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CALIBRATION METHODS IN MILLIMETER-WAVE RADIOASTRONOMY

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RESUMEN. Discutimos un método de calibración de observaciones en radio astronomia milimétrica que compensa automaticamente la atenuación atmosférica, aún en la presencia de una redoma o cuando la temperatura cinética media del cielo es menor que la temperatura ambiente.

ABSTRACT. We discuss a calibration method for millimeter wave observations that automatically compensates the atmospheric attenuation, even in the presence of a radome, or when the mean kinetic temperature of the sky is smaller than the ambient temperature.

Key words: millimeter-radioastronomy

I. INTRODUCTION

Absolute calibration of millimeter-wave continuum observations (i.e., the relation between measured antenna temperature and flux density) requires the observation of calibration sources of known flux density and the determination of the atmospheric absorption.

The observation of calibration sources is straightforward, can be done a number of times during an observing session and gives information about the antenna efficiency. Variations in the gain of the receiver can be monitored as often as necessary by connecting a noise source of known temperature.

Measurements of the atmospheric absorption presents more problems. They require measurements of the sky temperature as a function of the elevation angle and the process is time consuming. Besides that, the atmospheric opacity is highly variable, specially in the presence of clouds and during onset hours, when there is a large variation in humidity.

To overcome the need of measuring directly the atmospheric opacity, Penzias and Burrus (1973) described a calibration technique that automatically compensates the atmospheric attenuation. In this method, the receiver is calibrated by introducing an absorber at room temperature at a point just ahead of the feed horn. The calibration noise signal is the difference between the temperature of the absorber and that one of the sky.

Davis and Vanden Bout (1973) pointed out that the attenuation of the atmosphere is not completely accounted for when the sky is cooler than the ambient temperature. They showed that this is the case at the frequency of the J = 1-0 line of CO (115 GHz). At this frequency the principal atmospheric absorber is O_2 (Findlay, 1971) and the atmospheric temperature is about 246K. The derived antenna temperature was always lower than the real temperature and depended strongly on the elevation angle of the observed source.

In this paper we review the problem and we analyse the effect of a radome in the calibration of millimeter-wave sources and derive an algorithm that allows us to correct the observations without measuring the actual atmospheric absorption.

II. CALIBRATION TECHNIQUE

Let us consider a total power receiver, in which the input signal corresponds to the superposition of the system temperature (~ 1000 K), sky temperature (~ 100 K) and source temperature (~ 1 K). After passing through a square-law detector, a constant voltage is subtracted from the signal to account for the system temperature, and the remaining signal is amplified.

The relation between antenna temperature T and measured voltage ΔV, for a quadratic detector, is

$$T = C\,(\Delta V + V_o) \qquad (1)$$

where C is a constant that depends on the gain of the system and V_o a constant voltage.

The values of C and V_o can be obtained from the voltages ΔV_{nt} and ΔV_ℓ measured when a noise tube of known temperature T_{nt} and an ambient temperature T_{amb} load are connected.

$$C = \frac{T_{nt}}{\Delta V_{nt\,+\,sky} - \Delta V_{sky}} \qquad (2)$$

$$V_o = \frac{T_{amb}}{C} - \Delta V_\ell \qquad (3)$$

If the antenna is enclosed in a radome of transmission coefficient η, the antenna temperature of a source T_{so} outside the atmosphere will be related to the measured antenna temperature T_s by

$$T_s = \eta T_{so}\, e^{-\tau/\sin E} = C\,(\Delta V_{s\,+\,sky} - \Delta V_{sky}) \qquad (4)$$

where $\tau/\sin E$ is the optical depth of the atmosphere at elevation angle E, $\Delta V_{s\,+\,sky}$ is the contribution of a point source and the surrounding sky and ΔV_{sky} the contribution of the sky. From (4) we obtain

$$T_{so} = \frac{C}{\eta}\, e^{\tau/\sin E}\,(\Delta V_{s+sky} - \Delta V_{sky}) = K(E)C(\Delta V_{s+sky} - \Delta V_{sky})$$

where we have defined

$$K(E) = \frac{e^{\tau/\sin E}}{\eta} \qquad (5)$$

The emission from the atmosphere, in a plane-parallel approximation is given by

$$T_{sky} = \eta\, T^*_{sky}\,(1-e^{-\tau/\sin E}) = C\,(\Delta V_{sky} + V_o) \qquad (6)$$

where T^*_{sky} is the mean kinetic temperature of the sky in the region where most of the absorption takes place.

Let us calculate

$$\alpha\, T_{amb} - T_{sky} = \alpha\, T_{amb} - \eta\, T^*_{sky}\,(1 - e^{-\tau/\sin E}) \qquad (7)$$

with α defined by

$$\alpha = \frac{\eta T^*_{sky}}{T_{amb}} \qquad (8)$$

Combining (5), (6), (7) and (8) we obtain

$$CK(E) = \frac{T^*_{sky}}{\alpha(\Delta V_\ell + V_o) - (\Delta V_{sky} + V_o)} \qquad (9)$$

We define

$$B(E) = \frac{T_{amb}}{\Delta V_\ell - \Delta V_{sky}} = \frac{T_{amb}}{(\Delta V_\ell + V_o) - (\Delta V_{sky} + V_o)} \qquad (10)$$

From (9) and (10) we obtain

$$K(E) = \frac{\alpha}{\eta} = \frac{1}{(\alpha - 1) + \frac{C}{B(E)}} \qquad (11)$$

The quantities C and B (E) are determined from measurements of a noise tube and an ambient temperature load and the value of α can be determined for each frequency.

III. OBSERVATIONS

To test the calibration method described in II we made observations of Jupiter from rise to set on September 5, 1984 under conditions of changing atmospheric absorption. We used the radome-enclosed 13.7 m Itapetinga radiotelescope. The detector was a K-band total power receiver, operating at the frequency of 22 GHz; the system temperature was about 1000K. The radome transmission at this frequency was $\eta = 0.77$. Each observation was the average of 30scans across the source, preceeded by the observation of a noise source of 110 K and of a room temperature load. Each scan lasted 20 sec and had an amplitude of 1 degree. The scans were made alternatively in elevation and in azimuth to correct for any pointing errors. The observations started at 15 hours local time and lasted until midnight. We determined the atmospheric absorption several times during the observations by measuring the sky temperature at different elevations between 20^o and 60^o and fitting the function

$$T_{sky} = \eta T^*_{sky}\,(1 - e^{-\tau/\sin E})$$

with two unknown parameters, τ and T^*_{sky}. The results of the fitting, together with the weather parameters (relative humidity TH, and ambient temperature T_{amb}) and the local time(LT) are presented in Table 1.

TABLE 1. VALUES OF THE SKY TEMPERATURES AND ATMOSPHERIC ABSORPTION

LT	RH(%)	T_{amb}	T^*_{sky}	τ
15	30	25	300	0.21
18	40	20	295	0.22
21	75	12	287	0.24

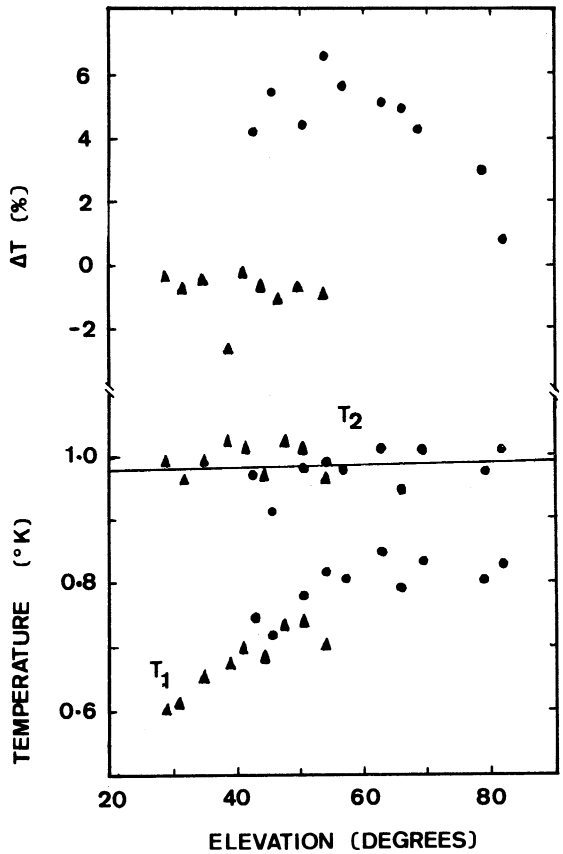

FIGURE 1. Antenna temperature of Jupiter obtained in September 5, 1984. T_1 is the antenna temperature before correcting for atmospheric attenuation, T_2 is the antenna temperature corrected with the method described in II, $\Delta T = (T_3 - T_2)/T_2$, where T_3 is obtained by multiplaying T_1 by $e^{\tau/\sin E}$, with $\tau = 0.21$ for the rise of the source (points) and $\tau = 0.24$ afterwards (triangles).

IV. RESULTS

(a) We obtained the peak temperature T_1 of each observation from the fitting of a gaussian to the data, after substracting a baseline representing the contribution of the sky. The transformation factor from voltage to antenna temperature was obtained from the observation of a noise source. Therefore T_1 is not corrected for atmospheric attenuation and the results are dependent on the elevation angle of the source, as can be seen in Fig. 1.

(b) We corrected the antenna temperature T_1 by the factor K(E) given by equation (11) and obtained the temperature T_2, that should be independent of the elevation. In fact we obtained the linear regression

$$T_2 = 0.978 + 0.0001*E$$

which proves that the effects of the atmosphere are accounted for.

(c) The temperature T_1 was multiplied by $e^{\tau/\sin E}$ with $\tau = 0.21$ from the begining of the observations until 18 hs LT and $\tau = 0.24$ afterwards to obtain T_3. The ratio $\Delta T = (T_3 - T_2)/T_2$ is shown in Fig. 1. Since the atmospheric absorption changes continuously but not regularly during the observations the value of ΔT can be as large as 6%.

We conclude therefore that the method derived in II is correct in the sense that compensates the atmospheric absorption, even in the presence of a radome or when the mean kinetic temperature of the atmosphere is not equal to the ambient temperature. Moreover it does not require the determination of the actual atmospheric absorption, which is always a time consuming measurement, allowing the observation of sources even under not ideal atmospheric conditions.

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