A. Colliander, J. Kettunen, M. T. Hallikainen, Calibration of End-to-End Phase Imbalance of Polarimetric Radiometers, IEEE Transactions on Geoscience and Remote Sensing, vol. 44, no. 10, pp. 2635-2641, October 2006.

Calibration of End-to-End Phase Imbalance of Polarimetric Radiometers

Andreas Colliander, *Student Member, IEEE*, Jani Kettunen, and Martti T. Hallikainen, *Fellow, IEEE*

***Abstract*—In this paper, the authors introduce a method for calibrating the end-to-end phase imbalance of polarimetric radiometers using a digital correlation technique. The method is based on the measurement of linearly polarized field at -45° and $+45^\circ$ angles with respect to the polarization plane of the transmitted field. This way, the effects of the polarization purity of the transmitted field and the polarization separation and cross-coupling of the antenna of the radiometer can be cancelled out. The remaining uncertainty consists of the pointing accuracy of the radiometer with respect to the transmitted field. It has been shown here that this effect can be reduced to the level that will make the method feasible.**

***Index Terms*—Digital correlation, phase imbalance, polarimetric radiometer, Stokes parameters.**

I. Introduction

THE CALIBRATION of fully polarimetric radiometers is one of the main issues when performance is considered. The first and second Stokes parameter can be calibrated with conventional means using cold and hot loads, but the third and fourth parameters impose a problem. One option is to create enough linearly independent combinations of Stokes parameters. The approach presented in [1] and [2] assumes this technique. The drawback is the complexity of the load, which even increases as the wavelength increases.

Digital correlation techniques have been presented which solve the correlation coefficient excluding the amplitude of the measured field [3]. This means that by only knowing the phase difference, or phase imbalance, between the two receivers measuring the orthogonal polarizations, the third and fourth Stokes parameter can be solved [3]. This is called as the phase calibration. In general, if the antenna is excluded, the calibration of the phase difference of the receiver paths can be performed relatively easily [4]. With the presented method, however, the antenna can be included in the calibration procedure. The method is based on measuring the digital correlation coefficient from a polarized target. Note that the calibration of the offset of the digitizer and the quadrature error is required as well, but the calibration of these parameters is out of the scope of this paper (see, e.g., [4] and [5]).

A linearly polarized antenna load is introduced for retrieving the end-to-end phase imbalance. The load consists of an electrically shielded box with the inside covered with absorption material and of an active noise source that transmits linearly polarized noise, the brightness temperature of which is approximately 375 K. The antenna of the radiometer is polarized in two orthogonal polarizations, namely: 1) vertical (V) and 2) horizontal (H). The procedure of calibrating the phase imbalance is to measure the linearly polarized field in two different angles by rotating the antenna plane of the radiometer and performing complex correlation measurements.

The presented calibration procedure is a part of the test campaign and the calibration procedure of the engineering model of an L-band (center frequency 1.413 GHz) polarimetric Noise Injection Radiometer (NIR) [6], [7]. The NIR is part of the Microwave Imaging Radiometer using Aperture Synthesis (MIRAS) instrument, which is the main instrument on the European Space Agency's (ESA) Soil Moisture and Ocean Salinity (SMOS) mission, scheduled for launch in 2007 [8], [9]. SMOS is a cooperation of ESA, the French Space Agency Centre National d'Études Spatiales (CNES), and Centro para el Desarrollo Tecnológico Industrial (CDTI) Spain. The main contractor of MIRAS is EADS CASA Espacio, Spain. The NIR engineering model (EM) has been developed by Elektrobit Microwave Ltd., Finland; the main subcontractor was the Helsinki University of Technology, Finland.

II. Theoretical Background

A. Stokes Parameters

The electromagnetic radiation is commonly described with propagating plane waves. For a uniform plane wave propagating in the direction of the positive z axis in a Cartesian coordinate system, the electric field must lie in the xy plane [10]. The electric field vector $\vec{E}$ is a function of time in any fixed point in space. The tip of the $\vec{E}$ vector draws a curve in the xy plane as time changes. The form of the resulting curve dictates the polarization state of the field. The electromagnetic waves emitted by natural objects consist of a superposition of many statistically independent waves of different polarizations. This kind of a wave is said to be incoherent or unpolarized [10], which means that it does not correlate.

A plane wave can be written as a sum of the x component and y component of the wave. This is, however, the same as the sum of two linearly polarized waves, which are equal to the aforementioned components [10], i.e.,

$$\begin{aligned}\vec{E}(z,t) &= E_x(z,t)\hat{x}+E_y(z,t)\hat{y}\\ &= E_{x0}\cos(\omega t-\beta z)\hat{x}+E_{y0}\cos(\omega t-\beta z+\theta)\hat{y}.\end{aligned} \quad (1)$$

Manuscript received September 23, 2005; revised March 6, 2006. This work was supported by U. Tuominen, J. Wihuri, A. Wihuri, W. Ahlström, and the Finnish Cultural Foundations.

The authors are with the Laboratory of Space Technology, Helsinki University of Technology, 02015 Espoo, Finland (e-mail: andreas.colliander@tkk.fi; jani.kettunen@tkk.fi; martti.hallikainen@tkk.fi).

Digital Object Identifier 10.1109/TGRS.2006.877759

The resulting polarization of the whole wave can be mathematically identified by the phase difference θ and the magnitudes E_{x0} and E_{y0} of the components. In the case of the linear polarization, the phase difference θ equals zero, which is an important property for this work.

The Stokes parameters provide a very useful way of describing the polarization state of an electromagnetic wave. The modified Stokes parameters, which are commonly used in radiometry, can be defined as [11]

$$\vec{T} = \begin{bmatrix} T_v \\ T_h \\ T_3 \\ T_4 \end{bmatrix} = \frac{\lambda^2}{k_B \eta B} \begin{bmatrix} \langle |E_v|^2 \rangle \\ \langle |E_h|^2 \rangle \\ 2\Re e \langle E_v E_h^* \rangle \\ 2\Im m \langle E_v E_h^* \rangle \end{bmatrix} = \begin{bmatrix} T_v \\ T_h \\ 2\sqrt{T_v T_h} \Re e\{V\} \\ 2\sqrt{T_v T_h} \Im m\{V\} \end{bmatrix} \tag{2}$$

where T_v, T_h, T_3, and T_4 are the brightness temperatures of the vertically and horizontally polarized radiation and third and fourth Stokes parameters, respectively; λ is the wavelength; k_B is Boltzmann's constant; η is the impedance of the medium; B is the bandwidth; E_v and E_h are the vertically and horizontally polarized electric fields, respectively; and V is the complex correlation between the vertical and horizontal fields. The brackets stand for infinite time average. Note that the phase of the complex correlation V is the phase difference of the V-component and H-component of the field.

B. Digital Correlation

If the normalized complex correlation of two receivers is measured using one-bit/two-level digital correlators, as is done in this paper, the correlation value is given according to the following equation [12]:

$$Z = \frac{1}{N} \sum_{i=1}^{N} \text{sign}\,(x(t_i))\,\text{sign}\,(y(t_i)) \tag{3}$$

in which $x(t)$ and $y(t)$ are the input signals being digitized and correlated and N is the number of samples being correlated. This digital correlation value is related to the analog correlation value, when it is applied to the signal that has a limited spectrum, as [13]

$$\mu = \sin\left(\frac{\pi}{2} Z\right) \tag{4}$$

where μ is called here as the normalized correlation coefficient.

After the normalized correlation coefficient μ is corrected for the digitizer offset and quadrature error, the correlation coefficient is called as the quadrature-corrected normalized correlation and denoted with M.

The goal of the polarimetric measurements is to solve the third and fourth Stokes parameters. For ideal noise-free horizontally and vertically polarized radiometer measurements, the parameters may be written as

$$\begin{aligned} T_3 &= 2\sqrt{T_v T_h} V|_{i,i} \\ T_4 &= 2\sqrt{T_v T_h} V|_{q,i} \end{aligned} \tag{5}$$

where $V|_{i,i}$ is the denormalized (i.e., obtained with a noise-free receiver) correlation coefficient of the in-phase outputs (I) of the V-channel and H-channel, corresponding to the real part of the complex correlation, and $V|_{q,i}$ is the denormalized correlation coefficient of the quadrature output (Q) of the V-channel and in-phase output of the H-channel, corresponding to the imaginary part of the complex correlation.

The complex correlation obtained with II and QI correlations is said to be nominal. It can also be obtained from QQ and IQ correlations and is then named as redundant. The measured redundant complex correlation is the complex conjugate of the nominal correlation.

For a real radiometric measurement, the denormalized correlation coefficient V of (5) is defined from the following relation:

$$M = \tilde{g} V \tag{6}$$

where

$$\tilde{g} = g_{\text{FW}} \sqrt{\frac{T_v}{T_v + T_{\text{rec},v}}} \sqrt{\frac{T_h}{T_h + T_{\text{rec},h}}} \tag{7}$$

in which $T_{\text{rec},v}$ and $T_{\text{rec},h}$ are the equivalent noise temperatures of V-receiver and H-receiver and g_{FW} is the so-called fringe-washing factor.

III. Principle of Method

A. Solving Phase Imbalance

The phase imbalance of the receivers of a polarimetric radiometer can be solved in an ideal case by measuring a pure linearly polarized electromagnetic field at a 45° angle with respect to the polarization plane of the antenna of the radiometer. This would yield a complex correlation coefficient, which has the phase equal to the phase imbalance of receivers because there is no phase difference in the transmitted field. In reality, however, there are two sources of nonidealities, which are as follows:

1) polarization purity of the transmitted field;
2) finite polarization separation and cross-coupling of the antenna of the radiometer.

Both of these sources create a residual offset to the measured correlation. The first is due to the fact that the nonprincipal polarization transmits undesired radiation added to the multipath propagation inside the load, and the second is due to the fact that the transmitted field leaks between receivers including the effect caused by the absorbers located in the near field of the antenna.

The solution is to rotate the transmitted linearly polarized field with respect to the polarization plane of the antenna of the radiometer by 90°, as is shown in Fig. 1. By rotating the polarization plane by 90°, the phase of the output signal is rotated by 180° as the field vector of one polarization (at the antenna plane) changes its sign, as happens for V-polarization in Fig. 1. The rotation of the phase is demonstrated in Fig. 2,

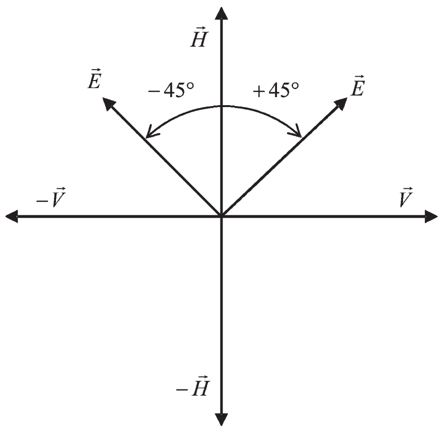

Fig. 1. Orientation of the measured electric field $\vec{E}$ with respect to the polarization plane, defined by the vertical ($\vec{V}$) and horizontal ($\vec{H}$) polarizations, of the antenna of the radiometer in the setups of $-45°$ and $+45°$ angles.

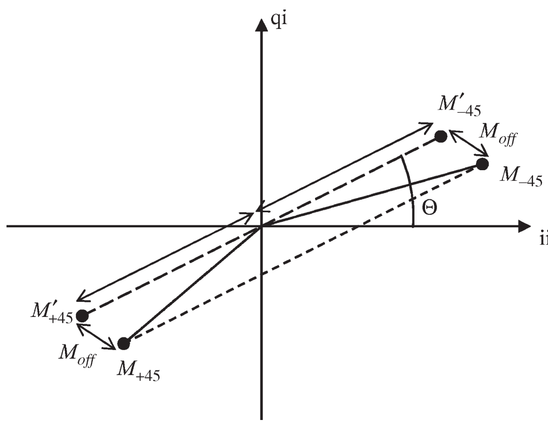

Fig. 2. Principle of the end-to-end phase difference retrieval. The offset remains the same in the two measurements, whereas the phase of the signal changes by 180°. M_{+45} and M_{-45} are the correlations measured at $+45°$ and $-45°$ angles, $M_{\rm off}$ is the offset of the measurement, and M'_{+45} and M'_{-45} are the correlations corrected with the offset.

which shows the measured correlations M_{+45} and M_{-45}, the offset $M_{\rm off}$, and the phase imbalance of the receivers δ. Note that, in the ideal case, the amplitudes of the measurements at $-45°$ and $+45°$ angles are equal. With this procedure, the nonidealities can be cancelled out as the offset is the same in both measurements, and the imbalance can be determined from the slope between the two measurement points.

B. Formulation

In the measurement of the end-to-end phase difference, the measured correlation coefficient between the V-channel and H-channel can be divided into two parts as follows:

$$M = M' + M_{\rm off} \tag{8}$$

where the correlation without the offset has an amplitude of

$$M' = \sqrt{\frac{T_v^c}{T_v + T_{{\rm rec},v}}}\sqrt{\frac{T_h^c}{T_h + T_{{\rm rec},h}}} \tag{9}$$

where T_v^c and T_h^c are the brightness temperatures of the correlated noise of V-polarization and H-polarization, respectively, and the offset has an amplitude of

$$\begin{aligned} M_{\rm off} &= \sqrt{\frac{T_v^c}{T_v + T_{{\rm rec},v}}}\sqrt{\frac{T_v^c|\chi_{vh}|^2}{T_h + T_{{\rm rec},h}}} \\ &\quad + \sqrt{\frac{T_h^c|\chi_{hv}|^2}{T_v + T_{{\rm rec},v}}}\sqrt{\frac{T_h^c}{T_h + T_{{\rm rec},h}}} \\ &= \frac{T_v^c|\chi_{vh}|^2 + T_h^c|\chi_{hv}|^2}{\sqrt{T_v + T_{{\rm rec},v}}\sqrt{T_h + T_{{\rm rec},h}}} \end{aligned} \tag{10}$$

in which χ_{vh} and χ_{hv} are the cross-coupling factors (complex) between the channels due to the polarization nonpurity and the polarization separation and cross-coupling of the antenna of the radiometer.

Under the assumption that the cross-coupling, the brightness temperature of H-polarization and V-polarization, and the equivalent noise temperatures of the receivers stay constant, the offset correlation is also constant during the measurement. This makes it possible to cancel out the offset when the measurement is done at the angles of $-45°$ and $+45°$ (see Fig. 2).

Hence, the phase imbalance can be solved from the measured correlation coefficients in a straightforward manner as follows:

$$\Theta = \arctan\left(\frac{M_{-45}|_{q,i} - M_{+45}|_{q,i}}{M_{-45}|_{i,i} - M_{+45}|_{i,i}}\right). \tag{11}$$

Furthermore, the solution for the offset in the measurement can be considered as the mean value of the two measurements yielding

$$M_{\rm off} = \frac{M_{-45}|_{i,i} + M_{+45}|_{i,i}}{2} + j\frac{M_{-45}|_{q,i} - M_{+45}|_{q,i}}{2}. \tag{12}$$

For understanding the measurement situation, the brightness temperature incident to the antenna of the radiometer can be written as

$$T_v = T_v^u + T_v^c = T_{p,{\rm load}} + T_C t_v(\alpha) \tag{13}$$

$$T_h = T_h^u + T_h^c = T_{p,{\rm load}} + T_C t_h(\alpha) \tag{14}$$

where T_v^u and T_h^u are the brightness temperatures of the uncorrelated noise of V-polarization and H-polarization, $T_{p,{\rm load}}$ is the physical temperature of the load equaling the brightness temperature of the load, T_C is the correlated noise transmitted by the antenna in the load, and t_v and t_h are functions of the rotation angle α, so that depending on the polarization, a certain amount of transmission to the channel of the radiometer is allowed. The relation of the functions for H-polarization and V-polarization can be stated as follows:

$$t_v(\alpha) + t_h(\alpha) \approx 1 \tag{15}$$

but otherwise, the functions are unknown because they depend on the polarization purity of the transmitted field and on the polarization separation and cross-coupling of the antenna of the radiometer.

The baseline assumption is that the physical temperature of the radiometer is the same as the physical temperature of the load, i.e., $T_{p,\mathrm{rec}} = T_{p,\mathrm{load}}$. Deviation from this equality results as a small correlation offset. However, this offset is the same in both -45° and $+45^\circ$ measurements and is thus cancelled out as well.

C. Error Bounds

The presented method cancels out all the systematic error sources when they remain constant during the two measurements performed at -45° and $+45^\circ$ rotation angles. Random uncertainty consists of noise of the measurement, the effect of which can be removed by averaging.

The main sources for systematic errors are the following.

1) Change of the multipath radiation and the absorber effects in the near field of the antenna of the radiometer.
2) Change of the properties of the transmitted field and the properties of the antenna of the radiometer.
3) Change of the brightness temperature emitted by the load.
4) Change of the equivalent noise temperatures of the receivers.
5) Change of the physical temperature of the load with respect to the physical temperature of the radiometer.
6) Change of the orientation of the radiometer from one measurement to another in dimensions other than that of the rotation.

The first point affects the offset of the correlation, but it is not expected to change significantly between the two measurements because the symmetry of the load does not change. Also, the second point can be considered negligible due to the stability of these properties.

The third point affects the amplitude of the measurement and does not affect the determination of the phase imbalance. However, it has an effect on the offset, which can be minimized by making sure that the physical temperature of the load and the output of the noise source remain constant. The fourth point affects also the amplitude, and the same conclusion as in the case of the third point can be made, with the exception that it is the physical temperature of the radiometer that needs to remain constant. By limiting the variation of the physical temperature to a couple of degrees, its contribution to the offset is negligible, ruling out the fifth point.

The sixth point creates uncertainty to the measurements if the pointing of the radiometer is not very accurate. The magnitude of this uncertainty can be solved during the measurement by repeating the measurement several times at different angles. The uncertainty can be defined as the root mean square (rms) of the deviation of the individual measurements from the characteristic line between -45° and $+45^\circ$ angle measurements. This is

$$\Delta M = \sqrt{\frac{1}{N}\sum \left(x - M|_{i,i}\right)^2 + \left(y - M|_{q,i}\right)^2} \qquad (16)$$

where x and y are the points on the line, M is the measured correlation, and N is the number of samples.

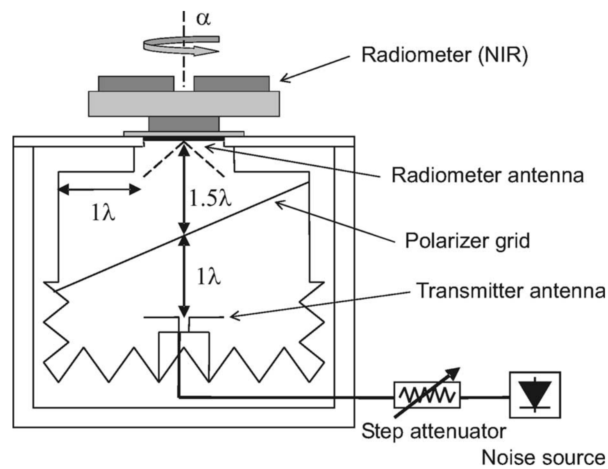

Fig. 3. Measurement setup utilizing the linearly polarized antenna target (λ stands for the free-space wavelength, which is 21 cm in this case).

The effect of the uncertainty of the offset on the measurement of the phase imbalance can be estimated by solving the magnitude of the angle that the uncertainty of the offset can manifest. This can be written as

$$\Delta\Theta = \arctan\left(\frac{\Delta M}{|M_{45}|}\right) \qquad (17)$$

where $|M_{45}|$ is the amplitude of the correlation in 45° angle measurement.

IV. Experiment

A. Measurement Setup

The measurement setup consists of a radiometer, which is the engineering model of SMOS NIR, and a linearly polarized antenna target. The linearly polarized antenna target is composed of an absorber load, linearly polarized transmitter antenna at the bottom of the load connected to a noise source through a step attenuator, and a polarizer grid made of wires. Fig. 3 shows a schematic diagram of the setup. With this setup, the phase imbalance of the radiometer can be measured at boresight, which is considered adequate. It is expected that the offset M_{off} describing, among others, the cross-polarization ratio of the antenna depends on the view angle, but because this is a mere by-product, the measurement was not extended over a range of view angles in this experiment.

The distance of the grid from both radiometer and transmitter antenna satisfies the far-field condition, which yields in this case

$$d = 2\frac{D^2}{\lambda} \approx \frac{1}{2}\lambda \qquad (18)$$

where d is the distance, D is the diameter of the antenna, and λ is the free-space wavelength. The distance of the antenna of the radiometer to the grid is one-and-a-half wavelengths and that of the transmitter antenna to the grid is one wavelength. The distance of the walls is about one wavelength from the edge of the antenna of the radiometer. See Fig. 3 for details.

The purpose of the polarizer grid is to improve the polarization purity of the transmitter antenna, although the presented

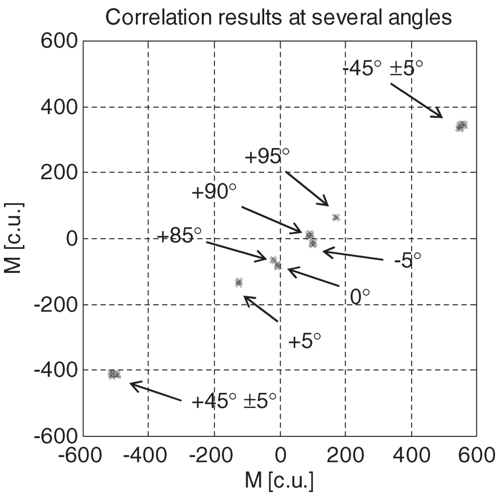

Fig. 4. Correlation results at rotation angles $-45° \pm 5°$, $0° \pm 5°$, $+45° \pm 5°$, and $+90° \pm 5°$ for nominal and redundant correlations.

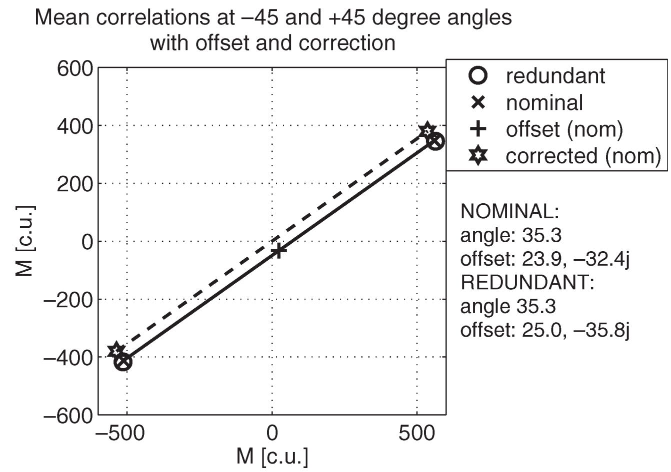

Fig. 5. Mean correlations at $-45°$ and $+45°$ rotation angles with offset and corrected values (for nominal correlations). The complex conjugate of the redundant correlation is taken before plotting.

method cancels out the impurity of the transmitted load. This was confirmed in the experiment as measurements without the grid were carried out as well.

The absorber load is made out of a metal box with electrically shielded cover and absorber material covering the inside walls. The cover has a hole for the antenna of the radiometer. Fig. 3 shows a schematic diagram of the load. The return loss of the absorber is specified to be more than 20 dB all around the walls of the box (normal incidence), where the absorber is flat, and more than 35 dB in the bottom of the load, where the absorber is pyramid shaped (pyramids being about one wavelength in length).

The transmitter antenna is a linearly polarized microstrip patch antenna with a cross-polarization ratio of about 25 dB. It is connected to a noise source through a step attenuator, which can be adjusted in the range of 0–30 dB with 1-dB steps. The noise temperature of the transmitted field is adjusted, so that the radiometer sees about 375 K in total (so that when the transmitted field is in the direction of either polarization, this polarization sees about 375 K). This value was chosen because it is used also for the internal phase calibration of the NIR.

The polarizer grid is a grid made out of metal wire with diameter of 3.0 mm and spacing of 9.4 mm. The total size of the grid is 540 × 630 mm. The attenuation of the grid at 1.4 GHz is 0.2 dB when the electric field is perpendicular to the grid and 32.5 dB when the electric field is parallel to the grid. The grid was designed based on the theory presented in [14] and [15].

NIR is a fully polarimetric radiometer using the noise injection method, but for this experiment, it is operated in a total-power measurement mode. Its vertical and horizontal receivers send one-bit/two-level digitized signals from in-phase and quadrature channels to a digital correlator, which solves the complex correlation coefficients.

B. Experimental Results

1) Phase Imbalance: Fig. 4 shows the obtained nominal correlations at angles equal to $-45° \pm 5°$, $0° \pm 5°$, $+45° \pm 5°$, and $+90° \pm 5°$. The results are clearly located on a straight line. At $0°$ and $+90°$ angles, the effect of a 5° step is large, but at $-45°$ and $+45°$ angles, it is very small as expected. There are also deviations from the line, especially at $0°$ and $-5°$, which is most probably due to the pointing inaccuracy of the radiometer. Also, there is a difference between the result at $0°$ and $90°$, which is due to the rotation angle inaccuracy.

TABLE I
PHASE IMBALANCE OF THE NIR AND THE OFFSET OF THE MEASUREMENT, WHEN MEASURED BOTH WITH AND WITHOUT THE POLARIZER GRID

		Phase imbalance Θ [deg]	**Offset [cu]**
Grid	Nominal	35.30	23.9-j32.4
	Redundant	35.26	25.0-j35.8
No Grid	Nominal	35.40	9.7-j14.1
	Redundant	35.37	10.7-j17.5

Fig. 5 shows the correlations at $-45°$ and $+45°$ angles, the offset calculated based on these using (12) and the corrected line without the offset. The angle, i.e., the phase imbalance, is calculated using (11). Table I lists the resulted phase imbalances and offset for nominal and redundant correlations, and Table II lists the obtained correlation values at $-45°$ and $+45°$ angles with the standard deviation of the measurement showing good resolution.

The uncertainty of the offset is calculated using (16) yielding 11.3 cu $(1\ \text{cu} = 10^{-4})$, which gives for the uncertainty of the phase imbalance measurement a value of $1°$, according to (17), as the amplitude of the 45° measurement is about 660 cu. The effect of this to the measured Stokes parameters can be evaluated by assuming that the maximum amplitude of either the third or fourth Stokes parameter is in a conservative case 10 K; thus, $1°$ uncertainty would cause an uncertainty of

$$\Delta T_{3/4} = 10\ \sin(1°) = 0.17\ \text{K} \tag{19}$$

which is acceptable.

2) Result Without Polarizer Grid: The measurements were also made without the polarizer grid at rotation angles $-45°$, $0°$,

TABLE II
MEASURED QUADRATURE-CORRECTED NORMALIZED CORRELATIONS WITH ±45° ANGLES, WHEN MEASURED BOTH WITH AND WITHOUT THE POLARIZER GRID. THE REDUNDANT CORRELATION IS PRESENTED AS THE COMPLEX CONJUGATE OF THE MEASUREMENT RESULT

	Angle [deg]	Nominal / Redundant	Mean [cu]	STD [cu]
Grid	-45	Nom	560.0+j347.8	3.5
	+45	Nom	-512.7-j412.2	3.1
	-45	Red	563.7+j344.9	3.3
	+45	Red	-513.6-j416.8	2.8
No Grid	-45	Nom	540.9+j363.4	3.0
	+45	Nom	-521.4-j391.5	3.2
	-45	Red	543.9+j361.1	3.3
	+45	Red	-522.6-j396.2	2.9

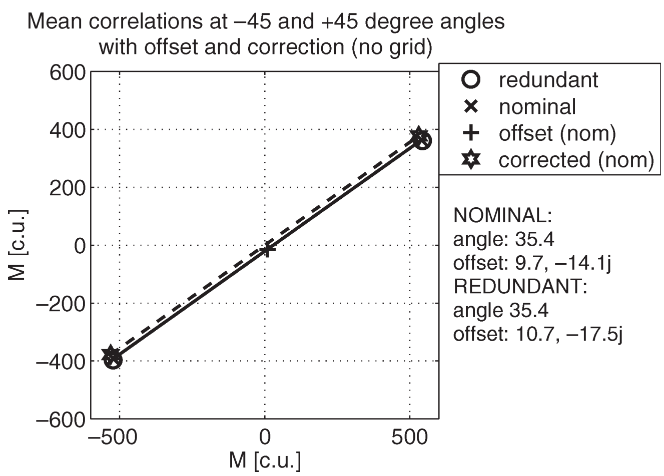

Fig. 6. Mean correlations at $-45°$ and $+45°$ rotation angles with the offset and the corrected values (for nominal correlations) when no grid was applied in the setup. The complex conjugate of the redundant correlation is taken before plotting.

$+45°$, and $+90°$. Fig. 6 shows the measured correlations, the offset, and the corrected line. The offset is clearly lower than in the measurement with the polarizer grid, and the measured phase imbalance is in a good agreement with the result obtained with the polarizer grid (see Table I). Table II lists the obtained correlation values at $-45°$ and $+45°$ angles with the standard deviation of the measurement showing similar resolution with the result obtained with the polarizer grid. The lower offset may be due to the fact that the polarization impurity has opposite phase as compared with the nonidealities of the antenna of the radiometer. The cross-polarization ratio of the transmitting antenna is about 25 dB, which, based on this result, seems to be enough for the application of this technique.

It can also be seen that as the polarization grid affects unavoidably both transmitted field and multipath radiation, it does not affect the phase imbalance result (Table I) or the sensitivity of the correlations (Table II).

V. CONCLUSION

A method for determining the end-to-end phase imbalance of a fully polarimetric radiometer using digital one-bit/two-level correlation was introduced and demonstrated with experiments. The method is based on measuring a linearly polarized field at $-45°$ and $+45°$ angles with respect to the polarization plane of the antenna of the radiometer. The method has a significant impact on the calibration of polarimetric radiometers because there has been a lack of well-defined and usable procedure, especially for low-frequency polarimetric radiometers.

The experiments showed that the pointing of the radiometer is important for the accuracy of the retrieval of the phase imbalance. Another observation was that a moderate (25 dB) polarization purity of the transmitted field is sufficient for the successful determination of the phase imbalance.

ACKNOWLEDGMENT

This work was performed within the SMOS Phase CD, which is managed by EADS CASA Espacio and funded by the European Space Agency. Elektrobit Microwave Ltd. (EBM) is subcontracted by EADS CASA Espacio, and Helsinki University of Technology is acting as a subcontractor of EBM.

REFERENCES

[1] J. Lahtinen, A. J. Gasiewski, M. Klein, and I. S. Corbella, "A calibration method for fully polarimetric microwave radiometers," *IEEE Trans. Geosci. Remote Sens.*, vol. 41, no. 3, pp. 588–602, Mar. 2003.

[2] J. Lahtinen and M. Hallikainen, "HUT fully polarimetric calibration standard for microwave radiometry," *IEEE Trans. Geosci. Remote Sens.*, vol. 41, no. 3, pp. 603–611, Mar. 2003.

[3] J. R. Piepmeier and A. J. Gasiewski, "Digital correlation microwave polarimetry: Analysis and demonstration," *IEEE Trans. Geosci. Remote Sens.*, vol. 39, no. 11, pp. 2392–2410, Nov. 2001.

[4] F. Torres, A. Camps, J. Bará, I. Corbella, and R. Ferrero, "On-board phase and modulus calibration of large aperture synthesis radiometers: Study applied to MIRAS," *IEEE Trans. Geosci. Remote Sens.*, vol. 34, no. 4, pp. 1000–1009, Jul. 1996.

[5] A. Camps, F. Torres, I. Corbella, J. Bara, and J. A. Lluch, "Threshold and timing errors of 1 bit/2 level digital correlators in Earth observation synthetic aperture radiometry," *Electron. Lett.*, vol. 33, no. 9, pp. 812–814, Apr. 24, 1997.

[6] J. Lahtinen, L. Ruokokoski, A. Colliander, V. Kangas, A. Aalto, M. Levander, and H. Greus, "Reference radiometer for interferometric radiometry from space," in *Proc. IGARSS*, Jul. 25–29, 2005, vol. 8, pp. 5551–5553.

[7] A. Colliander, S. Tauriainen, T. I. Auer, J. Kainulainen, J. Uusitalo, M. Toikka, and M. T. Hallikainen, "MIRAS reference radiometer: A fully polarimetric noise injection radiometer," *IEEE Trans. Geosci. Remote Sens.*, vol. 43, no. 5, pp. 1135–1143, May 2005.

[8] P. Silvestrin, M. Berger, Y. Kerr, and J. Font, "ESA's second Earth Explorer Opportunity Mission: The Soil Moisture and Ocean Salinity mission—SMOS," *IEEE Geosci. Remote Sens. Newslett.*, no. 118, pp. 11–14, Mar. 2001.

[9] M. Martín-Neira and J. M. Goutoule, "A two-dimensional aperture-synthesis radiometer for soil moisture and ocean salinity observations," *ESA Bull.*, no. 92, pp. 95–104, Nov. 1997.

[10] F. Ulaby, R. Moore, and A. Fung, "Microwave remote sensing, active and passive," in *Fundamentals and Radiometry*, vol. 1. Reading, MA: Addison-Wesley, 1981.

[11] L. Tsang, J. A. Kong, and R. T. Shin, *Theory of Microwave Remote Sensing*. Hoboken, NJ: Wiley, 1999.

[12] J. B. Hagen and D. T. Farley, "Digital-correlation techniques in radio science," *Radio Sci.*, vol. 8, no. 8/9, pp. 775–784, Aug./Sep. 1973.

[13] J. H. Van Vleck and D. Middleton, "The spectrum of clipped noise," *Proc. IEEE*, vol. 54, no. 1, pp. 2–19, Jan. 1966.

[14] T. Larsen, "A survey of the theory of wire grids," *IRE Trans. Microw. Theory Tech.*, vol. 10, no. 3, pp. 191–201, May 1962.

[15] T. Manabe and A. Murk, "Transmission and reflection characteristics of slightly irregular wire-grids with finite conductivity for arbitrary angles of incidence and grid rotation," *IEEE Trans. Antennas Propag.*, vol. 53, no. 1, pp. 250–259, Jan. 2005.

Andreas Colliander (S'04) was born in Imatra, Finland, in 1976. He received the M.Sc. and Lic.Sc. degrees from the Helsinki University of Technology (TKK), Espoo, Finland, in 2002 and 2005, respectively. He is currently working toward the D.Sc. degree at the Laboratory of Space Technology, TKK.

He is currently a Research Scientist and Project Manager with the Laboratory of Space Technology, TKK. He has a Research Student position in the National Graduate School for Remote Sensing, which is supported by the Finnish Ministry of Education and the Academy of Finland. His research is focused on microwave radiometer systems, with emphasis on polarimetric and interferometric radiometers, and on theoretical simulation of rough-surface backscattering. He has authored or coauthored 19 scientific publications on microwave remote sensing.

Mr. Colliander was a recipient of the TKK Master's Thesis Award, an annual award for top five Master's thesis of TKK.

Jani Kettunen was born in Finland, in 1977. He is currently working toward the Master's degree at the Helsinki University of Technology, Espoo, Finland. His Master's thesis is focused on HUT-2D interferometric L-band radiometer antenna parameter characterization.

Since 2002, he has been with the Laboratory of Space Technology, Helsinki University of Technology. In addition to his Master's thesis, he is working on the testing and characterization of the reference radiometers (L-band fully polarimetric noise injection radiometers) of the MIRAS instrument. The MIRAS instrument is the main instrument of the European Space Agency's Soil Moisture and Ocean Salinity mission.

Martti T. Hallikainen (M'83–SM'85–F'93) received the Engineering Diploma (M.Sc.) and the Dr.Sci.Tech. degree from the Helsinki University of Technology (TKK), Espoo, Finland, in 1971 and 1980, respectively.

Since 1987, he has been a Professor of space technology with the Helsinki University of Technology. In 1988, he established the TKK Laboratory of Space Technology, and currently serves as its Director. In 1993–1994, he was a Visiting Scientist with the Institute for Remote Sensing Applications, European Union's Joint Research Centre, Ispra, Italy. From 1981 to 1983, he was a Postdoctoral Fellow with the Remote Sensing Laboratory, University of Kansas. He was awarded with an Asla-Fulbright scholarship for graduate studies at the University of Texas at Austin in 1974–1975. His research interests include the development of microwave sensors for airborne and spaceborne remote sensing, development of methods to retrieve the characteristics of geophysical targets from satellite and airborne measurements, and cryospheric applications of remote sensing. His team is currently involved in the development of the L-band synthetic aperture radiometer MIRAS for the ESA SMOS satellite and a similar airborne instrument (HUT-2D) for the Laboratory's research aircraft.

Dr. Hallikainen has been a member of the IEEE Geoscience and Remote Sensing (GRSS) Administrative Committee since 1988 and served as President of IEEE GRSS in 1996–1997. He was the General Chair of the IGARSS'91 Symposium and the Guest Editor of the Special IGARSS'91 Issue of the IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING (TGARS). He was an Associate Editor of TGARS in 1992–2002. He has been the Vice President of the International Union of Radio Science (URSI) since 2005 and served as the Chair of URSI Commission F in 2002–2005. He has been a National Official Member of URSI Commission F since 1988 and was the Chair of URSI Finnish National Committee in 1997–2005. He has been the Vice Chair of the Finnish National Committee of COSPAR since 2000. He was a member of the European Space Agency's (ESA) Earth Science Advisory Committee in 1998–2001. He is a national delegate to the ESA Earth Observation Data Operations Scientific and Technical Advisory Group (DOSTAG) since 1995. He has been a member of the European Association of Remote Sensing Laboratories (EARSeL) Council since 1985. He was the Secretary General of EARSeL in 1989–1993 and the Chairman of the Organizing Committee for the EARSeL 1989 General Assembly and Symposium. He has been a member of the Advisory Committee for the European Microwave Signature Laboratory of the European Union's Joint Research Centre since 1992. He was the recipient of three IEEE GRSS awards: 1994 Outstanding Service Award, IGARSS'96 Interactive Paper Award, and 1999 Distinguished Achievement Award. He was awarded the Microwave Prize for the best paper in the 1992 European Microwave Conference and the IEEE Third Millennium Medal in 2000.