CALIBRATION OF CO-LOCATED CORRELATION RADIOMETERS FOR THE CASE OF CROSSTALK

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ABSTRACT

We propose a calibration method of correlation radiometers for cases when cross-coupling between channels cannot be ignored. The method requires sources that are stable with respect to temperature, impedance match, and Excess Noise Ratio (ENR). This treatment establishes a rationale for source stability and describes how these desirable characteristics may be realized. Next, it describes a method by which correlation radiometers may be calibrated and compensated for gain and phase imbalance between channels with the presence of cross-coupling between them.

***Index Terms*—** calibration, correlation, cross-coupling, gain balance, gain compensation, phase balance, radiometer

1. INTRODUCTION

Passive microwave remote sensing using radiometers was used in applications such as early detection of fire [1], forest surveillance [2], imminent volcanic eruptions [3], monitoring distribution and dynamics of ice [4], monitoring of agricultural output [5]. In contrast to this, synthetic aperture radiometry achieves high spatial resolution using interferometric techniques. Although interferometry is a mature technique in radio astronomy, its application to microwave radiometry is relatively recent [6]. The literature available is sparse and confined to narrow enough bands [7][8][9]. The trend towards wider bandwidths [10] to improve temperature and spatial resolution requires correlation among pairs of radiometers that receive the same noise from the scene. In synthetic aperture radiometry, correlation radiometers are used to extract spatial coherence information by measuring the complex visibility function across pairs of antenna elements.

One of the challenges in synthetic aperture radiometry is calibration. Its purpose is to establish the connection between the measured complex correlations with the scene brightness temperature, accounting for gain, phase, and coupling errors [11]. In systems where multiple radiometers are co-located or densely packed, electromagnetic coupling and shared circuitry can introduce non-negligible crosstalk between channels, which distorts the measured correlations and affects calibration accuracy. Early works such as Faris [12] laid the theoretical groundwork for correlation radiometer sensitivity and thermal noise considerations, while Dicke [13] introduced key principles of thermal noise mitigation in total power radiometers that influenced later radiometric system design. In [14], calibration of the two-channel correlation radiometer is done by 180 phase switching with 50% duty cycle of the local oscillator signal in one of the channels, incorporated in the RF (microwave). In [15], a calibration procedure is proposed requiring the injection of three polarized markers. In [16], centralized Pseudo-Random Noise (PRN) signals are used to calibrate correlation radiometers. Another calibration method [17] for polarization correlation millimeter wave radiometers in vacuum chamber consists of one polarization grid, one temperature adjusted targets, and one cold target and doesn't need any unpolarized target when calibrating a polarization correlation radiometer by regulating the physical of calibration targets.

In [18], we address the calibration of co-located correlation radiometers under the idealized condition that channel crosstalk can be ignored. However, this assumption may not hold in practical wideband or compact systems. In this paper, we extend the analysis to the more realistic case where crosstalk is present and must be accounted for during calibration. We present a model of channel coupling, analyze its impact on system performance, and propose a calibration approach that compensates for this interference. This work is a necessary step toward robust deployment of correlation radiometers in high-density synthetic aperture architectures.

2. PROPOSED CALIBRATION METHOD WHEN CROSSTALK IS PRESENT

Figure 1 shows the simplest form of a correlation radiometer [19]. It consists of two image-reject receivers, Σ and Δ, that are connected to the sum and difference ports of a 180° hybrid coupler. One input of the hybrid is connected to the antenna whose voltage, v_A, is split equally and in phase at each receiver input. The other input of the hybrid is connected to a reference (calibration) source whose voltage, v_{ref}, is split equally but 180° out of relative phase at the receiver input ports. The receivers are driven by a common local oscillator (LO) to realize image suppressed conversion at intermediate frequency (IF). The image suppressed IF outputs of each receiver are multiplied, and low-pass filtered to produce the correlated output, v_{Out}.

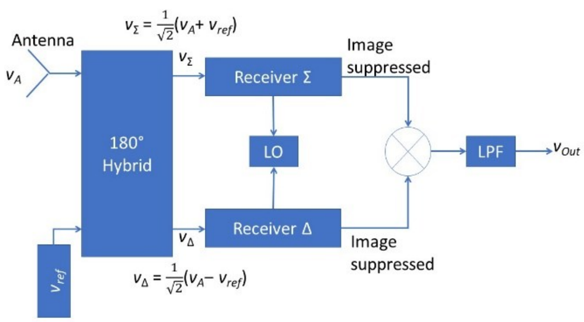

Fig. 1. Simplest form of a correlation radiometer.

The calibration method described in [18] is appropriate when crosstalk between channels can be ignored. A different method is needed when crosstalk cannot be ignored. First, a variation of the noise source from [18] conveniently mechanizes calibration of correlated radiometers when crosstalk cannot be ignored – see Figure 2.

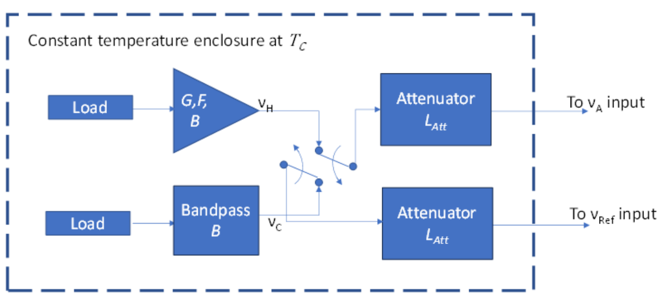

Fig. 2. Modified noise source for calibrating correlated radiometers with crosstalk.

The noise source has two outputs: one connected to the v_A input of the radiometer in Figure 1; the other connected to the v_{Ref} input of that radiometer. A transfer switch enables source's outputs, v_H and v_C, to be exchanged with the radiometer inputs. With this view in mind, the output voltage from the Σ channel is,

$$v_{o\Sigma} = A_\Sigma\left[\frac{(v_H + v_C)}{\sqrt{2}} + v_{n\Sigma} + S_{\Sigma\Delta}\left\{v_{n\Delta} + \frac{(v_H - v_C)}{\sqrt{2}}\right\}\right] \quad (1)$$

In (1), $S_{\Sigma\Delta}$ represents the coupling coefficient that causes leakage from the Δ channel into the Σ channel. Likewise, the output voltage from the Δ channel is,

$$v_{o\Delta} = A_\Delta\left[\frac{(v_H - v_C)}{\sqrt{2}} + v_{n\Delta} + S_{\Delta\Sigma}\left\{v_{n\Sigma} + \frac{(v_H + v_C)}{\sqrt{2}}\right\}\right] \quad (2)$$

In (2), $S_{\Delta\Sigma}$ represents the coupling coefficient that causes leakage from the Σ channel into the Δ channel. Cross correlation of these voltages supplies is:

$$\begin{aligned}4RC_{\Sigma\Delta} = v_{o\Sigma}v_{o\Delta}^* = A_\Sigma A_\Delta^*\Big[&\frac{1}{2}\left(1 + S_{\Sigma\Delta}S_{\Delta\Sigma}^*\right)\left(|v_H|^2 - |v_C|^2\right) + \\ &+ S_{\Sigma\Delta}|v_{n\Delta}|^2 + S_{\Delta\Sigma}^*|v_{n\Sigma}|^2 + \frac{1}{2}\left(S_{\Sigma\Delta} + S_{\Delta\Sigma}^*\right)\left(|v_H|^2 + |v_C|^2\right)\Big]\end{aligned} \quad (3)$$

The equivalent Johnson resistor is R. When the signals are exchanged,

$$v'_{o\Sigma} = A_\Sigma\left[\frac{(v_H + v_C)}{\sqrt{2}} + v_{n\Sigma} + S_{\Sigma\Delta}\left\{v_{n\Delta} - \frac{(v_H - v_C)}{\sqrt{2}}\right\}\right] \quad (4)$$

Likewise, the output voltage from the Δ channel is,

$$v'_{o\Delta} = A_\Delta\left[-\frac{(v_H - v_C)}{\sqrt{2}} + v_{n\Delta} + S_{\Delta\Sigma}\left\{v_{n\Sigma} + \frac{(v_H + v_C)}{\sqrt{2}}\right\}\right] \quad (5)$$

Cross correlation now provides,

$$\begin{aligned}4RC_{\Delta\Sigma} = v'_{o\Sigma}v'^*_{o\Delta} = A_\Sigma A_\Delta^*\Big[&-\frac{1}{2}\left(1 + S_{\Sigma\Delta}S_{\Delta\Sigma}^*\right)\left(|v_H|^2 - |v_C|^2\right) + \\ &+ S_{\Sigma\Delta}|v_{n\Delta}|^2 + S_{\Delta\Sigma}^*|v_{n\Sigma}|^2 + \frac{1}{2}\left(S_{\Sigma\Delta} + S_{\Delta\Sigma}^*\right)\left(|v_H|^2 + |v_C|^2\right)\Big]\end{aligned} \quad (6)$$

We convert the square of the voltages to temperature via the Johnson formula, and sum (3) and (6) to obtain the crosstalk term:

$$\begin{aligned}C_{\Sigma\Delta} + C_{\Delta\Sigma} = \kappa T_o B A_\Sigma A_\Delta^*\Big[&2\left(S_{\Sigma\Delta}T_{Rx\Delta} + S_{\Delta\Sigma}^*T_{Rx\Sigma}\right) + \\ &+ \left(S_{\Sigma\Delta} + S_{\Delta\Sigma}^*\right)\left(2T_C / T_0 + ENR\right)\Big]\end{aligned} \quad (7)$$

Crosstalk contains leakage contributions from the injected noise, T_H and T_C, as well as internal noise represented by $T_{Rx\Sigma}$ and $T_{Rx\Delta}$, generated within each receiver. Subtracting (6) from (3),

$$C_{\Sigma\Delta} - C_{\Delta\Sigma} = \kappa T_o B A_\Sigma A_\Delta^*\left(1 + S_{\Sigma\Delta}S_{\Delta\Sigma}^*\right)ENR \quad (8)$$

Equation (8) reveals that most of the crosstalk, except for the term, $S_{\Sigma\Delta}S_{\Delta\Sigma}^*$, is eliminated by taking the difference in cross-correlations from the two excitation conditions. If we divide (7) by (8) we obtain:

$$\left(C_{\Sigma\Delta}+C_{\Delta\Sigma}\right)/\left(C_{\Sigma\Delta}-C_{\Delta\Sigma}\right)=$$
$$\left[2\left(S_{\Sigma\Delta}T_{Rx\Delta}+S_{\Delta\Sigma}^{*}T_{Rx\Sigma}\right)+\left(S_{\Sigma\Delta}+S_{\Delta\Sigma}^{*}\right)\left(2T_C/T_o+ENR\right)\right]/ \quad (9)$$
$$/\left[\left(1+S_{\Sigma\Delta}S_{\Delta\Sigma}^{*}\right)ENR\right]$$

In typical cases, crosstalk coupling is reciprocal, i.e., $S_{\Sigma\Delta} = S_{\Delta\Sigma}$. Also, for systems with low losses as is needed to reduce noise in radiometers, coupled waves are in phase quadrature with their stimulus, so the coupling coefficients are imaginary. Under these circumstances, $S_{\Sigma\Delta}+S_{\Delta\Sigma}^{*}=0$, and injected signals do not contribute to cross-correlated crosstalk. Reciprocity also implies that $S_{\Sigma\Delta}S_{\Delta\Sigma}^{*}=\left|S_{\Sigma\Delta}\right|^{2}$, so from (8),

$$\frac{C_{\Sigma\Delta}+C_{\Delta\Sigma}}{C_{\Sigma\Delta}-C_{\Delta\Sigma}}=\frac{2S_{\Sigma\Delta}\left(T_{Rx\Delta}-T_{Rx\Sigma}\right)}{\left(1+\left|S_{\Sigma\Delta}\right|^{2}\right)ENR} \quad (10)$$

Equation (10) reveals the benefit of having receivers whose noise temperatures are closely matched, which causes the crosstalk term to vanish for coupling coefficients that obey reciprocity and are purely imaginary. If $T_{Rx\Delta} \neq T_{Rx\Sigma}$, then (10) may be used to solve for $|S_{\Sigma\Delta}|$. In this case,

$$A_{\Sigma}A_{\Delta}^{*}=\frac{C_{\Sigma\Delta}-C_{\Delta\Sigma}}{\kappa T_o B\cdot ENR\left(1+\left|S_{\Sigma\Delta}\right|^{2}\right)} \quad (11)$$

The denominator on the right-hand-side of (11) is real, and therefore,

$$\Delta\varphi=\arg\left(A_{\Sigma}A_{\Delta}^{*}\right)=\arg\left(C_{\Sigma\Delta}-C_{\Delta\Sigma}\right) \quad (12)$$

For well-designed radiometer pairs, crosstalk is small, e.g., $|S_{\Sigma\Delta}| < 0.1$ for 20-dB crosstalk. Consequently, the factor $(1+\left|S_{\Sigma\Delta}\right|^{2})$ is very close to unity and does not significantly impact the gain correction, which is identical to the method discussed in [18]. This method of calibration is appropriate when the correlated receivers reside on the same platform. Clearly, for this situation, implementation must strive to secure the lowest crosstalk possible.

It is noteworthy that ENR, G_{Σ}, G_{Δ}, and $\Delta\varphi$ are frequency dependent and specified in the frequency domain, whereas the voltages are sampled in the time domain. The entire development presented here assumes that voltages are transformed to the frequency domain before correlation is applied, and the gain and phase corrections are obtained therefrom and applied. The corrected data streams are first convolved and then transformed to the time domain to obtain the time difference of arrival of noise from the scene. If the receivers that participate in a cross correlation have internal mismatched propagation delays, the difference between delays is a systematic error given by

$$\Delta\tau=-\frac{1}{2\pi}\frac{d\left(\Delta\phi\right)}{df} \quad (13)$$

Typically, estimates of $\Delta\phi$ are noisy, and $\Delta\tau$ is taken as the slope of the best-fit straight line through the data and used to correct the time difference of arrival of noise from the scene. It is therefore important that the calibration paths to both receivers are equalized so as not to introduce spurious delay differences from the set-up.

One drawback of this method is that calibration and measurement are performed sequentially, so that the best sensitivity obtainable is that of a Dicke calibration.

3. CONCLUSIONS

This paper proposes a calibration method of co-located correlation radiometers for the case when cross-coupling between channels cannot be ignored. We show that most of the crosstalk, except for one term, is eliminated by taking the difference in cross-correlations from the two excitation conditions (leakage from the Σ channel into the Δ channel and vice-versa). For systems with low losses as is needed to reduce noise in radiometers, coupled waves are in phase quadrature with their stimulus, so the coupling coefficients are imaginary. We show the benefit of having receivers whose noise temperatures are closely matched, which causes the crosstalk term to vanish for coupling coefficients that obey reciprocity and are purely imaginary.

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