On-orbit Microwave Blackbody Calibration Using Regions of Dense Vegetation

Shannon Brown and Chris Ruf
University of Michigan
Ann Arbor, MI

I. INTRODUCTION

Satellite microwave radiometers have provided measurements of the vertical temperature distribution, cloud liquid water, radiometric path delay, sea ice concentration, precipitation, and various other geo-physical parameters for over 30 years [1]. Microwave radiometers take measurements of the apparent brightness temperature (TB) of a scene at various frequencies in order to retrieve atmospheric parameters. Accurate retrieval of these parameters requires a precise inversion algorithm and a well calibrated instrument.

Radiometers are calibrated on-orbit by comparing the measured brightness temperatures to on-Earth targets whose brightness temperature is known or can be accurately modeled. The dynamic range of brightness temperatures that an Earth observing radiometer will encounter is approximately 120 K – 310 K from 18 – 40 GHz and 0 – 55° incidence. The brightness temperatures must be calibrated accurately at both ends of the TB spectrum. A method developed by [2], which isolates a statistical lower bound for brightness temperature over the ocean, can be used to calibrate the TBs at the cold end of the spectrum. There remains a need for a stable on-Earth hot calibration reference target. An ideal target would be a large isothermal blackbody in the field of view of the Earth pointing antenna. Heavily vegetated regions of the Amazon rainforest can be treated as pseudo-blackbodies due to the emission of the canopy being independent of polarization and incidence angle. With a known surface emission, SSM/I TBs can be used to determine a hot calibration reference for frequencies from 18 – 40 GHz and incidence angles of 0 to 55°. Having this provides a calibration reference for any radiometer operating within that range.

II. METHODOLOGY

The brightness temperature of a vegetation canopy over a soil surface is a function of the emission from the soil surface and the vegetation layer [3]. This can be modeled as

\[
T_{B,\text{canopy}}(f, \theta, p) = \left(1 - \frac{1 - \Gamma_s(f, \theta, p)}{L(f, \theta)} \right) \left(1 - \frac{1}{L(f, \theta)} \right) \times (1 - a(f)) \Gamma_v + \left(1 - \frac{1 - \Gamma_s(f, \theta, p)}{L(f, \theta)} \right) \Gamma_v
\]

(1)

where
\[
\Gamma_s(f, \theta, p) \quad \text{soil-vegetation reflectivity},
\]
\[
L(f, \theta) \quad \text{loss factor of the vegetation canopy},
\]
\[
a(f) \quad \text{single scattering albedo of the canopy},
\]
\[
T_v \quad \text{physical temperature of the canopy},
\]
\[
T_s \quad \text{physical temperature of the surface}.
\]

At frequencies greater than 10 GHz with a dense canopy that has high moisture content, the optical depth becomes very large and the transmissivity (inverse of the loss factor) of the canopy approaches zero. In this case the brightness temperature of the canopy reduces to,

\[
T_{B,\text{canopy}} = (1 - a(f)) \Gamma_v
\]

(2)

where the single scattering albedo is isotropic and independent of polarization. It is reasonable to assume that the albedo varies with frequency since the wavelength of the radiation is changing relative to the leaf dimensions. Using this model as the surface contribution, the radiative transfer equation is written as

\[
TB_{\text{app}}(f, \theta) = (1 - a(f)) \Gamma_v e^{-\tau(f) \sec \theta} + TB_{\text{up}}(f, \theta) + \Gamma_{\text{scat}}(f) (TB_{\text{down}}(f)) e^{-\tau(f) \sec \theta}
\]

(3)

where
\[
\theta \quad \text{incidence angle},
\]
\[
\Gamma_{\text{scat}}(f) \quad \text{represents the fraction of downwelling radiation scattered into } \theta \text{ from the canopy},
\]
\[
TB_{\text{down}}(f) \quad \text{represents the hemispherical contribution of the downwelling brightness temperature},
\]
\[
TB_{\text{up}}(f, \theta) \quad \text{upwelling atmospheric brightness temperature},
\]
\[
TB_{\text{app}} \quad \text{main beam brightness temperature at the antenna},
\]
\[
\tau(f) \quad \text{optical depth of the atmosphere}.
\]
The surface contribution can be estimated from SSM/I brightness temperatures by inverting (3) and solving for $T_v$. This requires that $TB_{up}(f, \theta)$, $T(f)$, $TB_{down}(f)$, $\Gamma_{scat}(f)$, and $a(f)$ are known for SSM/I frequencies. These variables can be estimated from the SSM/I data.

Statistical inversion methods have been used to retrieve atmospheric parameters such as vertically integrated path delay and liquid water [4]. A similar method is used to find the atmospheric upwelling brightness temperature at any other frequency and incidence (18 – 40 GHz, 0 – 55°) can be found using

$$T_{up}(f, \theta) = c_1 F_w(f, \theta) \left[ T_{up}(22.235, 53^\circ) - T_{up}(19.35, 53^\circ) \right] + c_2 F_o(f, \theta) T_{up}(37.0, 53^\circ) + c_3 f^2 \sec(\theta).$$

where

$$F_w(f, \theta) = \sec(\theta) \frac{f^2}{f^2 + \gamma^2} \left[ \frac{1}{(f - f_w)^2 + \gamma^2} + \frac{1}{f^2 + \gamma^2} \right].$$

The first term in (8) is a measure of the shape and strength of the water vapor absorption line, $f_w$ is 22.235 and $f$ is in GHz. The third term is a measure of the absorption continuum and the second term is a measure of the shape and strength of the 60 GHz oxygen absorption line [6].

Using an average atmospheric effective radiating temperature over the Amazon and the SSM/I upwelling TBs determined from (4) [5], the integrated optical depth can be determined by

$$_{up}(f, 53^\circ) = c_0 + c_1 T_{app}(19.35, 53^\circ) + c_2 T_{app}(22.235, 53^\circ) + c_3 T_{app}(37.0, 53^\circ).$$

(4)

The hemispherical downwelling component is determined using the same form as (8), with the sec(\theta) terms removed. The integrated optical depth is found using (5) with the upwelling TBs determined from (8). Once $TB_{up}(f, \theta)$, $T(f)$, $TB_{down}(f)$, are determined, (3) is used with the $T_v$ determined from SSM/I to find the apparent TB at any other frequency and incidence from 18 - 40 GHz and 0 - 55° incidence. These values are the hot calibration reference temperatures for suitable regions in the Amazon rainforest.

III. MODEL PARAMETERIZATIONS

To determine the coefficients in the above equations, radiosonde data in the vicinity of the selected regions is used to model the apparent TBs, integrated optical depth, effective radiating temperature, and the upwelling and downwelling TBs. RaOb sounding data from October 2001 through September 2002 is used from four stations in the Amazon. The radiosonde data is acquired from NOAA’s Forecast Systems Laboratory (FSL) radiosonde database. A plane parallel radiative transfer model is used with an updated version of the Liebe 1987 [7] atmospheric water vapor absorption model and the Rosenkranz 1993 [8] oxygen absorption model to determine the brightness temperature from the RaOb profiles.

The measured apparent TB data set consists of measurements from October 2001 through September 2002 from the DMSP SSM/I F13, F14, and F15 platforms acquired from Remote Sensing Systems. Two regions are chosen where measurements from October 2001 through September 2002 is used from four stations in the Amazon. The measured TBs are found from the SSM/I upwelling TBs determined from (4). The atmospheric upwelling brightness temperature at any other frequency and incidence (18 – 40 GHz, 0 – 55°) can be found using

$$TB_{up}(f, \theta) = c_1 F_w(f, \theta) \left[ 1 - T_{up}(22.235, 53^\circ) + T_{up}(19.35, 53^\circ) \right] + c_2 F_o(f, \theta) T_{up}(37.0, 53^\circ) + c_3 f^2 \sec(\theta).$$

The third term is a measure of the absorption continuum and the second term is a measure of the shape and strength of the 60 GHz oxygen absorption line [6].
The equations in section II are parameterized using least-squares optimization of the modeled radiosonde database. The dependence of the single scattering albedo on frequency, (7), is determined by solving for $a(f)$ in (3) using average modeled values for the atmospheric TB components with average SSM/I apparent TBs at 19, 22, and 37 GHz.

The hot reference temperature is determined from 18 - 40 GHz and 0 – 55° incidence from the parameterizations of the equations in II. Fig. 1 and Fig. 2 show the hot reference temperature versus frequency and incidence averaged over local time and time of year. A microwave radiometer operating within this range can use these reference temperatures for the TB calibration at the hot end of the TB spectrum.

IV. CONCLUSIONS

Satellite microwave radiometers require precisely calibrated brightness temperatures for the accurate retrieval of geophysical parameters. The on-orbit calibration of brightness temperature involves calibrating the TBs at the hottest and coldest ends of the TB dynamic range. Equations are developed to determine apparent brightness temperatures at other frequencies and incidence using SSM/I TBs. The equations are parameterized from 18 – 40 GHz and 0 – 55° incidence using a radiative transfer model with RaOb profiles in the Amazon. In this way, a hot reference temperature is determined over regions of optically thick vegetation in the Amazon rainforest for the on-orbit calibration of microwave radiometers operating within this range.

V. REFERENCES