2001a]. In general, the Stokes parameters are modeled using the second-order harmonic model:

\[
T_v \approx T_{v0} + a_{v1} \cdot \cos(\phi_W) + a_{v2} \cdot \cos(2\phi_W) \tag{10}
\]

\[
T_h \approx T_{h0} + a_{h1} \cdot \cos(\phi_W) + a_{h2} \cdot \cos(2\phi_W) \tag{11}
\]

\[
T_3 \approx b_{31} \cdot \sin(\phi_W) + b_{32} \cdot \sin(2\phi_W) \tag{12}
\]

\[
T_4 \approx b_{41} \cdot \sin(\phi_W) + b_{42} \cdot \sin(2\phi_W), \tag{13}
\]

where \(\phi_W\) is the relative wind direction, \(T_{v0}\) and \(T_{h0}\) are the zeroth-order components of vertical and horizontal polarizations, respectively, \(a_{\alpha1}\) and \(a_{\alpha2}\) are, respectively, the first- and second-order harmonic coefficients for the first and second Stokes parameters \((\alpha = v \text{ or } h)\), and \(b_\beta\), and \(b_\beta\), respectively, are the first- and second-order harmonic coefficients for the third and fourth Stokes parameters \((\beta = 3 \text{ or } 4)\).

In the experiments reported so far, the applied frequencies have ranged from 1.4 GHz to 37 GHz; the optimal frequency or frequency combination, however, is still under study, as is the optimal incidence angle. More information on this topic will be obtained in the near future, since the first spaceborne polarimetric radiometer, WindSat, was launched in January 2003 on board the Coriolis satellite belonging to the U.S. Air Force. WindSat measures full Stokes vectors at 10.7 GHz, 18.7 GHz, and 37 GHz [Gaiser, 1999].
Although the measurement of wind vectors from space is also possible using conventional radiometers, as demonstrated by Wentz [1992], it has become clear that the measurement of additional Stokes parameters beyond the vertical and horizontal polarizations has several advantages. First, \( T_3 \) and \( T_4 \) have zero means over the full circle of azimuth measurement angles (see Eqs (12)-(13)), facilitating the absolute calibration of data. Second, \( T_3 \) and \( T_4 \) are much less influenced by clouds and other unpolarized geophysical variations than are orthogonal polarizations. Third, combining \( T_3 \) and \( T_4 \), which are odd functions, with \( T_v \) and \( T_h \), which are even functions with respect to wind direction, the accuracy of wind vector retrieval is improved and ambiguities are reduced. Due to radiometric and geophysical noise, however, ambiguities cannot be completely avoided.

An example of the Stokes parameters measured at 16 GHz and 34 GHz as a function of relative wind direction is presented in Fig. 2 [Laursen and Skou, 2001]. The data were collected in the North Sea and the wind speed was 17 ms\(^{-1}\). Each Stokes parameter measured is modeled using the second-order harmonic approximation. The sensitivity of orthogonal polarizations to atmospheric conditions can be seen clearly in the second “unmodified” Stokes parameter \( Q \) (see Eq. (4)): A heavy cloud was encountered at azimuth angles around 180°, causing a significant change in the detected vertical and horizontal signals. On the other hand, the influence of the cloud is small for the third and fourth Stokes parameters. Nevertheless, the wind vector signal is small, about 3 K peak-to-peak at maximum.

The polarized component in the thermal radiation of sea waves is more linearly polarized than circularly polarized [Yueh et al., 1997], as can also be seen in Fig. 2. The third Stokes parameter is thus a more lucrative candidate for wind vector measurements than the fourth parameter. However, sea waves do also exhibit a circularly polarized component of thermal emission, at least at certain frequencies and incidence angles. Therefore, accuracy in determining the wind vectors can be enhanced by measuring the full Stokes vector [Laursen and Skou, 2001], [P1]. The fourth Stokes parameter has the additional advantage of being independent of ionospheric Faraday rotation. If not compensated, the Faraday rotation can interfere with the third Stokes parameter considerably, especially at low frequencies [Yueh, 2000].
Figure 2. The difference between orthogonal brightness temperatures (Q), the third (U), and the fourth (V) Stokes parameter as a function of relative wind direction ($\psi_0$). Each parameter is modeled using a second-order harmonic approximation [Laursen and Skou, 2001].

Besides the determination of maritime wind vectors, polarimetric radiometer measurements also have other potential applications. Some of these applications are discussed below.

Approximately at the same time as the anisotropic brightness temperature signature of sea waves was discovered, a similar effect for the tilled row structures of soil was revealed [Wang et al., 1980]. It was concluded that the dependence of the vertical and horizontal brightness temperatures on the azimuth angle could have an appreciable effect on microwave emission from an agricultural field, and it was suggested that the effect of a tilled row structure should be corrected to improve the precision of microwave remote sensing of surface soil moisture content. These results inferred that a third Stokes parameter signal is generated by tilled row structures; the potential of polarimetric radiometry, however, was not yet recognized. Later on, Nghiem et al. [1991] investigated the polarized thermal emissions from a periodic soil surface; it was
discovered that significant values of the third Stokes parameter are indeed generated by such a structure.

The determination of the orientation distribution of hydrometeors in the atmosphere (e.g., rain drops and ice crystals) is a potential application of polarimetric radiometry. This subject has been studied both theoretically and experimentally in a few studies [Kutuza et al., 1998; Hornbostel et al., 1999; Camps et al., 2000]. When rain was measured at 10.68 GHz, the third and fourth Stokes parameters reached values of \( \sim 4 \) K and \( \sim 2 \) K, respectively, and were apparently modulated by both rain rate and horizontal wind intensity [Camps et al., 2000]. It has been suggested that spaceborne polarimetric measurements can provide additional information for the retrieval of parameters for the description of cloud form classification, determination of rain areas above land and the ocean, and defining the cloud phase structure and the spatial inhomogeneities of precipitation; the accuracy of precipitation measurements should also improve [Kutuza et al., 1998].

In the field of atmospheric remote sensing, a spaceborne fully polarimetric radiometer would be an optimal choice for the global retrieval of mesospheric temperature profiles; the best polarization to measure the upwelling brightness temperature varies with different geomagnetic conditions. The retrieval performance would thus be maximized by measuring all the Stokes parameters [Lipton, 2002].

Microwave radar backscatter and vertical and horizontal brightness temperatures obtained using spaceborne instruments (e.g., [Remy et al., 1992; Rack, 1995; Long and Drinkwater, 2000]) demonstrate azimuth signal variations over some regions of the Antarctic ice sheet. This modulation is correlated with surface roughness and slope environments that are formed under strong and directionally persistent katabatic winds. It is thus possible to retrieve wind streamline maps in these areas; note, however, that it is currently difficult to assess the magnitude of the wind more than qualitatively. The precise mechanism of these anisotropic signatures is still unclear; the aforementioned studies suggest large dunes and/or sastrugis (which are meter scale erosional features elongated in wind direction) to be the source. Recently, the azimuth modulation of radar backscatter has been reported also for the Greenland ice sheet [Ashcraft and Long, 2001]. These results infer that polarized brightness temperature signatures, similar to those from sea waves, are generated in continental ice sheets. Although more
studies are needed to confirm its capability, polarimetric radiometry is thus potentially valuable in retrieving wind information in polar regions.

Tsang [1991] showed theoretically that significant amounts of the third and fourth Stokes parameters are generated for certain asymmetrical configurations of discrete scatterers. In polarimetric radiometry, a potential application that takes advantage of this phenomenon is the detection of the c-axis anisotropies of sea ice [Yueh et al., 1992]. So far, however, no experimental data have been published, and the viability of polarimetric radiometry for such applications remains to be verified.

A different but nevertheless interesting approach was taken by Söllner [1998]. Fully polarimetric brightness temperature signatures of various natural and artificial objects were measured at 90 GHz. Such materials as a wooden plate made from a fir tree and an anisotropic cloth showed noticeable modulation as a function of azimuth observation angle. The cloth, for example, had a variation of up to 50 K in the third Stokes parameter. These results may be of limited value for remote sensing, but should provide motivation for the investigation of the potential of polarimetric radiometry for industrial applications.

In general, the use of the fourth Stokes parameter for various remote sensing applications has been investigated less than the use of the third Stokes parameter. This also has historical causes; many of the first polarimetric radiometers measured only the first three Stokes parameters. With regard to the correlating polarimetric radiometers, the lack of a reliable calibrating method has also been a problem.
4 Development of a Fully Polarimetric Radiometer

Helsinki University of Technology (HUT) Laboratory of Space Technology has developed a multichannel airborne radiometer system, HUTRAD [Hallikainen et al., 1998], to support algorithm development for existing and future remote sensing satellites. As a part of that work, a fully polarimetric radiometer at 36.5 GHz, the Fully Polarimetric Radiometer (FPoR) [P5], was developed in the current work. The development was motivated by the growing interest in polarimetric microwave radiometry discussed in Section 3.

The FPoR and the whole HUTRAD system were developed primarily for airborne measurements onboard HUT's Short Skyvan research aircraft. However, ground-based (e.g., roof-top) and laboratory measurements are also possible. When the system was being designed, the system parameters were selected so as to guarantee a high level of compatibility with existing and future satellite instruments. The specifications presented in [Panula-Ontto et al., 1995] for a 36.5 GHz receiver were adopted and the requirements for the radiometric resolution, stability, and accuracy of the FPoR were set to 0.5 K, 0.5 K, and 1.5 K, respectively. The practical constraints and limitations (mass, size, power consumption etc.) set by the Short Skyvan aircraft were also considered.

The profiling subsystem of the HUTRAD consists of several major assemblies networked together to form a local area network: the High Frequency Sensor Unit (for 23.8 GHz, 36.5 GHz, and 92 GHz) and its Power and Control Unit, the Low Frequency Sensor Unit (for 6.8 GHz, 10.7 GHz, and 18.7 GHz), and the Operator Interface Assembly. In airborne use the sensor units are accommodated in the rear cargo bay of the Short Skyvan aircraft.

4.1 Description of the Device

After considering the trade-offs associated with different polarimetric radiometer configurations, as discussed in Section 3.1, a direct cross-correlating topology with analog correlators was selected for the FPoR. The advantages of this architecture include, for example, the maximum effective integration time and lack of quantization errors, which both improve sensitivity, and the simple structure of both the receiver and
the cross-correlator, which reduces costs and increases reliability. Furthermore, power consumption is low. The 90° phase shift that is required for the detection of the fourth Stokes parameter is generated in the IF section; it was considered that the generation of the phase shift in the RF section would increase the receiver complexity, power consumption, and costs too much. The drawback of the applied solution is the requirement of SSB detection. To protect the RF amplifiers from man-made radio frequency interference, the image rejection filters are used as preselectors (i.e., in front of the RF amplifier in a receiver chain). It is noted, however, that this configuration is not optimal with respect to receiver noise temperature. The receiver applies Dicke switching topology to suppress the effect of receiver parameter fluctuations. Furthermore, all the components, from the antenna to the low-frequency electronics, are enclosed in a thermally stabilized enclosure.

The receiver is installed in the housing of the High Frequency Sensor Unit of the profiling subsystem of the HUTRAD. Functionally, the receiver consists of four systems: a) the radio frequency (RF) system, b) the intermediate frequency (IF) system, c) the low frequency (LF) electronics system, and d) the correlator system. The block diagram of the microwave circuit is shown in Fig. 3. The main functional parameters are listed with measured characteristics in Table 2 in Section 4.2.

The correlator system correlates the orthogonal signals in phase and in quadrature to directly measure $T_3$ and $T_4$, respectively. In essence, the system consists of a wide-band

---

**Figure 3.** Block diagram of the Fully Polarimetric Radiometer receiver (excluding the LF electronics system) [P5].
90° hybrid and two analog cross-correlator units. A photograph of a cross-correlator unit is presented in Fig. 4. Each cross-correlator unit [P4] is built around a commercially available analog multiplier with only a few additional components. The applied multipliers exploit the Gilbert cell structure, which features internal temperature compensation [Gilbert, 1968]. This makes them insensitive to temperature fluctuations. In order to minimize decorrelation due to different propagation time through vertical and horizontal receiver chains (the fringe-washing effect), the propagation time was measured and delay lines were installed to balance the electrical lengths. The fringe-washing effect is a zero-baseline special case of the so-called fringe-washing function, which is well known from the theory of interferometry [Thompson et al., 1986].

After the IF and correlator systems, respectively, the detected orthogonal and polarimetric signals are fed to the LF electronics circuitry. The radiometric signals are then transferred to the Power and Control Unit and further to the Operator Interface Assembly of the profiling subsystem of the HUTRAD.

Figure 4. The developed analog cross-correlator unit (lid open). The analog multiplier is the integrated circuit on the left-hand side of the circuit board. The components on the right-hand side of the enclosure are used to regulate the supply voltage.
### 4.2 Characteristics

The Fully Polarimetric Radiometer (FPoR) is a versatile instrument for laboratory, ground-based, and airborne measurements. A variety of measuring parameters can be adjusted, which gives the instrument a high level of flexibility. An extensive set of laboratory tests was carried out to verify the proper function of the FPoR and to characterize the performance of the receiver [P5] and the cross-correlators [P4]. Furthermore, the suitability of the FPoR for laboratory measurements was demonstrated in combination with the developed calibration standard (see Section 5); several parameters of the calibration standard were determined using the FPoR as a reference instrument. The feasibility of the radiometer for airborne measurement was determined in a wind vector experiment, discussed in Section 6. The characteristics of the FPoR are summarized in Table 2. The key parameters are discussed below.

It should be noted that the noise temperature of the orthogonal channels is relatively high. This is a consequence of applying the image rejection filters as pre-selectors (i.e., prior to the RF amplifiers). Furthermore, the influence of the antenna is included in the noise figure. Due to an effective temperature stabilization system, however, the relative gain fluctuations ($\Delta G/G_0$) are small, compensating for the influence of the relatively high noise temperature on radiometric resolution. In addition, the results indicate that the measured radiometric resolutions of the polarimetric channels are close to $(2\cdot\Delta T_v\cdot\Delta T_h)^{1/2}$ (within 11%), suggesting only a small fringe-washing effect.

As presented in Eq. (6), the antenna temperature and the response vector of a fully polarimetric radiometer are related via an offset vector and a gain matrix, which also includes the interchannel cross-talk (coupling) terms. Using the developed fully polarimetric calibration standard discussed in Section 5, the calibration coefficients of the FPoR were determined in a variety of calibrations both in the laboratory and in the field. With regard to the mean calibration coefficient values obtained with different receiver temperatures, the following observations can be made. In general, the mixing of orthogonal signals into polarimetric signals is relatively low, varying between $-16$ dB and $-27$ dB [P5]. This implies that cross-talk values close to those reported for digital cross-correlators [Piepmeier and Gasiewski, 2001b] are achievable by means of the careful design and construction of an analog direct cross-correlator. Note that
Table 2. The system characteristics of the Fully Polarimetric Radiometer [P4, P5].

<table>
<thead>
<tr>
<th>Parameter (Unit)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center frequency (GHz)</td>
<td>36.5</td>
</tr>
<tr>
<td>Intermediate frequency (MHz)</td>
<td>~ 90 - 520</td>
</tr>
<tr>
<td>Measured polarizations</td>
<td>$T_v, T_h, T_3, T_4$</td>
</tr>
<tr>
<td>Antenna type</td>
<td>Lens Loaded Horn Antenna</td>
</tr>
<tr>
<td>Antenna side lobe level (dB)</td>
<td>−25 (E), −21 (H)</td>
</tr>
<tr>
<td>Antenna 3 dB beam width (deg)</td>
<td>4.0</td>
</tr>
<tr>
<td>Incidence angle in airborne use (deg)</td>
<td>~ 40 - 60</td>
</tr>
<tr>
<td>Integration time (ms)</td>
<td>50 - 3000 (programmable)</td>
</tr>
<tr>
<td>Equivalent noise bandwidth of a correlator unit (MHz)</td>
<td>403</td>
</tr>
<tr>
<td>Degradation factor of a correlator unit (%)</td>
<td>96.5</td>
</tr>
<tr>
<td>$T_v$</td>
<td>$T_h$</td>
</tr>
<tr>
<td>Equivalent predetection noise bandwidth (MHz)</td>
<td>430 415 417 414</td>
</tr>
<tr>
<td>Degradation factor of the receiver (%)</td>
<td>- - 98.0 98.1</td>
</tr>
<tr>
<td>Receiver noise temperature (K)</td>
<td>1570 1210 - -</td>
</tr>
<tr>
<td>Radiometric resolution (K)</td>
<td>0.21 0.17 0.29 0.29</td>
</tr>
<tr>
<td>$\Delta G/G \times 10^3$</td>
<td>4.1 4.8 - -</td>
</tr>
<tr>
<td>Stability (mK)</td>
<td>7 6 4 6</td>
</tr>
<tr>
<td>Absolute accuracy (K)</td>
<td>0.5 0.6 0.5 0.8</td>
</tr>
</tbody>
</table>

\[ a \] 1 s integration time, 250 K antenna temperature
\[ b \] over 800 s for the orthogonal channels, over 8,000 s for the polarimetric channels
\[ c \] during a sample airborne wind vector measurement, potential non-linearity not included (see Section 6)

although the cross-talk terms are non-negligible, they are compensated for in calibration.

A novel method was applied to measure the frequency response of a correlator unit [P4]; the measurements indicate that the usable bandwidth is 700 MHz in the current configuration and up to 1 GHz if the input matching is improved [P4]. Besides wide bandwidth, the benefits of the applied analog multipliers include low power consumption (typically less than 300 mW) and small circuit size; as can be seen in Fig. 4, only a few additional components are required to construct a cross-correlator. As extremely small size was not required, two separate correlator units with a sparse component layout were developed and accommodated in standard device enclosures.
measuring 29×63×115 mm. For practical reasons, voltage regulation circuitry was also included in both units. Note, however, that further miniaturization is possible by integrating both correlator units into the same component board, condensing the component layout, and applying pre-regulated supply voltages.

The long-time stability of the FPoR was estimated in terms of Allan Standard Deviation (ASD) [P5], which is simply the square root of Allan variance [Allan, 1966]. Allan variance was originally developed to characterize the stability of frequency standards, but it is most suitable for characterizing the stability of radiometer receivers as well [Rau et al. 1984]. Considering the orthogonal channels of the FPoR, the noise corner lies at around 800 s (≈ 13 min), suggesting an ideal calibration cycle of 10 to 15 min. However, the results infer that the drift is insignificant (≤ 40 mK) over time periods of 2 to 3 hours, which is a typical calibration cycle of an airborne measurement. Furthermore, the polarimetric channels of the FPoR are even more stable than the orthogonal channels; the noise corner lies at around 8,000 s (≈ 2 h 13 min) [P5]. The higher stability of the polarimetric channels is an expected result, as the parameter fluctuations of the orthogonal channels are substantially uncorrelated. Note that in [P4] a noise corner of 10 s was obtained for the cross-correlators in a total-power type measurement. The much higher stability of the complete polarimetric channels (which include the correlators) in [P5] stresses the effectiveness of Dicke switching in drift reduction. Furthermore, the results in [P4] include the potential amplitude fluctuations of the coherent reference signal.

In estimating the absolute accuracy of the FPoR, the following factors were considered [P5]: calibration uncertainties, discussed in Section 5.4, the stability of the receiver and the dependence of the calibration parameters on receiver temperature, and the side-lobe level of the antenna. Furthermore, the inaccuracy of the attitude determination system [BEI Technologies, 1998] is accounted for in airborne measurement. The radiometer is assumed to be linear. Since the accuracy is dependent on several variables that vary between measurements, no universal estimate of the accuracy can be given. In general, however, the pixel-to-pixel absolute accuracy of the FPoR falls within the sub-Kelvin range in a typical airborne measurement, provided that the aircraft roll angle is below ~25°. An error estimate for a sample airborne wind vector measurement, discussed in Section 6, is given in Table 2. Since the mean values of $T_3$ and $T_4$ should be zero over a full circle of azimuth (see Eqs (12)-(13)), the
reliability of the error estimate can be evaluated by the airborne data obtained. The offsets measured using various roll and incidence angles of the antenna beam were indeed within the estimated values [P5]. It should be noted that the absolute accuracy of the data can be further improved by reducing the systematic uncertainties associated with the calibration standard, discussed in Section 5.1, or applying additional methods to improve calibration, e.g., removing the offset of $T_3$ and $T_4$ over a full circle of azimuth.

4.3 Contribution of the Work to Polarimetric Radiometer Technology

A fully polarimetric radiometer has been designed and constructed for microwave remote sensing at 36.5 GHz [P5]. The Fully Polarimetric Radiometer (FPoR) was developed primarily for airborne applications, but it can also be used for laboratory and ground-based (e.g., roof-top) measurements. The performance of the instrument was tested in a variety of laboratory measurements, confirming that the requirements set for radiometric resolution, stability, and absolute accuracy were fulfilled. Especially noteworthy is the high stability of the receiver, which is a particularly important parameter for wind vector measurements [Yueh et al., 1997]. Furthermore, given that the influence of non-linearity is small, the absolute accuracy of the FPoR is estimated to be in the sub-Kelvin range in a typical airborne wind vector measurement. This estimate is supported by the measurement results acquired in an airborne experiment.

The FPoR is the first polarimetric remote sensing radiometer that is based on analog direct cross-correlating topology. Compared to other receiver topologies, discussed in Section 3.2, the direct cross-correlating architecture has several advantages, e.g., maximum effective integration time combined with the simple structure of the receiver; only two receiver channels are needed to measure the whole Stokes vector, which is an asset in terms of costs, mass, size, power consumption, and reliability. Furthermore, the developed cross-correlator is built around commercially available wideband analog multipliers [P4]; the current work is the first successful demonstration of the use of analog multipliers in polarimetric microwave remote sensing radiometry. It should be noted, however, that a simultaneous piece of work applying wideband analog multipliers in aperture synthesis radio astronomy was reported in [Padin et al., 2001]. The advantages of the developed cross-correlators include the following: (A) the analog
topology provides maximum theoretical radiometric resolution, (B) besides analog multipliers, only a few additional components are required, which leads to small size and very straightforward topology, (C) the multipliers exploit the Gilbert cell structure with internal temperature compensation, which makes them insensitive to temperature fluctuations, (D) the power consumption is very low, (E) the measured degradation factor is close to ideal, and (F) the bandwidth can be extended up to 1 GHz with minor modifications.

It is noted that the coupling of orthogonal signals into the polarimetric channels is a potential weakness of analog cross-correlators compared to digital correlators. The determined coupling levels of the FPoR are indeed higher than those reported for a digital system in [Piepmeier and Gasiewski, 2001b]. However, the achieved level of polarization isolation is satisfactory and can, additionally, be fully compensated for in calibration.

The feasibility of the FPoR for laboratory and airborne measurements was demonstrated; it was verified that the applied analog direct correlating topology is a viable and competitive option in developing ground-based and airborne polarimetric radiometers. Furthermore, the results suggest that using a spaceborne polarimetric calibration standard, as proposed in [P1] and [Gasiewski and Kunkee, 1993], the analog cross-correlation technique is also a viable choice for satellite instruments.
5 Development of Polarimetric Calibration Technology

5.1 Calibration Method

As discussed in Section 3.3, the brightness temperature emitted by conventional blackbody standards is unpolarized; such standards are not sufficient for the external calibration of coherent detecting polarimetric radiometers. However, a linearly polarized calibration standard presented in [Gasiewski and Kunkee, 1993] facilitates the calibration of the channels for the first three Stokes parameters (but not the fourth parameter).

In order to calibrate the fourth Stokes parameter, a circularly polarized signal can be generated by inserting a biaxial phase retardation plate between a linearly polarized standard and the antenna of a radiometer [P1]. The retardation plate generates a predetermined phase shift between the perpendicular field components of the transmitted waves, transforming part of the linearly polarized component (the third Stokes parameter) into a circularly polarized signal (the fourth Stokes parameter). Henceforth in this work, this combination of a linearly polarized calibration standard and a retardation plate is referred to as a fully polarimetric standard. A schematic diagram of a fully polarimetric standard is presented in Fig. 5. The rotation angles of the linearly polarized standard and the retardation plate about the radiometer antenna polarization basis are $\theta$ and $\phi$, respectively. The angles $\theta = 0^\circ$ and $\phi = 0^\circ$ refer to the case where the grid wires of the linearly polarized standard and the slow axis of the retardation plate, respectively, are aligned with the vertical polarization of the radiometer antenna.

A fully polarimetric standard, along with an unpolarized reference brightness temperature, makes possible the calibration of all four Stokes parameters. This can be achieved to a high level of precision, provided that the various material and component parameters of the standard are known. By changing the rotation angles of the linearly polarized standard and the retardation plate, an infinite number of distinct reference brightness temperature scenes can be generated [P1].

A priori determination of the Stokes vector that is generated by a fully polarimetric standard proceeds by first calculating the tri-polarimetric Stokes vector of the linearly
polarized standard and then multiplying this vector by a transformation matrix describing the influence of the retardation plate. The tri-polarimetric Stokes vector $\overline{T}_T$ is [P1]:

$$
\overline{T}_T = \begin{bmatrix} T_v \\ T_h \\ T_3 \\ T_4 \end{bmatrix} = \begin{bmatrix} \cos^2 \theta & \sin^2 \theta \\ \sin^2 \theta & \cos^2 \theta \\ \sin(2\theta) & -\sin(2\theta) \\ 0 & 0 \end{bmatrix} \begin{bmatrix} T_{\text{HOT}} \\ T_{\text{COLD}} \end{bmatrix} = \begin{bmatrix} G \end{bmatrix} \begin{bmatrix} T_{\text{HOT}}' \\ T_{\text{COLD}}' \end{bmatrix},
$$

(14)

$$
\begin{bmatrix} T_{\text{HOT}}' \\ T_{\text{COLD}}' \end{bmatrix} = \begin{bmatrix} r_\parallel & t_\parallel & L_\parallel \\ r_\perp & t_\perp & L_\perp \end{bmatrix} \begin{bmatrix} T_{\text{HOT}} \\ T_{\text{COLD}} \\ T_G \end{bmatrix} = \begin{bmatrix} L \end{bmatrix} \begin{bmatrix} T_{\text{HOT}} \\ T_{\text{COLD}} \\ T_G \end{bmatrix},
$$

(15)

where $T_{\text{HOT}}$ and $T_{\text{COLD}}$ are the brightness temperatures of hot and cold blackbody targets inside the linearly polarized standard, respectively, $T_G$ is the physical temperature of the polarizing grid, and $r_\parallel$, $t_\parallel$, and $L_\parallel$ are the reflection coefficient, transmission coefficient, and ohmic losses of the grid for the waves polarized parallel to the grid wires, respectively. The analogous parameters for the waves polarized perpendicular to the grid wires are $r_\perp$, $t_\perp$, and $L_\perp$, respectively.
To simplify the analysis, let us first ignore the thermal emission contribution from the retardation plate. Using Eqs (14) and (15) the Stokes vector generated upon insertion of the retardation plate is \([P1]:\)

\[
\overline{T}_{C'} = \overline{F}^\tau \cdot \overline{T}_T = \overline{F}^\tau \cdot \overline{G} \cdot \overline{A} \cdot \begin{bmatrix} T_{HOT} \\ T_{COLD} \\ T_G \end{bmatrix} = \begin{bmatrix} 1 \\ \cos(2\phi) \\ \cos(4\phi) \\ \sin(2\phi) \\ \sin(4\phi) \end{bmatrix} = \overline{D}_\alpha \cdot \begin{bmatrix} 1 \\ \cos(2\phi) \\ \cos(4\phi) \\ \sin(2\phi) \\ \sin(4\phi) \end{bmatrix}.
\]

The non-zero elements of \(\overline{D}_v\) and \(\overline{D}_h\) (elements for vertical and horizontal polarization, respectively) for the general case (with losses) are presented in Appendix A. Appendix A also includes the derivation for the non-zero elements of \(\overline{D}_v\); the derivation is analogous for horizontal polarization. The non-zero elements of \(\overline{D}_3\) and \(\overline{D}_4\) (elements for the third and fourth Stokes parameters, respectively) and their derivation for the general case are presented in Appendix B. Note that the derivation for the non-zero elements of \(\overline{D}_v\) was presented earlier in [Salonen, 1986] for the lossless case.

Upon inclusion of the brightness temperature contribution of the retardation plate \(\overline{T}_R\), the resulting fully polarimetric Stokes vector \(\overline{T}_C\) becomes:

\[
\overline{T}_C = \overline{T}_{C'} + \overline{T}_R
\]
\[ \bar{T}_r = \frac{T_{P,R}}{2} \begin{bmatrix} 2 - \frac{1}{l_{\perp}^2} - \frac{1}{l_{\parallel}^2} + \left( \frac{1}{l_{\perp}^2} - \frac{1}{l_{\parallel}^2} \right) \cos(2\varphi) \\ 2 - \frac{1}{l_{\perp}^2} - \frac{1}{l_{\parallel}^2} + \left( \frac{1}{l_{\perp}^2} - \frac{1}{l_{\parallel}^2} \right) \cos(2\varphi) \\ 2 \left( \frac{1}{l_{\perp}^2} - \frac{1}{l_{\parallel}^2} \right) \sin(2\varphi) \\ 0 \end{bmatrix}, \] (20)

where \( T_{P,R} \) is the physical temperature of the retardation plate. The derivation of the elements of Eq. (20) is presented in Appendix C.

The estimates of the unknown calibration elements in Eq. (6) are determined via fully polarimetric calibration, which requires the generation of at least five linearly independent brightness temperature vectors [P1]. Redundant scenes can be applied to suppress random calibration uncertainties. In this case, the elements of the unknown gain estimate matrix \( \tilde{G} \) and offset estimate vector \( \tilde{o} \) are found using pseudo-inversion [P1]:

\[
\begin{bmatrix} \tilde{g} \\ \tilde{o} \end{bmatrix}^T = \left( \bar{C}_o \bar{C}_o \right)^{-1} \bar{C}_o \bar{r}_c, \tag{21}
\]

where \( \bar{r}_c \) is a \( M \times 4 \) size radiometer signal output matrix in calibration and \( M \) is the number of the applied brightness temperature scenes in calibration. The Stokes vector column matrix, \( \bar{C}_o \), is an \( M \times 5 \) size matrix containing the values of the generated brightness temperatures determined \textit{a priori}, augmented with a unity column vector.

Calibration errors are of fundamental importance when considering the absolute accuracy of a radiometer. Provided that the calibration is performed carefully, the calibration errors are mostly generated by inaccuracies in determining the brightness temperature of the applied calibration standard \textit{a priori}. A fully polarimetric calibration standard has a number of systematic and random parameter uncertainties. It is reasonable to consider the two types of uncertainties separately. The systematic uncertainties are time-invariant between different calibrations and can be reduced \textit{a posteriori} [P1]. Assuming that the receiver integration noise is made negligible by a
sufficiently long integration time, the uncertainty in the scene Stokes vector as a result of calibration uncertainties is [P1]:

\[
\Delta \bar{T}_B \approx -C_{B,0} \left( \bar{C}_0 \bar{C}_0 \right)^{-1} \bar{C}_0 \Delta \bar{T}_C,
\]

(22)

where \( C_{B,0} \) is an \( M \times 5 \) size brightness data matrix acquired during operation, augmented with a unity column vector. Matrix \( \Delta \bar{T}_C \) contains the Stokes vector uncertainties in calibration.

The calibration method described was developed to determine the calibration coefficients of fully polarimetric radiometers. Since the generated brightness temperatures can be adjusted, potential applications also include the determination of the linearity of a receiver [P3]. Furthermore, tri-polarimetric radiometers (that measure only three Stokes parameters) would benefit from the determination of the phase balance between orthogonal channels; the imperfect phase balance leads to the mixing of the third and fourth Stokes parameters. This mixing generates measurement errors if not compensated for.

### 5.2 HUT Fully Polarimetric Calibration Standard

To calibrate the Fully Polarimetric Radiometer (FPoR) discussed in Section 4, a passive calibration reference, the *Fully Polarimetric Calibration Standard* (FPCS) [P3], was developed in the current work. A photograph of the standard is presented in Fig. 6. The versatility of the standard is important, as the FPoR is used not only for airborne experiments but also for ground-based (e.g., roof-top) and laboratory measurements. On the other hand, the number of calibration personnel is often limited in measurement campaigns and the personnel may be changed. This emphasized the importance of good ergonomics. The FPCS has a modular structure, which enables high calibration accuracy to be combined with versatile application and ease of transport, mobilization, and operation. Furthermore, a standardized calibration procedure is followed in order to avoid flaws during calibration, minimize susceptibility to operating personnel, and
reduce temporal variations. This procedure applies unpolarized, tri-polarimetric, and fully polarimetric brightness temperature scenes to suppress calibration uncertainties [P3].

5.2.1 Subsystems

The FPCS comprises four subsystems: (A) the hot target subsystem, (B) the cold target subsystem, (C) the phase retardation plate, and (D) the pedestal [P3]. Details of the subsystems are presented in the following section.

The hot target subsystem includes a hot blackbody target and a large, freestanding, polarization-splitting metal wire grid [P2], both housed in an aluminum cylinder. The grid was fabricated using a simple and cost-effective piece of apparatus, shown in Fig. 7. The hot blackbody target is a microwave absorber attached to the inner surface of the
Figure 7. Wire winding apparatus for the manufacturing of polarizing grids: (A) grid frames and former; (B) manually rotatable lathe chuck; (C) computer control for linear translator; (D) linear translator, and (E) wire feeding tool [P2].

cylinder. For practical reasons the temperature is uncontrolled during calibration. Therefore, the temperature of the hot target is continuously monitored using three resistive temperature detectors embedded in the absorber.

The cold target subsystem consists of a convoluted microwave absorber in an aluminum container. Prior to calibration, the absorber is cooled to $\sim 77.4$ K using liquid nitrogen. During calibration, the hot target subsystem is attached inside the cold target subsystem; when combined, the two subsystems are equal to a linearly polarized standard.

In order to generate the full Stokes reference vector, a phase retardation plate is inserted into the RF path between the antenna of the FPoR and the linearly polarized standard. The retardation plate is a Rexolite slab with 1.82-mm wide and 6.58-mm deep parallel grooves at 3.25-mm spacing, the grooves being machined on one face. The total thickness of the plate is 11.73 mm. Rexolite was selected due to its excellent electrical and superior mechanical characteristics.

The linearly polarized standard is mounted on a pedestal, which holds the standard in the radiometer antenna beam; the panhead of the pedestal allows the standard to be steplessly rotated over $\theta$ about the antenna polarization basis.
5.2.2 Characteristics

Several tests were carried out to define the characteristics of the manufactured polarizing wire grid [P2] and the whole calibration system [P3]; the characteristics are summarized in Tables 3 and 4, respectively.

The developed grid has a large clear aperture; the fabrication of such a grid is non-trivial. The wire spacing, however, is relatively uniform, suggesting an applicable upper frequency of 100 GHz. Transmission measurements showed the grid to be an almost ideal polarizer and the co-polarized and cross-polarized transmission (Fig. 8) were found to be very close to theoretical predictions as a function of the rotation angle $\theta$ [P2].

When testing the FPCS it was noticed that the lowest generated brightness temperatures (vertical brightness temperature at $\theta = 90^\circ$ and horizontal at $\theta = 0^\circ$) have a warm bias compared to the brightness temperature of a conventional cold blackbody target [P3]. Furthermore, this bias is different at $\theta = 0^\circ$ ($\approx 5.8$ K) from that at $\theta = 90^\circ$ ($\approx 8.6$ K). It was also noticed that these biases are very repeatable; the standard

![Graph](image)

*Figure 8. The power transmission coefficient of the fabricated wire grid as a function of grid rotation angle. Experimental values are denoted by dots with error bars, theoretical co-polarized values by a solid line, and theoretical cross-polarized values by a dashed line [P2].*
deviations of the aforementioned values are 0.5 K and 0.3 K, respectively, for $\theta = 0^\circ$ and $\theta = 90^\circ$. Several sources were considered in an attempt to explain this anomaly: (A) the interchannel cross-talk of the radiometer; (B) emissions from the radiometer that are re-directed back to the antenna, and (C) the non-idealities of the polarizer grid. However, the interchannel cross-talk between the orthogonal channels of the FPoR was found to be low [P5]. To study the re-directed antenna emissions, the FPCS was steplessly translated perpendicular to the FPoR antenna line-of-sight in front of the antenna beam (at $\theta = 90^\circ$). The measured brightness temperature was not modulated, indicating that the reflected emissions from the grid-supporting frame are not the source of the anomaly. Similarly, the translation would have caused brightness temperature fluctuations in the presence of a re-directed interfering local oscillator (LO) signal [Jackson, 1999] or a backwards-flowing signal from the RF amplifiers. Furthermore, possible reflections from the air-nitrogen interface were studied keeping the standard in a fixed position in front of the antenna; no significant decrease in the cold brightness temperature was observed, indicating that such reflections are negligible [Blume, 1977]. It is noted that possible reflections of (incoherent) antenna emissions from the polarizing grid could not be excluded from the measurements taken. Such reflections, however, are predicted to be insignificant because of geometry; see Fig. 5. It was thus concluded that the source of the warm brightness temperature bias is most probably the non-ideality of the polarizing grid. Modeling the grid characteristics by the warm bias, however, gives somewhat deteriorated values (Table 4) compared to the nearly ideal values obtained in the transmissivity measurement (Table 3). A possible explanation for this discrepancy is the sacking of the wires during calibration; a stainless steel frame has over three times higher thermal coefficient than molybdenum wires [Schaffer et al., 1999]. During a polarimetric calibration the physical temperature of the grid is of the order of 0°C, whereas the measurements in [P2] were conducted at room temperature. The sacking of the wires would also explain the different results at $\theta = 0^\circ$ and $\theta = 90^\circ$. Another potential explanation for the sacking is the deterioration of the wire bonding.

Using the FPoR as a reference instrument, the comparison of the tri-polarimetric and fully polarimetric brightness temperature scenes made possible the determination
Table 3. The characteristics of the fabricated polarizing wire grid [P2].

<table>
<thead>
<tr>
<th>Parameter (Unit)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear aperture (mm)</td>
<td>240 × 340 (Oval)</td>
</tr>
<tr>
<td>Wire spacing (µm)</td>
<td>300±74</td>
</tr>
<tr>
<td>Wire diameter (µm)</td>
<td>100</td>
</tr>
<tr>
<td>Wire material</td>
<td>Molybdenum</td>
</tr>
<tr>
<td>Frame material</td>
<td>Stainless steel</td>
</tr>
<tr>
<td>The measured transmission coefficient in co-polarization, electric field perpendicular to the wires (%) (theoretical)</td>
<td>99.1±0.4 (99.6)</td>
</tr>
<tr>
<td>The measured transmission coefficient in co-polarization, electric field in parallel with the wires (%) (theoretical)</td>
<td>&lt; 0.3 (&lt; 0.1)</td>
</tr>
<tr>
<td>The measured ohmic losses (%) (theoretical)</td>
<td>0.3 &lt; L &lt; 1.3 (0.4)</td>
</tr>
</tbody>
</table>

Table 4. Measured characteristics of the Fully Polarimetric Calibration Standard (at 36.5 GHz where applicable) [P3].

<table>
<thead>
<tr>
<th>Parameter (Unit)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power transmission of the polarizing grid, electric field perpendicular to the grid wires (%)</td>
<td>97.0 (θ = 0°) 95.7 (θ = 90°)</td>
</tr>
<tr>
<td>Power transmission of the polarizing grid, electric field in parallel with the grid wires (%)</td>
<td>2.0 (θ = 0°) 3.3 (θ = 90°)</td>
</tr>
<tr>
<td>Ohmic losses of the polarizing grid (%)</td>
<td>1.0</td>
</tr>
<tr>
<td>Phase shift of the retardation plate (theoretical) (deg)</td>
<td>35.3 (37.0)</td>
</tr>
<tr>
<td>Transmission loss of the retardation plate in parallel with the grooves (theoretical)</td>
<td>1.0096 (1.011)</td>
</tr>
<tr>
<td>Transmission loss of the retardation plate perpendicular to the grooves (theoretical)</td>
<td>1.0073 (1.008)</td>
</tr>
<tr>
<td>Drift of the brightness temperature of the cold target in 10 min, 15 min, 20 min, and 25 min, respectively (K)</td>
<td>0.1, 0.35, 0.75, 1.3</td>
</tr>
<tr>
<td>Total weight (kg)</td>
<td>28</td>
</tr>
</tbody>
</table>

of the characteristics of the phase retardation plate. The measured insertion loss values are very close to the theoretical ones. The high repeatability of the measurements [P3] indicates that the retardation plate is well matched at the applied frequency band. The measured phase shift of the plate, however, deviates 1.7° from the theoretical value. Possible explanations are machining tolerances and uncertainties in estimating the dielectric constant of Rexolite.
5.3 NOAA/ETL Fully Polarimetric Calibration Standard

The function principle of the developed fully polarimetric calibration method was first verified using the 10.7 GHz receiver of the Polarimetric Scanning Radiometer (PSR) of the NOAA/ETL (National Oceanic and Atmospheric Administration, Environmental Technology Laboratory, USA), and a developed calibration standard [P1]. The PSR instrument and the calibration standard are presented in Fig. 9. The standard was implemented by developing a rotatable retardation plate and inserting it over the aperture of an existing linearly polarized calibration standard. The linearly polarized standard comprises a polarizing wire grid and blackbody targets at ambient and boiling nitrogen temperatures. The polarizing grid is a rectangular Duroid microwave board of a thickness of 0.40 mm with printed 0.17-mm-thick copper grid lines. The line width of the lines is 0.15 mm and the filling factor is 0.25. To improve mechanical stability, the grid is attached to a 13-mm-thick Styrofoam slab. The overall grid dimensions are 444 mm × 582 mm. The retardation plate has an aperture diameter of 518 mm and it was fabricated out of a Rexolite slab with 2.38-mm-wide and 15.12-mm-deep parallel

Figure 9. The NOAA fully polarimetric calibration standard and the Polarimetric Scanning Radiometer (PSR): (A) PSR housing, (B) PSR scanhead, (C) retardation plate, and (D) linearly polarized standard [P1].
grooves at a 5.07-mm spacing, the grooves being machined on both faces. The theoretical phase shift of the plate is 53.4° at 10.7 GHz; the theoretical power reflections are 1.9% and 1.0% for polarizations parallel with and perpendicular to the grooves, respectively. Both the linearly polarized standard and the retardation plate are rotatable around the vertical axis to any arbitrary angle, \( \theta \) and \( \phi \), respectively [P1].

5.4 Calibration Uncertainties in Wind Vector Measurements

As discussed in Section 3.4, one of the most promising applications of airborne and spaceborne polarimetric radiometry is near-surface wind vector retrieval, for which the impact of radiometric calibration accuracy was analyzed [P1], [P3].

The influence of calibration standard parameter uncertainties was studied for two wind vector measurement scenarios; an airborne radiometer at 36.5 GHz calibrated using the FPCS [P3] and a spaceborne three-frequency radiometer (at 10.7 GHz, 18.7 GHz, and 37 GHz) calibrated using a potential state-of-the-art calibration standard [P1], which, it was anticipated, would be realizable at the current level of technology. The parameter uncertainties of the FPCS and of the potential standard are presented in Table 5; the calibration error estimates, presented in Table 6, were obtained using Eq. (22). Since the systematic uncertainty can be compensated for \textit{a posteriori}, at least in part [P1], the random uncertainties are presented separately.

As a benchmark set of wind vector accuracy requirements, the criteria proposed by the U.S. NPOESS (National Polar Orbiting Environmental Satellite System) were selected. A mandatory rms direction accuracy of 20° for wind speeds greater than 5 m/s has been specified, and with 10° as a goal [NPOESS/IPO, 2000]. Assuming that the systematic uncertainties of the studied calibration standards are compensated for \textit{a posteriori}, the random uncertainties define the total calibration accuracy. It is further assumed that the calibration accuracy is the dominant factor in determining the absolute accuracy of the radiometer. Then, for 5 ms\(^{-1}\) wind speed and using only \( T_3 \) the achievable accuracy of the retrieved wind direction is approximately 50° for the FPCS scenario and in the order of 25°–40° (depending on frequency) for the potential state-of-the-art standard scenario. Note, however, that these estimates are conservative [P1]; for higher wind speeds the bias restrictions can be relaxed. Furthermore, if the number
Table 5. Random and systematic parameter uncertainties of two fully polarimetric calibration standards [P1], [P3].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fully Polarimetric Calibration Standard</th>
<th>Potential state-of-the-art calibration standard</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Random uncertainty</td>
<td>Systematic uncertainty</td>
</tr>
<tr>
<td>Brightness temperature of hot target (K)</td>
<td>0.15</td>
<td>0.2</td>
</tr>
<tr>
<td>Brightness temperature of cold target (K)</td>
<td>0.15</td>
<td>0.5</td>
</tr>
<tr>
<td>Brightness temp. of unpolarized target (K)</td>
<td>0.15</td>
<td>0.2</td>
</tr>
<tr>
<td>Physical temperature of retardation plate (K)</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Physical temperature of polarizing grid (K)</td>
<td>- a</td>
<td>- a</td>
</tr>
<tr>
<td>Rot. angle of linearly polarized standard (°)</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Rotation angle of retardation plate (°)</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Phase shift of retardation plate (°)</td>
<td>-</td>
<td>0.2</td>
</tr>
<tr>
<td>Transmission coefficient of polarizing grid, electric field in parallel with grid wires</td>
<td>-</td>
<td>- a</td>
</tr>
<tr>
<td>Transmission coefficient of polarizing grid, electric field perpendicular to grid wires</td>
<td>-</td>
<td>- a</td>
</tr>
<tr>
<td>Loss of ret. plate in parallel with slow axis</td>
<td>-</td>
<td>9·10⁻⁴</td>
</tr>
<tr>
<td>Loss of ret. plate perpendicular to slow axis</td>
<td>-</td>
<td>8·10⁻⁴</td>
</tr>
</tbody>
</table>

* included in the uncertainties of the hot and cold target

Table 6. The errors of measured wind vector brightness temperatures due to calibration standard uncertainties [P1], [P3].

<table>
<thead>
<tr>
<th>Calibration standard</th>
<th>Frequency (GHz)</th>
<th>Random uncertainty (K)</th>
<th>Total uncertainty (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T_v</td>
<td>T_h</td>
<td>T_3</td>
</tr>
<tr>
<td>Fully Polarimetric Calibration Standard</td>
<td>36.5</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Potential state-of-the-art calibration standard</td>
<td>10.7</td>
<td>0.07</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>18.7</td>
<td>0.06</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>37</td>
<td>0.06</td>
<td>0.03</td>
</tr>
</tbody>
</table>

of generated calibration scenes is increased and multiple radiometer channels are combined, the errors generated by random uncertainties of a potential calibration system fall within the prescribed NPOESS limits [P1]. To suppress the calibration errors of the FPCS within the NPOESS limits, however, the following methods should be considered: the removal of remaining offset using statistical methods; applying
circle flights and the assumption $<T_3(\phi_W)> \approx 0$, and using *in situ* reference data [P3]. In addition, the bias restrictions can be relaxed using the full Stokes vector [P1].

Compared to the retrieval of the wind direction, the sensitivity of wind speed retrieval to calibration uncertainties is much lower. The total uncertainties (both random and systematic) of the FPCS, for example, suggest an achievable wind speed measurement accuracy of the order of 0.25 ms\(^{-1}\) [P3].

### 5.5 Laboratory Demonstrations

The viability of the developed fully polarimetric calibration standards was demonstrated by performing several fully polarimetric calibrations. The Fully Polarimetric Radiometer (FPoR) was calibrated with the FPCS [P3]; the 10.7 GHz receiver of the PSR was calibrated with the NOAA standard [P1]. The unknown gain and offset terms of the calibrated radiometers were determined and the brightness temperatures generated by the standards were retrieved.

Fig. 10 illustrates the calibrated brightness temperature scenes that were generated by the FPCS during a sample calibration in the laboratory. The scenes without the retardation plate (tri-polarimetric calibration scenes) are optional, but they are used to improve the calibration accuracy [P3].

An example of the brightness temperature scenes generated with the NOAA fully polarimetric calibration standard is illustrated in Fig. 11. In this calibration experiment the rotation angle of the retardation plate \(\varphi\) was 90° and a large number (~400) of rotation angles of the linearly polarized standard \(\theta\) were applied.
Figure 10. Laboratory calibration demonstration using the FPCS: Tri- and fully polarimetric brightness temperature scenes are generated as a function of time. The data points applied in post-processing are indicated using dark vertical bars. The following target parameters were used: (A) \( \theta = 87.2 \degree, \phi = 0.7 \degree \); (B) \( \theta = 87.2 \degree, \phi = 90.7 \degree \); (C) \( \theta = 87.2 \degree, \) no retardation plate; (D) \( \theta = 45.6 \degree, \phi = 0.7 \degree \); (E) \( \theta = 45.6 \degree, \phi = 90.7 \degree \); (F) \( \theta = 45.6 \degree, \) no retardation plate; (G) \( \theta = 1.1 \degree, \phi = 0.7 \degree \); (H) \( \theta = 1.1 \degree, \phi = 90.7 \degree \); and (I) \( \theta = 1.1 \degree, \) no retardation plate [P3].
Figure 11. Laboratory demonstration using the NOAA/ETL fully polarimetric calibration standard: Generated Stokes parameters as a function of linearly polarized standard rotation angle $\theta$ ($\phi = 90^\circ$). The solid line represents the a priori brightness temperature, and the symbols the retrieved brightness temperature [P1].

5.6 Contribution of the Work to the Calibration of Polarimetric Radiometers

A novel fully polarimetric end-to-end calibration technique was developed in this work. The developed technique is based on a linearly polarized standard [Gasiewski and Kunkee, 1993] and a precision dielectric retardation plate. The theoretical background for the calibration method has been thoroughly studied and the mathematics necessary to determine the a priori Stokes vectors and error analysis are derived. A calibration matrix inversion technique is presented. Using the developed calibration technique, all the unknown calibration parameters of fully polarimetric radiometers can be retrieved. Hitherto, there have been no end-to-end calibration methods for coherent fully
polarimetric radiometers. Thus, the present work significantly improves the viability of a coherent approach in fully polarimetric radiometry, compared to incoherent solutions.

Applying the developed calibration technique, the Fully Polarimetric Calibration Standard (FPCS) was developed for the Fully Polarimetric Radiometer (FPoR), which was presented in Section 4. The calibration standard is based on a modular structure, which combines high calibration accuracy with ease of transport, mobilization, and operation; a single operator can take care of the whole calibration process, if necessary. One of the key components, a large-aperture free-standing metal wire polarizing grid, was constructed using a simple wire winding apparatus. The grid was analyzed in detail and, when tested, proved to be an almost ideal polarizer at the applied frequency band. Furthermore, an existing linearly polarized calibration standard of NOAA/ETL was extended into a fully polarimetric one. The function of both standards was successfully demonstrated. In addition, a variety of laboratory tests were performed to define the characteristics of the FPCS and the associated uncertainties. To suppress calibration uncertainties, an advanced calibration procedure, which applies both tri-polarimetric and fully polarimetric brightness temperature scenes, was developed. It was demonstrated that the procedure also makes possible the accurate determination of retardation plate characteristics.

Using calibration parameter uncertainties and an anticipated oceanic brightness temperature scene, the applicability of fully polarimetric calibration standards to wind vector radiometry was studied. Specifically, it was shown that the NPOESS brightness accuracy requirements [NPOESS/IPO, 2000] prescribed for wind vector measurements could be achieved using a potential state-of-the-art fully polarimetric calibration system based on the principles presented and the current level of technology. On the other hand, although the calibration accuracy of the FPCS was shown by analysis to fall within the sub-Kelvin range for a sample wind vector measurement, the achievable pixel-to-pixel wind direction accuracy does not fulfill the NPOESS requirements if only the third Stokes parameter is applied for the retrieval. Therefore, the application of the whole Stokes vector and additional calibration methods, such as circle flights [Yueh et al., 1995] and/or in situ reference data, should be considered.

The current work also contributes to the calibration of radiometers in general, e.g., to error analysis and to the determination of calibration standard characteristics.
6 Airborne Experiment

The results presented in [Lahtinen et al., 2001] suggest that wind-generated maritime brightness temperature signatures may vary locally. To acquire fully polarimetric measurement data for a semi-enclosed sea, to test the airborne function of the Fully Polarimetric Radiometer, and to verify the feasibility of the whole polarimetric radiometer system for wind vector measurements, a flight campaign was carried out in March 2002 over the Kallbådagrund area, Gulf of Finland, the Baltic Sea [P5]. The Baltic Sea is a semi-enclosed brackish water basin in northern Europe. Circular flights were carried out to collect fully polarimetric brightness temperature signatures as a function of the azimuth angle with respect to the surface wind direction. Data were collected with a variety of incidence angles between 44° and 53° by altering the roll and pitch angles of the aircraft between different sets of circular flights. The radiometer was calibrated as described in [P3]. The mixing of the first three Stokes parameters due to the rotation of the antenna polarization basis was compensated for in post-processing; attitude data was provided by the GPS/INS system of the aircraft, which has a maximum inaccuracy of 0.1° [BEI Technologies, 1998].

6.1 Results

In the measurement campaign a total of 22 datasets were obtained for three different surface wind speeds: 7.4 ms\(^{-1}\), 8.9 ms\(^{-1}\), and 9.0 ms\(^{-1}\) reduced to 19.5 m elevation. The wind speed was scaled according to [Smith, 1988]. Note, however, that due to an unfortunate failure of the attitude determination system of the aircraft, the datasets collected with an 8.9 ms\(^{-1}\) wind speed are of limited value and are thus not discussed here.

An example of the retrieved Stokes parameters with respect to wind direction at 9.0 ms\(^{-1}\) wind speed is presented in Fig. 12 [P5]. In this particular dataset, the mean incidence angle and banking of the aircraft (\(\sim\) the roll angle of the antenna beam) were 43.6° and −2.2°, respectively. During the measurement the attitude of the aircraft was relatively stable; the standard deviations for the aforementioned parameters were 0.9° and 1.7°, respectively. As can also be seen in the sample dataset (Fig. 12), the potential
Figure 12. Polarimetric brightness temperatures of the sea surface, measured using the developed Fully Polarimetric Radiometer. Individual points indicate the measurement values with respect to wind direction; the solid line represents the fitted second-order harmonic model for the first three Stokes parameters. Data points within 9° of the direction of the Sun are circled. The data was collected using a mean incidence angle of 43.6° (standard deviation 0.9°) and the in situ wind speed was 9.0 ms⁻¹ referenced to 19.5 m above the surface [P5].

The harmonic modulation of the fourth Stokes parameter is very small (< 0.1 K) in the datasets collected. This result is in agreement with observations reported in [Laursen and Skou, 2001] for 34 GHz (see Fig. 2). On the other hand, the orthogonal brightness temperatures and the third Stokes parameter demonstrate, respectively, even and odd harmonic azimuth dependence on relative wind direction, as reported earlier, e.g., in [Yueh et al., 1999; Piepmeier and Gasiewski, 2001a; Laursen and Skou, 2001]. The fitting of second-order harmonic models (Eqs (10)-(12)) to the retrieved brightness temperatures gives very good results for the first three Stokes parameters; excluding the
Table 7. Harmonic coefficients of the measured Stokes parameters [P5]. For comparison, the coefficients based on [Yueh et al., 1999] are given in parenthesis.

<table>
<thead>
<tr>
<th>Harmonic</th>
<th>$T_r$ (K)</th>
<th>$T_b$ (K)</th>
<th>$T_3$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Harmonic</td>
<td>0.38 (1.0)</td>
<td>0.05 (0.1)</td>
<td>−0.41 (−0.8)</td>
</tr>
<tr>
<td>2nd Harmonic</td>
<td>0.18 (0.3)</td>
<td>−0.65 (−1.1)</td>
<td>−0.69 (−1.4)</td>
</tr>
</tbody>
</table>

data that was corrupted by sun glint (highlighted in Fig. 12), the standard deviation from the model is 0.11 K, 0.22 K, and 0.15 K for $T_r$, $T_b$, and $T_3$, respectively. For comparison, the instrumental noise for the data is 0.11 K, 0.09 K, and 0.14 K for $T_r$, $T_b$, and $T_3$, respectively. This suggests very low — if not negligible — geophysical noise.

The first- and second-order harmonic coefficients obtained for the first three Stokes parameters for the sample dataset are presented in Table 7; for comparison, the empirical model values presented in [Yueh et al., 1999] for comparable wind speed, incidence angle, and frequency range are also included. In general, the harmonic coefficients of all the datasets measured were much smaller than those presented in [Yueh et al., 1999]; for the sample dataset, the coefficients are about 50% smaller. These results suggest that the relationship between the wind vector and the Stokes parameters may vary locally; the measurements in [Yueh et al., 1999] were carried out off the Californian coast, in the Pacific Ocean.

In estimating the absolute accuracy of this measurement, the error sources discussed in Section 4.2 were accounted for. If the different error sources are assumed to be independent, the overall pixel-to-pixel absolute accuracy becomes 0.5 K, 0.6 K, 0.5 K, and 0.8 K for $T_r$, $T_b$, $T_3$, and $T_4$, respectively. The most significant error source is the calibration uncertainty. Note, however, that the absolute accuracy of the data was further enhanced by assuming the third and fourth Stokes parameters to be zero mean over a full circle of azimuth.

6.2 Contribution of the Work to Polarimetric Wind Vector Radiometry

The feasibility of the developed radiometer system for airborne measurements was verified in a wind vector experiment. In the experiment, the fully polarimetric brightness temperature signatures of the sea surface were measured and compared to the azimuth angle of surface wind. The first fully polarimetric dataset of semi-enclosed seas is presented.
The results suggest that the applicability of the fourth Stokes parameter is limited for wind vector determination at a 44°-53° incidence angle range at 36.5 GHz. Note, however, that the signature of the fourth parameter should increase with an increasing incidence angle [Söllner, 1997; Yueh et al., 1997]. Nevertheless, the results of the first three Stokes parameters confirm the usefulness of these parameters in retrieving surface wind vectors in sea areas. On the other hand, the harmonic coefficients of the azimuth modulation were found to be much lower than those reported in [Yueh et al., 1999]. This suggests that the relationship between the wind vector and the Stokes parameters may vary locally. Furthermore, the geophysical noise of the measured Stokes parameters is small, indicating very homogeneous wave conditions in the test area. The minimal scatter of the results also confirms the correct functioning and high quality of the measurement system.
7 Conclusions

During the last decade, polarimetric remote sensing radiometry has been the subject of intensive study. In particular, the measurement of maritime wind vectors is one of the most promising applications. There are several potential polarimetric radiometer architectures viable for airborne and/or spaceborne remote sensing. Up till now, however, the benefits and limitations associated with different topologies have not been thoroughly studied. In presenting results for a fully polarimetric radiometer that is based on analog direct cross-correlating architecture and presenting results on the calibration of such a radiometer, the current work reduces the uncertainties in evaluating the optimal technique with respect to applications and user requirements.

In the current work, a fully polarimetric radiometer (Helsinki University of Technology’s Fully Polarimetric Radiometer, FPoR) has been designed and constructed for microwave remote sensing. The radiometer operates at 36.5 GHz; besides airborne measurements, it is also suited for ground-based and laboratory applications. The FPoR is the first successful demonstration of a polarimetric remote sensing radiometer that is based on analog direct cross-correlating topology; commercial analog multipliers were used as correlating elements. Compared to other polarimetric radiometer topologies, the applied solution provides several advantages, e.g., the simple structure of both the receiver and the cross-correlator, which increases reliability and reduces costs, mass, size, and power consumption.

A novel fully polarimetric calibration technique was developed. Hitherto, there have been no reliable means for the end-to-end calibration of coherent fully polarimetric radiometers. The theoretical background of the technique was also studied. Using the principles presented, the Fully Polarimetric Calibration Standard (FPCS) was developed to calibrate the FPoR. The work also included the development of the key quasioptical components, a large polarizing grid and a phase retardation plate. Furthermore, the existing linearly polarized calibration standard of the NOAA/ETL was extended into a fully polarimetric one. The function of both calibration standards was successfully demonstrated.

Since the lack of a reliable end-to-end calibration method has been a serious disadvantage when comparing correlating fully polarimetric radiometers with those based on the polarization combining approach, the developed calibration technique...
significantly increases the feasibility of coherent fully polarimetric radiometers for remote sensing applications. In particular, correlating radiometers based on analog cross-correlators benefit from the new calibration system.

The characteristics and function of the FPoR and the FPCS were studied in a variety of laboratory measurements. It was verified that the requirements set for the radiometric resolution, stability, and absolute accuracy of the radiometer were met. Furthermore, the design was proven to be ergonomically functional; a single operator can transport, mobilize, and operate the system, if necessary. The feasibility of the system for airborne measurements was successfully demonstrated in a wind vector experiment. The results indicate that the developed radiometer system is a useful tool in developing wind vector retrieval algorithms for present and future operational airborne and spaceborne satellite instruments; other potential applications include, for instance, the detection of the distribution of hydrometeors. Furthermore, it was demonstrated that the applied analog direct correlating concept and the developed calibration technique are feasible and competitive options for building ground-based and airborne polarimetric radiometers; the use of these techniques for spaceborne radiometers remains to be verified.

Due to its precise calibration, the absolute accuracy of the developed radiometer system falls into the sub-Kelvin range for a typical wind vector measurement, given that the possible non-linearity of the receiver is small. Although the absolute accuracy achieved is high, the use of the whole Stokes vector and potentially additional calibration methods (e.g., circle flights and the use of in situ reference data) are necessary to fulfill the wind vector accuracy requirements proposed for the U.S. NPOESS (National Polar Orbiting Environmental Satellite System). It was shown, however, that using a spaceborne fully polarimetric calibration system based on the principles presented and constructed at the current level of technology, the absolute pixel-to-pixel accuracy necessary to meet the NPOESS requirements could be achieved.

Using the developed radiometer system, an airborne experiment was conducted over the Gulf of Finland. The results of the fourth Stokes parameter suggest that the applicability of that parameter is limited for wind vector determination at the applied frequency and incidence angle range. Nevertheless, the first three Stokes parameters show clear azimuth modulation, confirming the earlier results of the usefulness of these
parameters in retrieving surface wind vectors in sea areas. However, the harmonic coefficients of the azimuth modulation were found to be significantly lower than those reported in [Yueh et al., 1999]. Although more measurements are needed to verify these results, they suggest that the relationship between the wind vector and the Stokes parameters may vary locally. The result emphasizes the importance of further study of the possible spatial variation of the polarimetric signature dependence on wind vectors; with regard to present and future operational airborne and spaceborne instruments, improved accuracy in retrieving wind vector maps should prove beneficial for many local and global applications.
8 Summary of Appended Papers

[P1]

A technique for absolute end-to-end calibration of a fully polarimetric microwave radiometer is presented. The technique is based on the tri-polarimetric calibration technique of Gasiewski and Kunkee but extended to provide a means of calibrating all four Stokes parameters. The extension is facilitated using a biaxial phase-retarding microwave plate to provide a precisely known fourth Stokes signal from the Gasiewski-Kunkee linearly polarized standard. The relations are presented that are needed to determine the Stokes vector produced by the augmented standard, and the effects of non-idealities in the various components are discussed. The application of the extended standard is illustrated to determining the complete set of radiometer constants (the calibration matrix elements) for the NOAA Polarimetric Scanning Radiometer (PSR) in a laboratory environment. A calibration matrix inversion technique and error analysis are described. The uncertainties associated with practical implementation of the fully polarimetric standard for spaceborne wind vector measurements are discussed relative to error thresholds anticipated for wind vector retrieval from the U.S. National Polar-Orbiting Environmental Satellite System (NPOESS).

[P2]

The construction of large-aperture free-standing metal wire grids is demonstrated for the lower end of the millimeter wave spectral region. For the two grids constructed the co-polarized and cross-polarized components of the power transmitted were measured at a 45° oblique incidence. The measurements were performed as a function of wire orientation angle and in more detail at selected angles. The results are in good agreement with the theoretical results presented in the literature. In order to save time and cost the construction apparatus was simplified from those reported previously by other authors. It was shown that for this frequency range the grid characteristics are not degraded when such an apparatus is used. The grids were manufactured for the calibration system of the Helsinki University of Technology (HUT) polarimetric radiometer.
This paper describes the Helsinki University of Technology (HUT) Fully Polarimetric Calibration Standard (FPCS). The developed standard generates a complete Stokes reference vector and it is applied for the end-to-end absolute calibration of a fully polarimetric microwave radiometer at 36.5 GHz. The FPCS is based on the function principle of a Gasiewski-Kunkee linearly polarized (tri-polarimetric) standard, with an additional phase retardation plate to generate the fourth Stokes parameter. Design considerations and operational aspects of the standard are discussed in this paper. An advanced calibration procedure, which takes advantage of both the tri-polarimetric and fully polarimetric calibration scenes to suppress calibration uncertainties, is introduced. The feasibility of the standard has been verified and the generated brightness temperatures in a sample calibration are presented. An extensive set of tests has been performed to evaluate the characteristics and performance of the calibration standard. Furthermore, the use of the advanced calibration procedure to measure the characteristics of the phase retardation plate has been successfully demonstrated. The achievable calibration accuracy is analyzed and discussed relative to requirements for maritime wind vector measurements; the results indicate that the pixel-to-pixel retrieval of the wind speed is possible with high accuracy and the retrieval of the wind direction with at least moderate accuracy. In addition to calibration of a fully polarimetric radiometer, other potential applications, e.g., linearity measurements, are discussed.

Two different designs of analog correlators for radiometry are compared in this paper. A continuum correlator based on a microwave non-linear device is a simple and inexpensive way to detect wide-band polarized signals. Analysis and extensive measurements including linearity, dynamic range, amplitude response, phase balance, and stability are presented, and the suitability of the designs for microwave radiometry is discussed. Both correlators showed nearly ideal performance. A novel method for determining the correlator degradation factor is applied.
The design, characteristics, and operation of the Helsinki University of Technology Fully Polarimetric Radiometer (FPoR) are described. The developed radiometer can be used for airborne remote sensing at 36.5 GHz; however, ground based and laboratory measurements are also possible. A direct cross-correlation technique with analog correlators, which measures all four Stokes parameters simultaneously, is applied. This paper is the first successful demonstration of an analog direct cross-correlation technique for polarimetric remote sensing radiometry.

The radiometer was subjected to a variety of laboratory tests and considerable attention is given to analysis of the characteristics of the instrument. Owing to the effective active temperature control system of the receiver, the radiometric stability of the instrument was found to be very high; test results showing stabilities below 10 mK and of 4-40 mK on time scales of 800 s (±13 min) and 8,000 s (±2 h 13 min), respectively, are presented. Furthermore, the absolute accuracy of the system is analyzed to be at a sub-Kelvin level for most measurement conditions.

A maritime wind vector experiment was carried out over the Gulf of Finland. The feasibility and performance of the applied correlation technique and the whole radiometer system were verified for fully polarimetric airborne measurements. The obtained brightness temperatures of the first three Stokes parameters show typical harmonic behavior with respect to the surface wind; the results suggest, however, that the model coefficients presented earlier for oceans may not be directly applicable for different conditions.
References


T. J. Jackson, R. Bindlish, M. Klein, A. Gasiewski, and E. G. Njoku, "Soil moisture retrieval and AMSR validation using airborne microwave radiometry during


Appendix A. The Effect of a Retardation Plate on Orthogonal Brightness Temperatures

This appendix contains the derivation for the effect of a retardation plate on vertical brightness temperature. The derivation for the horizontal polarization is analogous; therefore, only results are given. The brightness temperature contribution of retardation plate losses is excluded in this analysis but is presented in Appendix C. The results are discussed in Section 5.1.

Using the notations of Fig. A-1, an electric field at a certain frequency can be written:

\[ \bar{E}(t) = \bar{E}_x(t) + \bar{E}_y(t) = E_{x0}(t) \cdot \cos(\omega \cdot t) \cdot \bar{u}_x + E_{y0}(t) \cdot \cos(\omega \cdot t + \phi(t)) \cdot \bar{u}_y, \quad (A.1) \]

where \( E_{x0} \) and \( E_{y0} \) are the amplitudes of the electric field in the \( x \) and \( y \) directions, respectively, \( t \) is time, \( \omega \) radian frequency, and \( \phi \) the phase difference between electromagnetic radiation in the \( y \)- and \( x \)-axes. Here the \( x \)-axis orientation coincides with the radiometer’s vertical polarization, the \( y \)-axis with the radiometer’s horizontal polarization.

**Figure A-1.** The relationship between the electric fields in an antenna-based coordinate system and in a retardation plate-based coordinate system.
As \( E_{x0}, E_{y0}, \) and \( \phi \) change only slowly with time, for the sake of simplicity they will here be considered to be time independent. If it is assumed that a retardation plate with machined grooves is matched with the surrounding medium (air), after passing the plate the electric fields relative to the plate are:

\[
E_{||}(t) = \frac{E_{x0}}{l_{||}} \cos(\omega \cdot t - \zeta) \cos(\phi) + \frac{E_{y0}}{l_{||}} \cos(\omega \cdot t + \phi - \zeta) \sin(\phi) \tag{A.2}
\]

\[
E_\perp(t) = -\frac{E_{x0}}{l_{\perp}} \cos(\omega \cdot t) \sin(\phi) + \frac{E_{y0}}{l_{\perp}} \cos(\omega \cdot t + \phi) \cos(\phi), \tag{A.3}
\]

where \( l_{||} \) and \( l_{\perp} \) are the losses parallel with and perpendicular to the retardation plate grooves, respectively. The phase shift generated between the axes perpendicular to (\( \perp \)) and parallel with (\( || \)) the grooves is \( \zeta \), and \( \phi \) is the rotation angle of the retardation plate with respect to the \( x \)-axis. In the \( x-y \) system Eqs (A.2) - (A.3) are:

\[
E_x'(t) = \frac{E_{x0}}{l_{||}} \cos(\omega \cdot t - \zeta) \cos^2(\phi) + \frac{E_{y0}}{l_{||}} \cos(\omega \cdot t + \phi - \zeta) \sin(\phi) \cos(\phi) \tag{A.4}
\]

\[
+ \frac{E_{x0}}{l_{\perp}} \cos(\omega \cdot t) \sin^2(\phi) - \frac{E_{y0}}{l_{\perp}} \cos(\omega \cdot t + \phi) \cos(\phi) \sin(\phi)
\]

\[
E_y'(t) = \frac{E_{x0}}{l_{||}} \cos(\omega \cdot t - \zeta) \cos(\phi) \sin(\phi) + \frac{E_{y0}}{l_{||}} \cos(\omega \cdot t + \phi - \zeta) \sin^2(\phi) \tag{A.5}
\]

\[
- \frac{E_{x0}}{l_{\perp}} \cos(\omega \cdot t) \sin(\phi) \cos(\phi) + \frac{E_{y0}}{l_{\perp}} \cos(\omega \cdot t + \phi) \cos^2(\phi).
\]

The generated vertical brightness temperature is derived as follows:
\[
\langle E_t^4 \rangle = \left( \frac{E_{x0}^2}{l_{||}^2} \right) \cos^2(\omega \cdot t - \zeta) \cos^4(\varphi)
+ 2 \frac{E_{x0}^2}{l_{||}^2} \cos(\omega \cdot t - \zeta) \cos(\omega \cdot t + \phi - \zeta) \cos^3(\varphi) \sin(\varphi)
+ 2 \frac{E_{y0}^2}{l_{\perp}^2} \cos(\omega \cdot t - \zeta) \cos(\omega \cdot t) \cos^2(\varphi) \sin^2(\varphi)
- 2 \frac{E_{x0}^2}{l_{||}^2} \cos(\omega \cdot t + \phi - \zeta) \cos(\omega \cdot t + \phi) \cos^3(\varphi) \sin(\varphi) + \frac{E_{x0}^2}{l_{||}^2} \cos^2(\omega \cdot t + \phi - \zeta) \sin^2(\varphi) \cos^2(\varphi)
+ 2 \frac{E_{y0}^2}{l_{||}^2} \cos(\omega \cdot t + \phi - \zeta) \cos(\omega \cdot t + \phi) \cos(\varphi) \sin^3(\varphi)
- 2 \frac{E_{x0}^2}{l_{\perp}^2} \cos(\omega \cdot t + \phi - \zeta) \cos(\omega \cdot t + \phi) \cos^2(\varphi) \sin^2(\varphi) + \frac{E_{x0}^2}{l_{\perp}^2} \cos^2(\omega \cdot t + \phi) \sin^4(\varphi)
- 2 \frac{E_{y0}^2}{l_{\perp}^2} \cos(\omega \cdot t + \phi) \cos(\varphi) \sin^3(\varphi) + \frac{E_{y0}^2}{l_{\perp}^2} \cos^2(\omega \cdot t + \phi) \cos^2(\varphi) \sin^2(\varphi)
\right).
\]

(A.6)

Using the sum and power rules for trigonometric functions and the rules \(\cos^2 \alpha + \sin^2 \alpha = 1\), \(\langle \sin^2(\omega t) \rangle = \langle \cos^2(\omega t) \rangle = \frac{1}{2}\), and \(\langle \sin(\omega t) \cdot \cos(\omega t) \rangle = 0\), Eq. (A.6) becomes:

\[
\langle |E_x|^4 \rangle = \sin^2(\varphi) \cos^2(\varphi) \left[ \frac{E_{x0}^2}{l_{||}^2} \cos(\zeta) - \frac{E_{y0}^2}{l_{||}^2} \cos(\zeta) + \frac{1}{2} \left( \frac{E_{x0}^2}{l_{||}^2} + \frac{E_{y0}^2}{l_{\perp}^2} \right) \right] + \\
+ \cos^3(\varphi) \sin(\varphi) \left[ \frac{E_{x0}^2}{l_{||}^2} \cos(\phi) - \frac{E_{y0}^2}{l_{||}^2} \cos(\phi) \cos(\zeta) \cos(\phi) \sin(\zeta) \sin(\phi) \right] + \\
+ \sin^3(\varphi) \cos(\varphi) \left[ \frac{E_{x0}^2}{l_{||}^2} \cos(\zeta) \cos(\phi) \cos(\zeta) \cos(\phi) \sin(\zeta) \sin(\phi) \right] - \frac{E_{y0}^2}{l_{\perp}^2} \cos(\phi) + \\
+ \frac{1}{2} \cos^4(\varphi) \left[ \frac{E_{x0}^2}{l_{||}^2} \right] + \frac{1}{2} \sin^4(\varphi) \cdot \left[ \frac{E_{x0}^2}{l_{\perp}^2} \right].
\]

(A.7)

Using Eqs (A.8)-(A.12), Eq. (A.7) can be regrouped according to retardation plate rotation angle multiples:
\[
\cos^4(\varphi) = \frac{1}{8} \left[ \cos(4\varphi) + 4\cos(2\varphi) + 3 \right]
\] (A.8)

\[
\sin^4(\varphi) = \frac{1}{8} \left[ \cos(4\varphi) - 4\cos(2\varphi) + 3 \right]
\] (A.9)

\[
\cos^2(\varphi) \sin^2(\varphi) = \frac{1}{8} - \frac{1}{8} \cos(4\varphi)
\] (A.10)

\[
\cos^3(\varphi) \sin(\varphi) = \frac{1}{8} \sin(2\varphi) + \frac{1}{8} \sin(4\varphi)
\] (A.11)

\[
\cos(\varphi) \sin^3(\varphi) = \frac{1}{8} \sin(2\varphi) - \frac{1}{8} \sin(4\varphi).
\] (A.12)

Eq. (A.7) can now be written:

\[
\left\langle \left| E_x \right|^2 \right\rangle = \left[ q_{1v} + q_{2v} \cos(2\varphi) + q_{3v} \cos(4\varphi) + q_{4v} \sin(2\varphi) + q_{5v} \sin(4\varphi) \right]
\] (A.13)

\[
q_{1v} = \frac{1}{16} \left[ \frac{E_{x0}^2}{I_{||}^2} + \frac{3}{2} \frac{E_{x0}^2}{I_{\perp}^2} + \frac{E_{y0}^2}{I_{||}^2} + \frac{E_{y0}^2}{I_{\perp}^2} + 2 \left( E_{x0}^2 - E_{y0}^2 \right) \frac{\cos(\zeta)}{I_{||} I_{\perp}} \right]
\] (A.14)

\[
q_{2v} = \frac{1}{4} \left[ \frac{E_{x0}^2}{I_{||}^2} - \frac{E_{y0}^2}{I_{\perp}^2} \right]
\] (A.15)

\[
q_{3v} = \frac{E_{x0}^2 - E_{y0}^2}{16} \left[ \frac{1}{I_{||}^2} + \frac{1}{I_{\perp}^2} - 2 \frac{\cos(\zeta)}{I_{||} I_{\perp}} \right]
\] (A.16)

\[
q_{4v} = \frac{1}{4} \left[ \left( \frac{1}{I_{||}^2} - \frac{1}{I_{\perp}^2} \right) E_{x0} E_{y0} \cos(\varphi) + 2 \frac{E_{x0} E_{y0}}{I_{||} I_{\perp}} \sin(\varphi) \sin(\zeta) \right]
\] (A.17)

\[
q_{5v} = \frac{1}{8} \left[ \left( \frac{1}{I_{||}^2} + \frac{1}{I_{\perp}^2} \right) E_{x0} E_{y0} \cos(\varphi) - 2 \frac{E_{x0} E_{y0}}{I_{||} I_{\perp}} \cos(\varphi) \cos(\zeta) \right].
\] (A.18)

The associations between the electric field components per unit bandwidth (\(V\cdot m^{-1}\cdot Hz^{-1/2}\)) and the Stokes parameters are:

\[
E_{x0}^2 = 2 \left\langle \left| E_x \right|^2 \right\rangle = 2 \frac{T_{B,v} \cdot k_B \cdot \eta}{\lambda^2}
\] (A.19)

\[
E_{y0}^2 = 2 \left\langle \left| E_y \right|^2 \right\rangle = 2 \frac{T_{B,v} \cdot k_B \cdot \eta}{\lambda^2}
\] (A.20)
\[ E_{x0}E_{y0} \cos(\phi) = 2 \cdot \Re \langle E_x, E_x^* \rangle = \frac{T_{B;3} \cdot k_B \cdot \eta}{\lambda^2} \]  
(A.21)

\[ E_{x0}E_{y0} \sin(\phi) = 2 \cdot \Im \langle E_x, E_x^* \rangle = \frac{T_{B;4} \cdot k_B \cdot \eta}{\lambda^2}. \]  
(A.22)

Combining Eqs (A.13)-(A.18) with Eqs (A.19)-(A.22), the generated vertical brightness temperature during calibration is:

\[ T_{Cv,0} = \frac{\lambda^2 \cdot \langle |E_v|^2 \rangle}{k_B \cdot \eta} = \left[ Q_{v1} + Q_{2v} \cos(2\varphi) + Q_{3v} \cos(4\varphi) + Q_{4v} \sin(2\varphi) + Q_{5v} \sin(4\varphi) \right], \]  
(A.23)

where

\[ Q_{v1} = T_v \left[ \frac{3}{8} \left( \frac{1}{l_{||}^2} + \frac{1}{l_{\perp}^2} \right) + \frac{1}{4} \frac{\cos(\zeta)}{l_{||}^2 l_{\perp}^2} \right] + T_h \left[ \frac{1}{8} \left( \frac{1}{l_{||}^2} + \frac{1}{l_{\perp}^2} \right) - \frac{1}{4} \frac{\cos(\zeta)}{l_{||}^2 l_{\perp}^2} \right], \]  
(A.24)

\[ Q_{2v} = T_v \left( \frac{1}{2} \left( \frac{1}{l_{||}^2} - \frac{1}{l_{\perp}^2} \right) \right), \]  
(A.25)

\[ Q_{3v} = T_v \left[ \frac{1}{8} \left( \frac{1}{l_{||}^2} + \frac{1}{l_{\perp}^2} - 2 \frac{\cos(\zeta)}{l_{||}^2 l_{\perp}^2} \right) + T_h \left[ \frac{1}{8} \left( \frac{2 \cos(\zeta)}{l_{||}^2 l_{\perp}^2} - \frac{1}{l_{||}^2 l_{\perp}^2} \right) \right], \]  
(A.26)

\[ Q_{4v} = T_v \left( \frac{1}{4} \left( \frac{1}{l_{||}^2} - \frac{1}{l_{\perp}^2} \right) \right) + T_4 \left( \frac{1}{2} \frac{\sin(\zeta)}{l_{||}^2 l_{\perp}^2} \right), \]  
(A.27)

\[ Q_{5v} = T_v \left[ \frac{1}{8} \left( \frac{1}{l_{||}^2} + \frac{1}{l_{\perp}^2} - 2 \frac{\cos(\zeta)}{l_{||}^2 l_{\perp}^2} \right) \right]. \]  
(A.28)

The derivation for horizontal polarization is analogous. After passing the retardation plate, the horizontal brightness temperature is:
\[ T_{Ch,0} = \frac{\lambda^2}{k_b \cdot \eta} \langle |E_h|^2 \rangle = [Q_{1h} + Q_{2h} \cos(2\varphi) + Q_{3h} \cos(4\varphi) + Q_{4h} \sin(2\varphi) + Q_{5h} \sin(4\varphi)], \] (A.29)

where

\[ Q_{1h} = T_v \left[ \frac{1}{8} \left( \frac{l_2^2}{l_{||}^2} + \frac{1}{l_{||}^2} \right) - \frac{1}{4} \frac{l_{||}^2}{l_{\perp}^2} \right] \bigg|_{D_{011}} + T_h \left[ \frac{3}{8} \left( \frac{l_2^2}{l_{||}^2} + \frac{1}{l_{||}^2} \right) + \frac{1}{4} \frac{l_{||}^2}{l_{\perp}^2} \right] \bigg|_{D_{21}}, \] (A.30)

\[ Q_{2h} = T_h \left[ \frac{1}{2} \left( \frac{l_2^2}{l_{\perp}^2} - \frac{1}{l_{||}^2} \right) \right] \bigg|_{D_{322}}, \] (A.31)

\[ Q_{3h} = T_v \left[ \frac{1}{8} \left( \frac{2 \cos(\zeta)}{l_{||} l_{\perp}} - \frac{1}{l_{||}^2} \frac{1}{l_{\perp}^2} \right) \right] \bigg|_{D_{015}} + T_h \left[ \frac{1}{8} \left( \frac{l_2^2}{l_{||}^2} + \frac{1}{l_{||}^2} - 2 \frac{\cos(\zeta)}{l_{||} l_{\perp}} \right) \right] \bigg|_{D_{23}}, \] (A.32)

\[ Q_{4h} = T_v \left[ \frac{1}{4} \left( \frac{l_2^2}{l_{||}^2} - \frac{1}{l_{\perp}^2} \right) \right] \bigg|_{D_{034}} + T_h \left[ \frac{2}{2} \frac{\sin(\zeta)}{l_{||} l_{\perp}} \right] \bigg|_{D_{44}}, \] (A.33)

\[ Q_{5h} = T_v \left[ \frac{1}{8} \left( \frac{2 \cos(\zeta)}{l_{||} l_{\perp}} - \frac{1}{l_{||}^2} \frac{1}{l_{\perp}^2} \right) \right] \bigg|_{D_{045}}. \] (A.34)

The derivation of the trigonometric formulae was verified using the Matlab symbolic toolbox.
Appendix B. The Effect of a Retardation Plate on Polarimetric Brightness Temperatures

This appendix contains the derivation for the effect of a retardation plate on polarimetric brightness temperatures. The brightness temperature contribution of retardation plate losses is excluded in this analysis but is presented in Appendix C. The results are discussed in Section 5.1.

The third and fourth Stokes parameters generated are derived by the cross-correlation of the vertical and horizontal electric field components, respectively, in phase and in quadrature. Using the notations introduced in Appendix A, the in-phase correlation is:

\[
2 \cdot \Re \left\{ E_y^* \right\} = 2 \cdot \left( \frac{E_{x0}^2}{I_{||}} \cos^2 (\omega \cdot t - \zeta) \cos^3 (\phi) \sin (\phi) \right.
\]

\[
+ \frac{E_{x0}}{I_{||}} \cos (\omega \cdot t - \zeta) \cos (\omega \cdot t + \phi - \zeta) \cos^2 (\phi) \sin^2 (\phi)
\]

\[
- \frac{E_{y0}^2}{I_{\perp}} \cos (\omega \cdot t - \zeta) \cos^3 (\phi) \sin (\phi) + \frac{E_{x0}}{I_{||}} \cos (\omega \cdot t - \zeta) \cos (\omega \cdot t + \phi) \cos^4 (\phi)
\]

\[
+ \frac{E_{x0}}{I_{||}} \cos (\omega \cdot t - \zeta) \cos (\omega \cdot t + \phi - \zeta) \cos^2 (\phi) \sin^2 (\phi) + \frac{E_{y0}^2}{I_{\perp}} \cos^2 (\omega \cdot t + \phi - \zeta) \cos (\phi) \sin^3 (\phi)
\]

\[
- \frac{E_{x0}}{I_{||}} \cos (\omega \cdot t + \phi - \zeta) \cos (\omega \cdot t) \cos^2 (\phi) \sin^2 (\phi)
\]

\[
+ \frac{E_{y0}^2}{I_{\perp}} \cos (\omega \cdot t + \phi) \cos^3 (\phi) \sin (\phi) + \frac{E_{x0}}{I_{||}} \cos (\omega \cdot t - \zeta) \cos (\phi) \sin^4 (\phi)
\]

\[
+ \frac{E_{x0}}{I_{||}} \cos (\omega \cdot t + \phi) \cos (\omega \cdot t + \phi - \zeta) \sin (\phi) - \frac{E_{x0}}{I_{\perp}} \cos^2 (\omega \cdot t) \cos (\phi) \sin^3 (\phi)
\]

\[
+ \frac{E_{x0}}{I_{\perp}} \cos (\omega \cdot t) \cos^2 (\phi) \sin^2 (\phi)
\]

\[
- \frac{E_{x0}}{I_{||}} \cos (\omega \cdot t + \phi) \cos (\omega \cdot t - \zeta) \cos^2 (\phi) \sin^2 (\phi)
\]

\[
- \frac{E_{y0}^2}{I_{\perp}} \cos (\omega \cdot t + \phi) \cos (\omega \cdot t + \phi - \zeta) \cos (\phi) \sin^3 (\phi)
\]

\[
+ \frac{E_{x0}}{I_{||}} \cos (\omega \cdot t + \phi) \cos (\omega \cdot t) \cos^2 (\phi) \sin^2 (\phi) - \frac{E_{x0}}{I_{\perp}} \cos^2 (\omega \cdot t + \phi) \cos^3 (\phi) \sin (\phi) \right),
\]

(B.1)
Using the same rules for trigonometric functions as in Appendix A, Eq. (B.1) becomes:

\[
2 \cdot \text{Re}\left\{ E_v 'E_h'' \right\} = 2 \cdot \sin^2(\phi) \cos^2(\phi) \cdot \left[ \frac{E_{\phi 0}E_{\phi 0}}{l_{||}^2} \cos(\phi) + \frac{E_{\phi 0}E_{\phi 0}}{l_{\perp}^2} \cos(\phi) - \frac{E_{\phi 0}E_{\phi 0}}{l_{||} l_{\perp}} \cos(\phi) \cos(\zeta) \right]
\]

\[
+ \cos^3(\phi) \sin(\phi) \cdot \left[ \frac{E_{\zeta 0}^2}{l_{||}^2} - \frac{E_{\zeta 0}^2}{l_{\perp}^2} \cos(\zeta) + \frac{E_{\zeta 0}^2}{l_{||} l_{\perp}} \cos(\zeta) - \frac{E_{\zeta 0}^2}{l_{||} l_{\perp}} \right]
\]

\[
+ \cos(\phi) \sin^3(\phi) \cdot \left[ \frac{E_{\chi 0}^2}{l_{||}^2} - \frac{E_{\chi 0}^2}{l_{\perp}^2} \cos(\zeta) - \frac{E_{\chi 0}^2}{l_{||} l_{\perp}} + \frac{E_{\chi 0}^2}{l_{||} l_{\perp}} \cos(\zeta) \right]
\]

\[
+ \cos^4(\phi) \frac{E_{\phi 0}^2}{l_{||} l_{\perp}} \left[ \cos(\phi) \cos(\zeta) - \sin(\phi) \sin(\zeta) \right]
\]

\[
+ \sin^4(\phi) \frac{E_{\phi 0}^2}{l_{||} l_{\perp}} \left[ \cos(\phi) \cos(\zeta) + \sin(\phi) \sin(\zeta) \right]
\]

(B.2)

Using Eqs (A.8)-(A.12), Eq. (B.2) can be regrouped according to retardation plate rotation angle multiples:

\[
2 \cdot \text{Re}\left\{ E_v 'E_h'' \right\} = [d_1 + d_2 \cos(2\phi) + d_3 \cos(4\phi) + d_4 \sin(2\phi) + d_5 \sin(4\phi)], \quad (B.3)
\]

\[
q_1 = \frac{1}{4} \left[ \frac{E_{\phi 0}^2}{l_{||}^2} \cos(\phi) + \frac{E_{\phi 0}^2}{l_{\perp}^2} \cos(\phi) + 2 \frac{E_{\phi 0}^2}{l_{||} l_{\perp}} \cos(\phi) \cos(\zeta) \right] \quad (B.4)
\]

\[
q_2 = -\frac{E_{\phi 0}^2}{l_{||} l_{\perp}} \sin(\phi) \sin(\zeta) \quad (B.5)
\]

\[
q_3 = \frac{1}{4} \left[ 2 \frac{E_{\phi 0}^2}{l_{||} l_{\perp}} \cos(\phi) \cos(\zeta) - \frac{E_{\phi 0}^2}{l_{||}^2} \cos(\phi) - \frac{E_{\phi 0}^2}{l_{\perp}^2} \cos(\phi) \right] \quad (B.6)
\]

\[
q_4 = \frac{1}{4} \left[ \frac{E_{\phi 0}^2}{l_{||}^2} - \frac{E_{\phi 0}^2}{l_{\perp}^2} + \frac{E_{\phi 0}^2}{l_{||} l_{\perp}} - \frac{E_{\phi 0}^2}{l_{||} l_{\perp}} \right] \quad (B.7)
\]

\[
q_5 = \frac{1}{8} \left[ \frac{E_{\phi 0}^2}{l_{||}^2} + \frac{E_{\phi 0}^2}{l_{\perp}^2} - 2 \frac{E_{\phi 0}^2}{l_{||} l_{\perp}} \cos(\zeta) \right] - \frac{1}{8} \left[ \frac{E_{\phi 0}^2}{l_{||}^2} + \frac{E_{\phi 0}^2}{l_{\perp}^2} - 2 \frac{E_{\phi 0}^2}{l_{||} l_{\perp}} \cos(\zeta) \right] \quad (B.8)
\]
Using Eqs (A.19)-(A.22), the generated third Stokes parameter \( T_{C3,0} \) is:

\[
T_{C3,0} = 2\frac{\lambda^3}{k_B \eta} \cdot \text{Re}(E_y E_x^*) = \left[ Q_{13} + Q_{23} \cos(2\varphi) + Q_{33} \cos(4\varphi) + Q_{43} \sin(2\varphi) + Q_{53} \sin(4\varphi) \right]
\]

(B.9)

where

\[
Q_{13} = T_3 \frac{1}{4} \left[ \frac{2 \cos(\zeta)}{l_{11}^l l_{11}^l} + \frac{1}{l_{11}^l} + \frac{1}{l_{11}^l} \right] \quad (B.10)
\]

\[
Q_{23} = T_4 \frac{-\sin(\zeta)}{l_{11}^l l_{11}^l} \quad (B.11)
\]

\[
Q_{33} = T_3 \frac{1}{4} \left[ \frac{2 \cos(\zeta)}{l_{11}^l l_{11}^l} - \frac{1}{l_{11}^l} - \frac{1}{l_{11}^l} \right] \quad (B.12)
\]

\[
Q_{43} = T_5 \frac{1}{4} \left( \frac{1}{l_{11}^l} - \frac{1}{l_{11}^l} \right) + T_6 \frac{1}{2} \left( \frac{1}{l_{11}^l} - \frac{1}{l_{11}^l} \right) \quad (B.13)
\]

\[
Q_{53} = T_7 \frac{1}{4} \left( \frac{1}{l_{11}^l} + \frac{1}{l_{11}^l} - 2 \frac{\cos(\zeta)}{l_{11}^l l_{11}^l} \right) + T_8 \frac{1}{4} \left[ \frac{2 \cos(\zeta)}{l_{11}^l l_{11}^l} - \frac{1}{l_{11}^l} - \frac{1}{l_{11}^l} \right] \quad (B.14)
\]

The fourth Stokes parameter is obtained by the correlation of vertical and horizontal brightness temperatures in quadrature, i.e., the horizontal signal (which is aligned with the \( y \)-axis) is phase shifted by 90° prior to correlation. Using Eq. (A.5) it follows that:

\[
E_y \left( -\frac{\pi}{2}, -\frac{\pi}{2} \right) = \frac{E_{\varphi}}{l_{11}} \sin(\omega \cdot t - \zeta) \cos(\varphi) \sin(\varphi) + \frac{E_{\varphi}}{l_{11}} \sin(\omega \cdot t + \phi - \zeta) \sin^2(\varphi)
\]

\( - \frac{E_{\varphi}}{l_{11}} \sin(\omega \cdot t) \sin(\varphi) \cos(\varphi) + \frac{E_{\varphi}}{l_{11}} \sin(\omega \cdot t + \phi) \cos^2(\varphi) \). (B.15)
2 \cdot \text{Im}\langle E_x', E_y'' \rangle = \left( \frac{E_{v_0}^2}{l_1^2} \cos(\omega \cdot t - \zeta) \sin(\omega \cdot t) \cos^3(\varphi) \sin(\varphi) \right. \\
+ \frac{E_{v_0} E_{v_0}^*}{l_1^2} \cos(\omega \cdot t - \zeta) \sin(\omega \cdot t + \phi - \zeta) \cos^2(\varphi) \sin^2(\varphi) \\
- \frac{E_{v_0}^2}{l_1^2} \cos(\omega \cdot t - \zeta) \sin(\omega \cdot t) \cos^3(\varphi) \sin(\varphi) + \frac{E_{v_0} E_{v_0}^*}{l_1^2} \cos(\omega \cdot t - \zeta) \sin(\omega \cdot t + \phi) \cos^4(\varphi) \\
+ \frac{E_{v_0}^2}{l_1^2} \cos(\omega \cdot t + \phi - \zeta) \sin(\omega \cdot t - \zeta) \cos^2(\varphi) \sin^2(\varphi) \\
+ \frac{E_{v_0}^2}{l_1^2} \cos(\omega \cdot t + \phi - \zeta) \sin(\omega \cdot t - \zeta) \cos^2(\varphi) \sin^2(\varphi) \\
+ \frac{E_{v_0}^2}{l_1^2} \cos(\omega \cdot t + \phi - \zeta) \sin(\omega \cdot t + \phi - \zeta) \cos^3(\varphi) \sin(\varphi) \\
+ \frac{E_{v_0} E_{v_0}^*}{l_1^2} \cos(\omega \cdot t) \sin(\omega \cdot t - \zeta) \cos(\varphi) \sin^3(\varphi) + \frac{E_{v_0} E_{v_0}^*}{l_1^2} \cos(\omega \cdot t) \sin(\omega \cdot t + \phi - \zeta) \sin^4(\varphi) \\
- \frac{E_{v_0}^2}{l_1^2} \cos(\omega \cdot t) \sin(\omega \cdot t) \cos(\varphi) \sin^3(\varphi) + \frac{E_{v_0} E_{v_0}^*}{l_1^2} \cos(\omega \cdot t) \sin(\omega \cdot t + \phi) \cos^2(\varphi) \sin^2(\varphi) \\
- \frac{E_{v_0} E_{v_0}^*}{l_1^2} \cos(\omega \cdot t + \phi) \sin(\omega \cdot t - \zeta) \cos(\varphi) \sin^3(\varphi) \\
- \frac{E_{v_0}^2}{l_1^2} \cos(\omega \cdot t + \phi) \sin(\omega \cdot t - \zeta) \cos^2(\varphi) \sin^2(\varphi) \\
+ \frac{E_{v_0} E_{v_0}^*}{l_1^2} \cos(\omega \cdot t + \phi) \sin(\omega \cdot t) \cos^2(\varphi) \sin^2(\varphi) \\
- \frac{E_{v_0}^2}{l_1^2} \cos(\omega \cdot t + \phi) \sin(\omega \cdot t + \phi) \cos^3(\varphi) \sin(\varphi) \right). \\
(B.16)

Using the same rules for trigonometric functions as in Appendix A, Eq. (B.16) becomes:
Using Eqs (A.8)-(A.12), Eq. (B.17) can be regrouped according to retardation plate rotation angle multiples:

\[
2 \cdot \text{Im}\left\{ E_x \, E_y^* \right\} = 2 \cdot \sin^2(\phi) \cos^2(\phi) \frac{E_x^0 E_y^0}{l_{||} l_{\perp}} \sin(\phi) \cos(\zeta)
\]  

\[
+ \cos^3(\phi) \sin(\phi) \left[ \frac{E_x^2}{l_{||} l_{\perp}} \sin(\zeta) - \frac{E_y^2}{l_{||} l_{\perp}} \sin(\zeta) \right]
\]  

\[
+ \cos(\phi) \sin^3(\phi) \left[ \frac{E_y^2}{l_{||} l_{\perp}} \sin(\zeta) - \frac{E_x^2}{l_{||} l_{\perp}} \sin(\zeta) \right]
\]  

\[
+ \cos^4(\phi) \frac{E_x^0 E_y^0}{l_{||} l_{\perp}} [\sin(\phi) \cos(\zeta) + \cos(\phi) \sin(\zeta)]
\]  

\[
+ \sin^4(\phi) \frac{E_y^0 E_x^0}{l_{||} l_{\perp}} [\sin(\phi) \cos(\zeta) - \cos(\phi) \sin(\zeta)]
\]

Using Eqs (A.8)-(A.12), Eq. (B.17) can be regrouped according to retardation plate rotation angle multiples:

\[
2 \cdot \text{Im}\left\{ E_x \, E_y^* \right\} = [q_1 + q_2 \cos(2\phi) + q_3 \sin(2\phi)]
\]  

\[
q_1 = \frac{E_x^0 E_y^0}{l_{||} l_{\perp}} \sin(\phi) \cos(\zeta)
\]  

\[
q_2 = \frac{E_x^0 E_y^0}{l_{||} l_{\perp}} \cos(\phi) \sin(\zeta)
\]  

\[
q_3 = \frac{1}{2} \left[ - \frac{E_x^2}{l_{||} l_{\perp}} \sin(\zeta) + \frac{E_y^2}{l_{||} l_{\perp}} \sin(\zeta) \right]
\]

Using Eqs (A.19)-(A.22), the generated fourth Stokes parameter \( T_{4,0} \) becomes:

\[
T_{4,0} = 2 \frac{\lambda^2}{k_0 \cdot \eta} \cdot \text{Im}\left\{ E_x \, E_x^* \right\} = [Q_{14} + Q_{24} \cos(2\phi) + Q_{34} \sin(2\phi)]
\]  

\[
Q_{14} = T_4 \frac{\cos(\zeta)}{l_{||} l_{\perp}} \frac{D_{414}}{D_{411}}
\]  

\[
Q_{24} = T_3 \frac{\sin(\zeta)}{l_{||} l_{\perp}} \frac{D_{412}}{D_{413}}
\]  

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\[ Q_{44} = T_v \frac{-\sin(\zeta)}{D_{444}} + T_h \frac{\sin(\zeta)}{D_{224}} \]  

(B.25)

The derivation of the trigonometric formulae was verified using Matlab symbolic toolbox.
Appendix C. The Brightness Temperatures Contribution due to Retardation Plate Losses

This appendix contains the derivation of the brightness temperature contribution due to retardation plate losses, discussed in Section 5.1.

Similarly to the derivation in Appendix A and in Appendix B, the electric field generated by the thermal emission of the retardation plate is:

\[
\bar{E}_R(t) = \bar{E}_{R,x}(t) + \bar{E}_{R,y}(t) = E_{R,x0}(t) \cdot \cos(\omega \cdot t) \cdot \bar{u}_x + E_{R,y0}(t) \cdot \cos(\omega \cdot t + \phi(t)) \cdot \bar{u}_y, \quad (C.1)
\]

The amplitudes in the \(x\)- and \(y\)-directions (\(E_{R,x0}\) and \(E_{R,y0}\), respectively), and the phase difference \(\phi\), change only slowly with time. For the sake of simplicity they will here be considered to be time independent. The generated electric fields in the antenna-based coordinate system are:

\[
E_{R,x}(t) = E_{R0,||} \cos(\omega \cdot t) \cos(\phi) - E_{R0,\perp} \cos(\omega \cdot t) \sin(\phi) \quad (C.2)
\]

\[
E_{R,y}(t) = E_{R0,||} \cos(\omega \cdot t) \sin(\phi) + E_{R0,\perp} \sin(\omega \cdot t) \sin(\phi). \quad (C.3)
\]

The generated vertical brightness temperature is obtained as follows:

\[
\langle E_{R,v}(t)^2 \rangle = \left( E_{R0,||}^2 \right) \left( \cos^2(\omega \cdot t) \cos^2(\phi) + E_{R0,\perp}^2 \cos^2(\omega \cdot t) \sin^2(\phi) \right) + 2E_{R0,||} E_{R0,\perp} \cos(\omega \cdot t) \cos(\phi) \sin(\phi) = \underbrace{\frac{1}{4} \left[ E_{R0,||}^2 + E_{R0,\perp}^2 + (E_{R0,||}^2 - E_{R0,\perp}^2) \cos(2\phi) \right]}_{\text{Do not correlate}} \quad (C.4)
\]

On the other hand, the generated brightness temperatures parallel with and perpendicular to the retardation plate grooves are:

\[
T_{R,x} = \frac{\chi^2}{2 \cdot k_B \cdot \eta} E_{R0,x}^2 \cdot T_{P,R} \left( 1 - \frac{1}{l_s^2} \right), \quad (C.5)
\]
where \( s \) is \( \parallel \) or \( \perp \). The generated brightness temperature parallel to radiometer antenna vertical polarization is:

\[
T_{R,v} = \frac{1}{2} T_{P,R} \left[ 2 - \frac{1}{I_{\parallel}} - \frac{1}{I_{\perp}} + \left( \frac{1}{I_{\parallel} - \frac{1}{I_{\perp}}} \right) \cos(2\varphi) \right]. \tag{C.6}
\]

Similarly, the generated horizontal brightness temperature is:

\[
T_{R,h} = \frac{1}{2} T_{P,R} \left[ 2 - \frac{1}{I_{\parallel}} - \frac{1}{I_{\perp}} + \left( \frac{1}{I_{\parallel} - \frac{1}{I_{\perp}}} \right) \cos(2\varphi) \right]. \tag{C.7}
\]

The third Stokes parameter is obtained by correlating the orthogonal signals in phase:

\[
2 \cdot \text{Re}\left\langle E_{R,v}(t)E_{R,h}^*(t) \right\rangle = \\
2 \cdot \left\{ E_{R,0,\parallel}^2 \cos^2(\omega \cdot t) \cos(\varphi) \sin(\varphi) - E_{R,0,\perp}^2 \cos^2(\omega \cdot t) \cos(\varphi) \sin(\varphi) \right\} = \\
\frac{1}{2} \left( E_{R,0,\parallel}^2 - E_{R,0,\perp}^2 \right) \sin(2\varphi). \tag{C.8}
\]

This gives the generated brightness temperature:

\[
T_{R,3} = T_{P,R} \left( \frac{1}{I_{\parallel}} - \frac{1}{I_{\perp}} \right) \sin(2\varphi). \tag{C.9}
\]

The fourth Stokes parameter is obtained by correlating the orthogonal signals in quadrature:

\[
2 \cdot \text{Im}\left\langle E_{R,v}(t)E_{R,h}^*(t) \right\rangle = \\
2 \cdot \left\{ E_{R,0,\parallel}^2 \cos(\omega \cdot t) \sin(\varphi) \cos(\varphi) \sin(\varphi) - E_{R,0,\perp}^2 \cos(\omega \cdot t) \sin(\varphi) \cos(\varphi) \sin(\varphi) \right\} = 0. \tag{C.10}
\]

This gives the generated brightness temperature:
\[ T_{E,A} = 0. \quad \text{(C.11)} \]

The derivation of the trigonometric formulae was verified using the Matlab symbolic toolbox.