Optimal Calibration of Radiometers Using System Identification Techniques

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ABSTRACT

Microwave radiometers are valuable for obtaining geophysical information such as the ocean surface salinity, stratiform precipitation, water vapor, temperature, soil moisture, vegetation cover, and others [1]. These environmental monitoring applications of passive microwave remote sensing systems require precision measurements of brightness temperatures over a range of more than 300K with absolute accuracy as good as 0.1K or better depending on the application. Therefore, developing an accurate and practical internal radiometer/sensor calibration technique becomes necessary and critical to future radiometer application success.

The classical two-load calibration technique is in terms of a predominantly linear dependence between brightness temperature (*T*) and detected voltage (*v*) [2]. This simple relationship $v = mT + b$, where m is the receiver gain and b is the offset, is often adequate to describe the aggregate system response of the instrument. Subsequently, the classical two-load calibration technique is widely applied in many radiometer calibration applications with great success in the past thirty years [2-6].

However, due to the following reasons the classical two-load technique is inadequate to account for variations in system response that occur in the path from the antenna and calibration references to the receiver. First, there can potentially be unwanted thermal emission sources in between the calibration references and the receiver, thus producing additional unaccounted emission. Second, the calibration references may themselves be imperfect blackbodies, thus reflecting radiation from other unknown sources [7, 8]. They may also exhibit instabilities that require characterization or redundancy [9]. Third, there are in general, unknown emissions from losses in the antenna itself. In calibration reference design, the parametric optimization of target geometry has been discussed with respect to electromagnetic and thermal analysis [7, 8] including trough-to-tip temperature profile, wave scattering and absorption from the target surface, target shapes, and coating thickness. Long-term calibration stability can be achieved with frequent recalibration of the noise diodes using external calibration techniques [9].

In our radiometer studies, we have found that radiometer front-end components produce significant thermal noise contribution with the following characteristics: 1) these thermal noise contributions are very hard to be determined to desired levels of precision, 2) their emission changes subtly when components are removed and re-installed, 3) they exhibit emission variations with thermal drift. Further, the gain and offset of a radiometer are not constants but vary with time and ambient temperature. To this

end we find that in radiometer calibration there are two time scales and two classes of stability: radiometers commonly exhibit random fluctuations in gain (therefore in offset) that occur on short time scales (~0.001-100 sec.) and fluctuations in noise temperature that are the result of relatively slow but measurable thermal variations need to be considered.

Therefore, instead of describing radiometer calibration in terms of a simple linear dependence between brightness temperature and detected voltage, in our study a radiometer is treated as linear instrument with a number of unknown non-ideal front-end parameters in addition to radiometer systematic gain and offset. Based on the above assumption a general expression for the response of a radiometer to antenna temperature, with additional input data being the measured front-end components temperatures is defined to characterize the non-idealities:

$$\bar{v} = \begin{bmatrix} v_A \\ v_C \\ v_H \end{bmatrix} = m\bar{T}_{sys} + \bar{b} + \bar{n}_v = m\bar{\bar{W}}\bar{T} + \bar{b} + \bar{n}_v, \tag{1}$$

where m, b and $\bar{n}_v$ are system gain, offset and random noise (respectively) and the subscripts *A, C, H,* represent the three calibration states of scene, internal cold and hot view (respectively). The column vector $\bar{T}$ contains the antenna scene temperature T_A and all the measured front-end components temperatures. The weighting matrix $\bar{\bar{W}}$ contains information on the manner in which specific front-end components contribute to the gain and offset in each calibration state. Details of (1) are available in [10]. In our research, the front end components of interest include waveguides, couplers, PIN and ferrite switches, isolators, reference terminations, noise diodes, and low noise amplifiers. All of these component types contribute noise in ways that are difficult to model precisely using manufacturers' specifications.

Since in calibration process all measured front-end components temperatures are precisely known and given sufficient integration time, the random noise in (1) can be neglected, therefore in order to solve (1) in terms of T_A, m and b, $\bar{\bar{W}}$ must be precisely determined. Thus (1) needs to be considered as a calibration inverse problem [11] and solved within the context of estimation theory. To do so, a perturbation method (PM) is applied: $\bar{\bar{W}} = <\bar{\bar{W}}> + \delta\bar{\bar{W}}$, where $\langle\cdot\rangle$ denotes *a-priori* values of $\bar{\bar{W}}$ from laboratory measurements and/or manufacturer's specifications, and δ denotes unknown variations. The technique builds upon the work of Thompson et al. [12] who demonstrated that radiometer output variations caused by thermal fluctuations can be (to some degree) compensated.

The technique used to account for the two aforementioned classes of fluctuations in a radiometer is: 1) for the gain variations a statistical method based on the LMMSE estimation [13] is used to determine the gain and offset on a short time scale, and 2) system identification based upon an independent set of system thermal perturbations is set to estimate the deterministic response to thermal fluctuations on longer time scales. The procedure is shown in (2). By applying this PM-LMMSE algorithm and using initial information on the $\bar{\bar{W}}$ matrix, the 0^{th} order values of gain and offset can be computed through (2-a). This information is then used in (2-b) to calculate the 1^{st} order estimation of $\delta\bar{\bar{W}}$ matrix. Through the above recursion relation the estimation procedure is iterated until the $\delta\bar{\bar{W}}$ matrix converges [14], [15]:

$$\begin{bmatrix} m^{(n)} \\ b^{(n)} \end{bmatrix} = \begin{bmatrix} < m^{(n)} > \\ < b^{(n)} > \end{bmatrix} + \overline{\overline{D}}^{(n)} \begin{bmatrix} \delta v_C - \dfrac{< W_{21} > + \delta \hat{W}_{21}^{(n)}}{< W_{11} > + \delta \hat{W}_{11}^{(n)}} \delta v_A \\ \delta v_H - \dfrac{< W_{31} > + \delta \hat{W}_{31}^{(n)}}{< W_{11} > + \delta \hat{W}_{11}^{(n)}} \delta v_A \end{bmatrix} \quad \text{(2-a)}$$

$$\delta \hat{\overline{W}}_{\alpha}^{(n)} = [\frac{1}{m^{(n-1)}}(\overline{v}_{\alpha} - \overline{b}^{(n-1)}) - < \overline{W}_{\alpha} > \overline{\overline{T}}](\overline{\overline{T}}^T \overline{\overline{T}})^{-1} \overline{\overline{T}}^T , \alpha = A, C, H \quad \text{(2-b)}$$

Based on the PM-LMMSE, we further develop a Jacobian perturbation model (JPM) by incorporating a Jacobian operator into the PM estimation equation so that (1) is revised as:

$$\overline{v} = m\left\langle \overline{\overline{W}} \right\rangle \overline{T} + m\left(\sum_{i=1}^{n} \frac{\partial \overline{\overline{W}}}{\partial P_i} \delta P_i \right) \overline{T} + \overline{b} + \overline{n}_v \quad (3)$$

where $\overline{P} = \left\langle \overline{P} \right\rangle + \delta \overline{P}$ contains the physical radiometer parameters. In the JPM, $\delta \overline{P}$ is estimated by following the same PM-LMMSE procedure shown in (2), and in doing so we compute information for all relevant radiometer front-end components in a self-consistent manner.

In this research, the relationship between the estimated system gain and offset and the initial (*a-priori*) values of the front-end components parameters (usually with uncertain error) is discussed. We show that the above algorithm leads to a modified PM model called the “zero mean offset perturbation model” (ZMOPM), which assumes the offset to be a white noise process with zero mean.

The above calibration models are applied to calibrate an L-band radiometer (LRAD), although it can be readily extended to general radiometer calibration. A series of system identification experiments (SID) had been performed using the LRAD at Boulder, Colorado during July 2007. There are two major epochs in the SID data: 1) putting an external calibrator (~290K) on the LRAD's pyramidal horn antenna; 2) pointing the LRAD to observe cold space at zenith. In both epochs the major front-end components are thermally perturbed by warming up and cooling down in every 3 minutes. The experiment data from the SID is used in our developed calibration models and so we can estimate $\overline{\overline{W}}$ via (2). After $\overline{\overline{W}}$ has been obtained, it will be used in the data from another set of experiment, which only uses the cold cosmic background as a radiation field without any thermal perturbation to estimate the sky temperature.

Details of the algorithm for the above calibration model and validation results that illustrate the stability of the calibrated radiometer data under random thermal fluctuations will be presented.

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