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Compensation of Elevation Angle Variations in Polarimetric Brightness Temperature Measurements from Airborne Microwave Radiometers

I. Corbella, A. J. Gasiewski, M. Klein, and J. R. Piepmeier

***Abstract*—This paper presents a method for compensating the elevation angle fluctuations occurring in airborne radiometry due to aircraft roll and pitch. The correction is based on a radiative transfer model, and is demonstrated by real data from conical scans over the ocean, showing good results.**

***Index Terms*—Calibration, radiometry.**

I. INTRODUCTION

Airborne microwave radiometry is very useful for retrieving important geophysical parameters such as surface wind speed and direction, with high spatial resolution and short revisit time. This requires brightness temperature T_b to be measured at constant elevation angles, so a conically scanned system is highly useful. In practice, however, platform roll and pitch motion produces variations in the true incidence angle, thus causing fluctuations in the measured brightness temperature as well as rotation of the radiometer polarization basis. The problem is particularly acute for airborne platforms.

For a given class of terrain, T_b is a function of the elevation angle and can be computed using models based on radiative transfer [1] and/or rough surface scattering theory. Whereas the absolute value of T_b is difficult to predict due to its sensitivity to several often poorly known parameters, its slope with respect to the elevation angle at a given incidence angle, height, surface type, and atmospheric state, can be quite accurately computed. Provided that the platform attitude is well known, the theoretical slopes can be subsequently applied to the measured brightness temperatures to compensate to first order for variation in brightness as a function of the elevation angle.

This attitude compensation has been successfully carried out on data gathered by the NOAA/ETL polarimetric scanning radiometer (PSR/A) [2] at frequencies of 10.7 GHz, 18.7 GHz, 21.5 GHz, 37 GHz, and 89 GHz. The PSR was mounted onboard a NASA DC-8 aircraft during the third Convection and Moisture Experiment (CAMEX3, August–September 1998). Polarimetric brightness temperatures of the ocean surface were measured under a variety of meteorological conditions, particularly at high winds. Full (360°) conical scans with 53.1° incidence (identical to the SSM/I) were used.

At all the measurement frequencies and for both vertical and horizontal polarizations the compensation method shows a significant reduction of the correlation between the true brightness temperature and the true elevation angle as measured using aircraft inertial navigation system data, thus achieving an effective compensation.

II. COMPENSATION TECHNIQUE

The correction algorithm is based upon calculating the true elevation angle and polarization rotation given the PSR position encoder values and the aircraft pitch, roll, and heading data. First, the antenna pointing and horizontal polarization vectors are transformed into the world coordinate frame using five rotational transforms. Then the azimuth, elevation (from nadir), and polarization rotation angles are computed from the output vectors. Once these angles are found, the corrections to the brightness temperatures can be made. The transformation of the antenna pointing and polarization vectors to the world coordinate frame is achieved using five rotational transform operations [3]. These rotations are performed about the scanhead elevation and azimuth axes, the aircraft roll and pitch axes, and finally, the compass heading axis. Fig. 1 illustrates each of these coordinate frame rotations. In vector notation, the compound transformation is

$$\hat{\overline{X}} = \overline{\overline{R}}_z^{-1}(\text{head}) \cdot \overline{\overline{R}}_y^{-1}(\text{pitch}) \cdot \overline{\overline{R}}_x^{-1}(\text{roll}) \cdot \overline{\overline{R}}_z^{-1}(az) \cdot \overline{\overline{R}}_y^{-1}(el) \cdot \hat{\overline{x}} \quad (1)$$

where $\hat{\overline{x}}$ is the pointing or polarization unit vector in the antenna coordinate frame, and $\hat{\overline{X}}$ is the respective unit vector in the world coordinate frame. The antenna pointing unit vector is $(0; 0; 1)^T$, and the horizontal polarization unit vector is $(0; 1; 0)^T$. The rotation operators are given by the following:

$$\overline{\overline{R}}_x^{-1}(\theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix};$$

$$\overline{\overline{R}}_y^{-1}(\theta) = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix};$$

$$\overline{\overline{R}}_z^{-1}(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (2)$$

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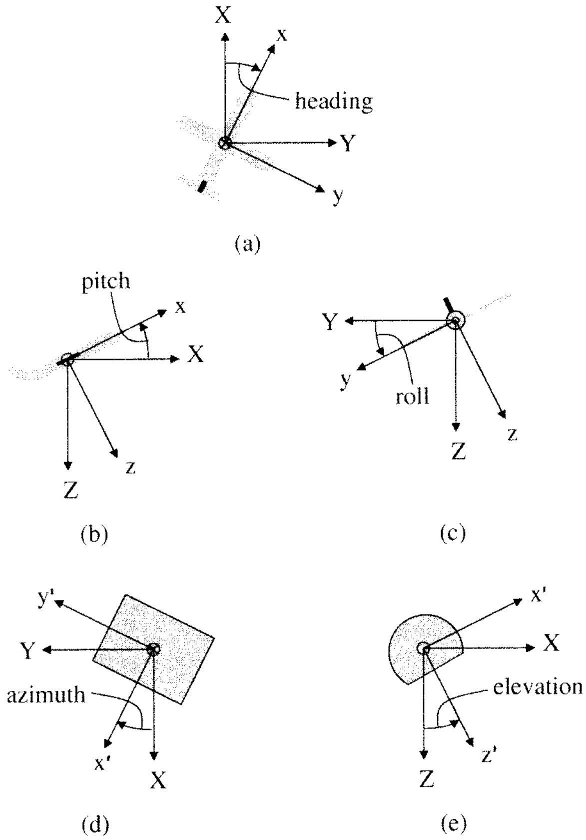

Fig. 1. The five rotational operations used to compute the PSR pointing and polarization vectors in the world coordinate frame. (a)–(c) describe the aircraft attitude, and (d) and (e) describe the instrument pointing with respect to the aircraft. X, Y, and Z denote world coordinates (North-East-Nadir), and x, y, z are airplane local coordinates (Front–Right–Bottom), and x', y', and z' scanhead coordinates.

θ being a general symbol for the rotation angle which, while substituting the above in (1), will represent heading, pitch, roll, azimuth, or elevation angle. The true azimuth, elevation, and polarization angles can be found from the different vector components. The true elevation angle on ground (from zenith) θ_e is

$$\theta_e = \tan^{-1} \frac{\sqrt{\hat{k}_x^2 + \hat{k}_y^2}}{\hat{k}_z} \tag{3}$$

where $\hat{k}_x$, $\hat{k}_y$, and $\hat{k}_z$ are the x, y, and z components of the pointing vector in the world coordinate frame. The true azimuth angle ϕ, in the compass rose orientation, is

$$\phi = \tan^{-1} \frac{\hat{k}_y}{\hat{k}_x}. \tag{4}$$

The polarization rotation angle is found by first projecting the polarization vector in world coordinate frame $\hat{\bar{p}} = (\hat{p}_x, \hat{p}_y, \hat{p}_z)^T$ into the spherical polarization components using (1), and then taking an arctangent

$$\alpha = \tan^{-1} \frac{\hat{p}_x \cos\theta \cos\phi + \hat{p}_y \cos\theta \sin\phi - \hat{p}_z \sin\theta}{-\hat{p}_x \sin\phi + \hat{p}_y \cos\phi} \tag{5}$$

The polarization rotation angle can be used to correct the third Stokes parameter with respect to the polarization basis rotation [4]

$$T_{fU} = T_U \cos 2\alpha - (T_v - T_h) \sin 2\alpha. \tag{6}$$

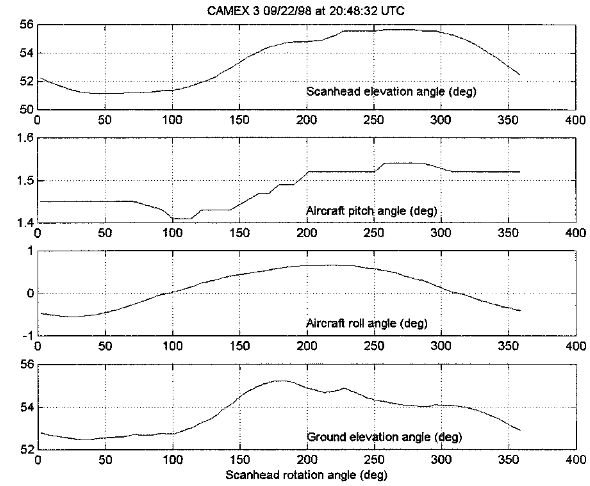

Fig. 2. From top to bottom: Measured scanhead elevation angle referred to "downlooking" in local scanhead coordinates, measured pitch and roll angles of aircraft, and computed true ground elevation angle (from nadir).

For a typical aircraft flight, the true elevation angle as computed from the coordinate rotation is continuously changing during each scan, as illustrated in Fig. 2. In this particular example, the true elevation angle varied from a minimum of 52.5° to a maximum of 55.2° during a single conical scan, whereas the nominal elevation angle was set to 53.1°. For meaningful analyses of the radiometric data, this elevation angle should be kept constant, particularly for comparison with satellite data.

The compensation procedure is based upon a linear approximation of the brightness temperature with respect to the elevation angle for small increments

$$T_B(\theta_e) \approx T_B(\theta_0) + (\theta_e - \theta_0) \left. \frac{dT_B}{d\theta} \right|_{\theta_0} \tag{7}$$

where T_B represents vertical or horizontal brightness temperature, and θ_0 is the nominal elevation angle. Upon correction, the radiometer output is the first term of the above equation, and the compensated brightness temperature is its value at the nominal angle $T_B(\theta_0)$.

The theoretical dependence of the brightness temperature with respect to the elevation angle can be computed using, e.g., the radiative transfer model (MRT) of [5]. Here, it is sufficient to use the statistical parameters of the atmosphere, the type of surface, and the altitude. To obtain the slope, a sixth degree polynomial approximation was fitted to data computed over the angular range of 0 to 89° (Fig. 3), and the derivative of the polynomial was used to estimate $dT_B/d\theta$. Table I shows the results of this computation for statistical fall, mid-latitude atmosphere parameters at 10 km altitude and for wind-driven ocean with surface wind speed of 7 m/s. A cloud-free atmosphere was assumed. The surface model used is based on the Wilheit model [6] of a rough ocean surface and the sea water dielectric model of Klein and Swift [7].

III. Results

The results of the correction are shown in Fig. 4, in which the brightness temperatures measured at 10.7 GHz (vertical and horizontal) are plotted as a function of the true elevation angle. When no correction is performed, a high correlation (Table II) between T_B and the true elevation angle Θ is clearly seen for both polarizations and for all frequencies. As predicted from the theory and shown in the curves of Fig. 3, at these elevation angles, for vertical polarization, the slope is positive, whereas the slope for horizontal polarization is negative. When corrected using the theoretical slope, the brightness temperatures are

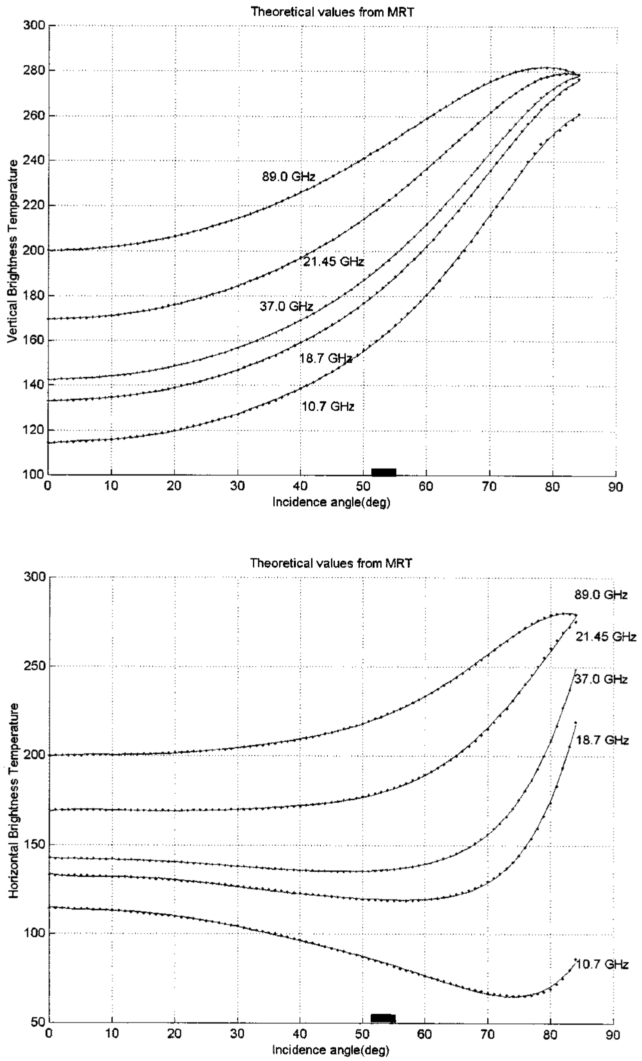

Fig. 3. Theoretical dependence of brightness temperature with incidence angle. The range of elevation angles during the experiment is shown.

TABLE I
COMPUTED SLOPE OF BRIGHTNESS TEMPERATURE WITH RESPECT TO THE ELEVATION ANGLE ($dT_B/d\theta$) AT $\theta_0 = 53.1°$ USING MICROWAVE RADIATIVE TRANSFER AND MODELS FOR THE OCEAN SURFACE AND THE ATMOSPHERE

Frequency	$dT_b/d\theta$ (K/°)	
GHz	vert	horiz
10.7	2.3385	-1.0364
18.7	2.3885	-0.1216
21.5	2.1717	1.0039
37.0	2.3667	0.2436
89.0	1.7643	1.3768

practically independent of the elevation angle, although some overcorrection is observed in the horizontal channel. Similar results are obtained for the remaining channels.

IV. CONCLUSIONS

A method for compensating the elevation angle variation in airborne microwave radiometry over the ocean has been presented. The method uses computed theoretical values of brightness temperature as a function of the elevation angle to determine the expected slope. By subtracting this theoretical slope, the brightness temperature at the nominal elevation angle is computed. Results are presented showing that this approach can effectively reduce the correlation between the true elevation angle and the brightness temperature.

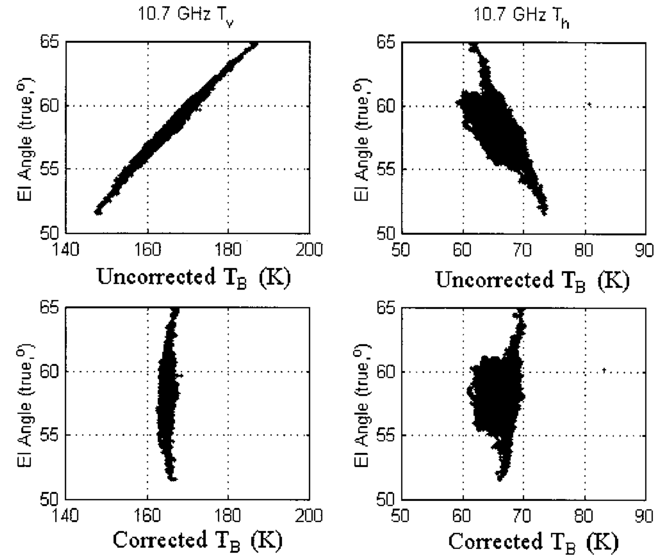

Fig. 4. Uncorrected and corrected brightness temperature as a function of elevation angle.

TABLE II
CORRELATION COEFFICIENT BETWEEN THE BRIGHTNESS TEMPERATURE AND THE ELEVATION ANGLE, BOTH BEFORE AND AFTER COMPENSATION. THEY HAVE BEEN COMPUTED FROM DATA COLLECTED ON SEPTEMBER 22, 1998 DURING THE CAMEX-3 CAMPAIGN

Channel	No correction	After Correction
10.7 GHz (vertical)	0.806	0.009
10.7 GHz (horizontal)	-0.607	-0.004
18.7 GHz (vertical)	0.648	-0.057
18.7 GHz (horizontal)	-0.066	-0.007
21.5 GHz (vertical)	0.586	-0.193
21.5 GHz (horizontal)	0.886	0.175
37.0 GHz (vertical)	0.765	0.085
37.0 GHz (horizontal)	0.467	0.311
89.0 GHz (vertical)	0.375	-0.186
89.0 GHz (horizontal)	0.332	0.011

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