IMPROVING SATELLITE ANTENNA TEMPERATURE ESTIMATION BY HIGH-RESOLUTION EMISSION MODEL OF THE EARTH

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Abstract

This paper describes the recent results of a study aimed at accurately determining the antenna noise temperature used to calculate uplink G/T for satellite-borne receivers. The antenna noise temperature is calculated from a brightness temperature database of the Earth which, for each surface pixel ($1° \times 1°$), includes the effects of season, observation angle and frequency. Good correlation has been found by comparison with In-Orbit Test (IOT) measurements.

1 INTRODUCTION

Experience from existing telecommunications satellites shows that large (exceeding 2 dB) discrepancies often exist between the predicted and the in-orbit measured satellite uplink gain-to-noise ratio G/T. The basic reason for these discrepancies is believed to lie in the estimate of the system noise temperature T_{sys}, which is usually performed assuming a fixed satellite antenna temperature $T_A = 290$ K. When the repeater noise is high, its contribution to the system temperature is predominant, and the above assumption has little bearing on the accuracy of the estimate. However, since with improved technology the noise of repeaters has decreased, T_A tends to become a crucial parameter, and the correctness of its estimate can substantially affect the overall accuracy of the predicted G/T.

The accuracy of the estimate depends on the faithfulness of the available model in reproducing the actual features of the apparent Earth's brightness temperature. A simple first model, usable for wide-beam antennas, was developed by the European Space Agency (ESA) [1, 2]. However, this model neglected several features of the apparent temperature (e.g., the dependence on elevation angle), assumed simple spatial distributions (i.e., continents were assumed to be of uniform brightness temperature), and was developed for a single frequency. Consequently, a more refined and comprehensive model of the apparent temperature was desirable.

A more realistic model of emission of the Earth has been developed at Tor Vergata University [3] to simulate the spatial distribution of the microwave brightness temperature observed by a satellite antenna, which results from contributions by the surface and the atmosphere, including interactions. These contributions depend on type and state of both surface and atmosphere and vary with geographical location and season. Hence the global emission model that has been developed is based on a detailed ($1° \times 1°$ latitude by longitude) description of the local surface and on its characterization from the emissivity point of view. The local emitting and attenuating properties of the overlying atmosphere and the surface-atmosphere interaction are also incorporated to determine the overall emission.

The frequency limits (5–50 GHz) considered by the model include the main telecommunications frequency bands (C, K_u, and K_a); the range of observation angles (i.e., the angle from the local zenith) up to 87.5° is able to cover any orbital location; and the $1° \times 1°$ spatial resolution allows regional beam evaluations, too.

2 EMISSION FROM THE EARTH SURFACE

To model the power density emitted at microwave frequencies from the Earth's surface in the various seasons, the significant surface categories present on the planet have to be identified and their emissivity estimated. For each category, emission depends both on the receiving system parameters (frequency, angle, and polarization) and on the surface time-dependent physical properties. These affect the permittivity and the geometric structure in a way which is different among the various cases; hence the contribution to the antenna noise power is peculiar of both the particular surface type and its state.

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2.1 Surface characterization

The whole surface of the Earth has been subdivided into $1° \times 1°$ (latitude by longitude) parcels, and the nature of the surface within each pixel has been identified. Seasonal variations have been taken into account by considering four different data sets, each referring to a season. Land pixels have been separated from sea pixels by using the land/sea mask. In turn, the sea parcels have been subdivided into water, first-year and multiyear ice, and mixed-type, also taking into account seasonal sea ice concentration.

The characterization of the land parcels allows desert, bare ground, water bodies, and continental ice to be separated from vegetation covers. Moreover, it provides several classes of vegetation covers; some of them are of permanent type, such as evergreen broadleaf and coniferous forests, while others exhibit seasonal cycles, like agricultural vegetation, for which additional information about monthly means of the leaf area index (LAI) has been used. Arboreous vegetation has been subdivided into two classes, i.e., dense and sparse, which have been chosen as reference forests for emissivity computation. In turn, the 2-year values of LAI averaged over the 3-month seasons, which give an indication of the density of nonarboreous vegetation (dense or sparse) were used in the seasonal computations of emissivity. The effects of soil roughness and moisture content have also been taken into account by introducing additional classes of "sparse" vegetation over dry and wet soils. Finally, a snow depth database has been used on the seasonal basis to introduce the possible snow cover (dry or wet, depending on season) into the emissivity computations. Mixed-type pixels have also been occasionally introduced, when needed.

2.2 Emissivity characterization

To model emissivity, results obtained by the remote sensing community in the last decades were found fundamental. Data collected by ground-based, airborne, and spaceborne radiometers, as well as theoretical and empirical models, were used, generally adopting a mixed approach. For some surface types for which extensive measurements are available, emission numerical algorithms based on interpolation and extrapolation of experimental data have been used. In other cases electromagnetic models have been employed, after validation over available experimental data sets.

Details on the emissivity models used for each type of surface together with an extended reference list can be found in [3].

3 ATMOSPHERIC EFFECTS

In most of the considered frequency range, emission from each pixel of the Earth depends not only on the type of surface but also on the structure of the overlying atmosphere. Hence the model requires the identification of the moisture and thermal characteristics of the atmosphere over each $1° \times 1°$ pixel.

Radiosonde data have been used to model the atmospheric characteristics over the different locations. 169 meteorological stations have been selected to generate a grid that, at least over land, is dense enough to take possible significant climatic variations into account. Contours have been generated, surrounding each radiosonde launch site and shaped according to the homogeneity of the surface characteristics, and the corresponding 10-year (1980–1989) radiosonde profile data, averaged over the four 3-month periods, have been used to seasonally characterize the atmosphere over all parcels included within each contour.

4 EMISSION FROM THE SURFACE-ATMOSPHERE SYSTEM

To estimate the emission observed from space, the contribution of the surface has been combined with the atmospheric one, taking also into account the surface/atmosphere interaction. Emission from the surface has been computed by use of the emissivity models for each surface type, assuming the proper surface temperature.

The attenuation and the upward and downward emission of the atmosphere have been computed at the desired frequency and elevation angle by using the millimeter-wave propagation model (MPM) of H. Liebe [4], fed by the seasonally averaged temperature and water vapor profiles measured by the radiosondes and by the seasonal liquid profile.

The computed quantities have then been combined to yield the global brightness temperatures of each Earth parcel at the needed frequency, angle and polarization.

5 DATABASE VALIDATION

To validate the database, the global experimental data set provided by the Defense Meteorological Satellite Program special sensor microwave imager (SSM/I) [5], was used. To this end, the SSM/I measurements covering the entire year 1992 taken by the 19-, 22-, and 37-GHz channels have been selected as the reference "radiometric truth" data set. The calibrated and quality-checked brightness temperatures have been assigned to the $1° \times 1°$ Earth parcels and averaged over the four groups of 3 months corresponding to the seasons. Then the brightness temperatures obtained from the database at the same observation angle, frequencies, and polarizations at which the SSM/I data are taken, have been compared with those measured by the satellite on a pixel-by-pixel basis and separately for each season.

The brightness temperature maps obtained by the database reveal appreciable agreement with the experimental ones also in rather fine details [3].

6 INTEGRATION INTO SOFTWARE FOR ANTENNA NOISE TEMPERATURE EVALUATIONS

A software has been developed by TICRA which is able to calculate the total antenna system noise temperature using as inputs: a contoured beam given as field values in a regular grid in satellite antenna coordinates, the brightness temperature data for the relevant frequency range, and the system component noise data.

As a first step the antenna incident noise temperature is calculated from the following integral:

$$T_A = \frac{1}{4\pi} \int_{4\pi} \left[\left| T_{B_1}(a,b,\theta) E_1^2(\psi,\phi) \right| + \left| T_{B_2}(a,b,\theta) E_2^2(\psi,\phi) \right| \right] d\Omega \qquad (1)$$

where angles ψ and ϕ denote the direction from which the emitted power incomes; $a(\psi,\phi)$ and $b(\psi,\phi)$ are the corresponding latitude and longitude of the Earth's surface parcel where emission originates; $\theta(\psi,\phi)$ is the angle with respect to the local zenith; $E_1(\psi,\phi)$ and $E_2(\psi,\phi)$ are the two normalized orthogonal polarizations components of farfield; and $T_{B_1}(a,b,\theta)$ and $T_{B_2}(a,b,\theta)$ are the corresponding brightness temperatures of the Earth.

For the area of the farfield region inside the Earth rim the brightness temperature database is applied for T_{B_1} and T_{B_2}. Outside the Earth rim a uniform deep space temperature can be defined by the user. Furthermore, the program will calculate the amount of power in the grid window. Assuming that the field is normalized over the farfield sphere, it is possible to derive the amount of power outside the window (again at deep space temperature, in case including the contribution from the satellite body). The program adds this temperature to the antenna noise temperature.

Finally, it is possible to define a position for the Sun and its temperature either given by $T_{\mathrm{sun}}(\mathrm{K}) = 60000 \times F(\mathrm{GHz})^{0.75}$ or defined directly by the user.

From the incident antenna noise temperature the user may now obtain the total system noise temperature by defining the physical temperature, T_{ci}, and the loss, L_i, for a number of feed chain components and the repeater temperature, T_{rep}. The output noise temperature from each component is given by

$$T_i = T_{i-1}\frac{1}{L_i} + T_{ci}\frac{L_i - 1}{L_i} \qquad (2)$$

For n components we have $T_{\mathrm{sys}} = T_n + T_{\mathrm{rep}}$.

7 VALIDATION OF SOFTWARE

A sample contoured beam from EUTELSAT-II, FM6 receive antenna has been used as input for the validation test and compared to various noise temperature measurements. The frequency is 12.9 GHz, and the polarization is linear North-South.

Assuming that the noise measurements have been carried out in Spring, the brightness temperature data associated to this season have been used to calculate an antenna incident noise temperature of 143.9 K. This includes the contribution from the Earth and from deep space inside the recorded field window assuming a deep space temperature of 4 K.

The calculation also indicates that 16.6% of the total power is radiated outside the recorded window. Since the actual reflector geometry is a dual Gregorian, it is assumed that half this power is passing the subreflector "looking" at a deep space temperature of 4 K. This provides a contribution of $0.083 \times 4\,K = 0.3\,K$. The other half of the power is passing the main reflector and "looks into" the satellite body which is assumed to have a physical temperature of 373 K and a reflective loss of 0.2 dB ($\simeq 1.047$). This results in a contribution from the satellite body of $(0.083 \times ((1.047-1)/1.047)) \times 373\,K = 1.4\,K$. Finally, the part of the main reflector spillover which is reflected in the satellite body will see the cold sky (4 K) providing an increment of $(1/1.047)0.083 \times 4\,K = 0.3\,K$. Hence, the total antenna incident noise temperature is $143.9\,K + 0.3\,K + 1.4\,K + 0.3\,K = 145.9\,K$. In comparison measurements at 2 different locations have indicated 148.4 K and 142.6 K, hence, correlating very well with the analytical prediction. (*The data presented in this section do not represent the minimum guaranteed performance of the EUTELSAT system.*)

8 CONCLUSIONS

An accurate approach for determining Earth brightness temperature and the associated software development have been described. The program includes frequency and polarisation dependence. Also, the model contains information of seasonal effects and provides a fine resolution for regional and spot beam computation. The model heavily relies on theoretical modeling of Earth and atmosphere emission and interaction. Finally, it has been tuned on the basis of experimental data collected by SSM/I space-borne imaging system. Results on antenna temperature prediction for EUTELSAT II satellites have been presented and compared with in-orbit measurements resulting in a very good correlation.

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