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Atmospheric opacity correction in C-band at Irbene RT-16 radio telescope

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The method (Kraus (2007)) for correcting atmospheric opacity in the C-band was applied to the RT-16 radio telescope of the Irbene observatory. The method is based on the calculation of the noise temperature T_0, which is almost independent of the environment and is determined by the characteristics of the receiver and radio telescope antenna. T_0 is determined using sky dip observations. The atmospheric opacity in the zenith is calculated using T_0. We have determined the time dependence of T_0 over a long period of time. It is shown that the T_0 error increases the error of the flux density by no more than 0.5%.

Keywords: Correction of atmospheric opacity, radio telescope, C-band

1 Introduction

During the observations of astronomical sources, it is necessary to take into account the opacity in the Earth atmosphere. Atmospheric opacity in the zenith τ in the C-band is small. Its value is 0.015 Np in good weather (Bolli et al. (2015)). Therefore, the relative error of the flux density of astronomical sources associated with the uncertainty of τ is small ($\delta_\tau \sim 1.5$).

This is less than errors caused by other factors. However, knowledge of the zenith opacity is necessary. The elevation angle during observations at radio telescopes is less than 90. In this case, the δ_τ increases in proportion to airmass. With the deterioration of weather conditions, the error δ_τ will also increase. In addition, the zenith opacity

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can be used as a parameter for exclusion of the data obtained in bad weather. This is especially true for remotely conducted observations, when the observer is away from the telescope.

Currently, several methods for determining the zenith opacity are known. You can use the technique of sky dip observations (Prandoni et al. (2017)), or use the atmosphere model (Braatz (2009)). Nykiel et al. (2018) used the Integrated Water Vapor (IWV) Obtained from Global Navigation Satellite Systems to define τ. We used the method described in Kraus (2007) and applied it to determine the zenith opacity in C-band for calibration of data obtained at the RT-16 radio telescope Irbene Observatory (Ventspils).

2 Methodology

During observations of astronomical sources, the influence of the atmosphere is manifested in the form of $e^{\tau AM}$ that is multiplied by the antenna temperature:

$$T_a^* = T_a e^{\tau AM} \tag{1}$$

or

$$S = \frac{T_a e^{\tau AM}}{DPFU\,(El)}. \tag{2}$$

Here T_a is the antenna temperature of the source, T_a^* is the antenna temperature of the source adjusted for opacity in the atmosphere, S is the flux density, $DPFU\,(El)$ is elevation dependent antenna gain in Degrees Per Flux Unit. $DPFU\,(El) = \frac{A_{eff}\,(El)}{2k_B}$ 10^{-26} where $A_{eff}\,(El)$ is effective area of antenna, K_B is Boltzmann constant. El is elevation, AM is airmass. $AM = 1/\sin(El)$.

The $e^{\tau AM}$ can be calculated using the system temperature T_{sys}. On the one hand, T_{sys} is easily calculated using a calibration diode. On the other hand, T_{sys} can be represented as follows:

$$T_{sys} = T_0 + T_{Atm}\left(1 - e^{-\tau AM}\right). \tag{3}$$

Or, since $\tau \ll 1$ is in the C-band,

$$T_{sys} \simeq T_0 + T_{Atm} \cdot \tau \cdot AM. \tag{4}$$

Here T_0 is noise temperature determined by the influence of the antenna's sidelobes, a horn and a receiver. T_0 does not depend on the atmospheric opacity in the zenith τ and weakly depends on the ambient temperature T_{ground}. T_0 usually changes slightly over time. T_{Atm} is average atmospheric temperature. To calculate it, we used the formula $T_{Atm} \simeq T_{ground} - 17$ K (Kraus (2007)).

First, preliminary observations are carried out to determine T_0. In this case, T_{sys} is measured at several elevations (sky dip observation). T_0 is determined by fitting using the least squares method from formula (3). Then, with a known T_0, astronomical observations are carried out. $e^{\tau AM}$ and τ are calculated using the following formulas:

$$e^{\tau AM} = \frac{T_{Atm}}{T_{Atm} + T_0 - T_{sys}}, \tag{5}$$

$$\tau = -\frac{1}{AM} \ln\left(1 - \frac{T_{sys} - T_0}{T_{Atm}}\right). \tag{6}$$

Thus, the purpose of this work is to carry out preliminary observations and to determine T_0 and its stability in the long run. Also, it is necessary to calculate the error of T_0 and the impact of this error on flux density (that is, on $e^{\tau AM}$).

3 Dependence of T_0 on AM

It is known that T_0 at small El may vary, since the sidelobes of the antennas will be directed to the ground. Therefore, before carrying out sky dip observations, it is necessary to determine the range of airmass AM, in which T_0 remains constant. For this, sky dip of the atmosphere was performed in a wide range of AM (Fig. 1). In Fig. 1 crosses show experimental dependence of T_{sys} on AM. In this figure it can be seen that at small AM the dependence of T_0 on AM is linear and corresponds to formula (4). The deflection of T_{sys} from the line in the region of large AM is explained by an increase in T_0 at small El. To calculate T_0, the system noise temperature T_{sys} was approximated by the line in the range $1 < AM < 2$ (the solid line in Fig. 1). The dependence of T_0 on AM was defined as the difference of T_{sys} and this line. The

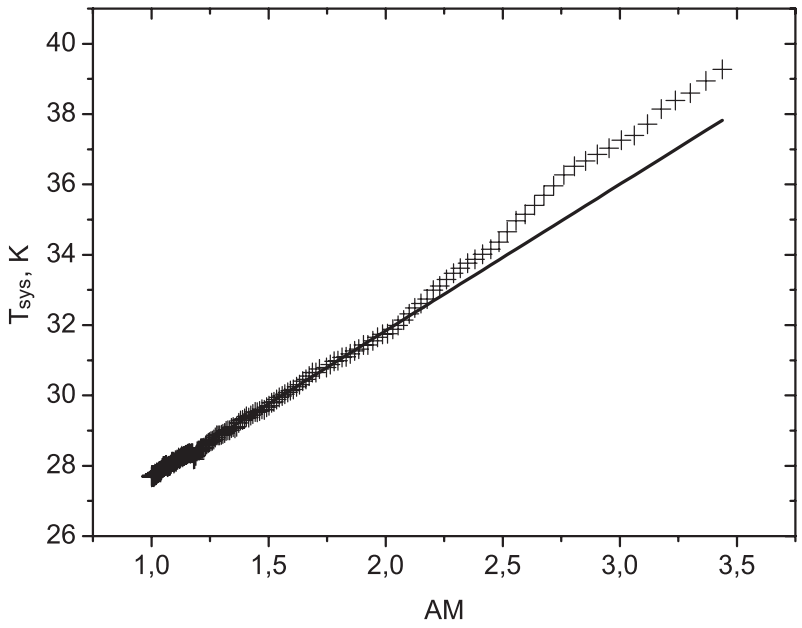


Figure 1 Crosses show experimental dependence of T_{sys} on AM. Solid line is the approximation T_{sys} by the line in the range $1 < AM < 2$.

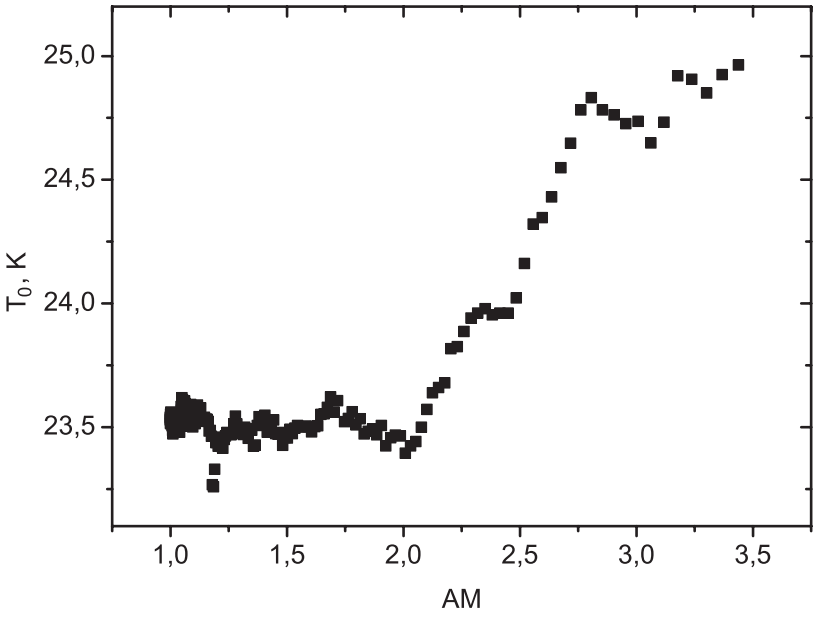


Figure 2 Dependence of T_0 on AM.

dependence of T_0 on AM is shown in Fig. 2. Figure 2 shows that T_0 remains constant at $1 < AM < 2.4$. This range of airmass was used in preliminary observations.

4 Preliminary observations. Determination of T_0

Preliminary observations to determine T_0 were carried out between September 2019 and January 2020. During this time, about 200 sky dip observations were carried out. For each observation, T_0 and τ were obtained by fitting according to formula 3. If the conditions $15 < T_0 < 30$ and $0.01 < \tau < 0.04$ were met, the results were considered reliable. Otherwise, the weather conditions were considered unsuitable and the results were ignored. The ambient temperature was provided by the metrological station "Vicaki".

Figures 3 and 4 show the results of calculations for left- and right-hand circular polarizations (LCP and RCP). Figures 3a and 4b show the time dependence of the zenith opacity τ. Figures 3b and 4b show the time dependences of the noise temperatures T_0 and their approximation by a polynomial of the 4th degree T_0fit. Figures 3c and 4c show the difference between T_0 and T_0fit.

5 T_0 and $e^{\tau AM}$ errors

The standard deviation of T_0 can be determined for each sky dip observation by calculating covariance matrices. It can also be estimated for the entire time dependence

of T_0 by calculating the standard deviation of the $T_0 - T_0fit$ value. Both methods give approximately the same solution for LCP and RCP. In all cases, $\sigma_{T_0} \approx 1$ K. Therefore, we consider T_0fit as the true value of T_0, and we interpret the deviation from T_0fit as an error of T_0.

When calculating the flux density S, the influence of atmospheric opacity is manifested in the form of a factor $e^{\tau AM}$ (see Eq. (2)). Therefore, to assess the impact of the τ error on S, it is necessary to find $e^{\tau AM}$ errors. The calculation of the standard deviation of $e^{\tau AM}$ was carried out using the formula for indirect measurement errors. The dependence of $e^{\tau AM}$ on T_0 is determined by Eq. (5). Assuming that T_{Atm} and T_{sys} do not introduce additional errors, the standard deviation of $\sigma_{e^{\tau AM}}$ is determined by the formula

$$\sigma_{e^{\tau AM}} = \sqrt{\left(\frac{\partial\left(e^{\tau AM}\right)}{\partial T_0}\right)^2 \cdot \sigma_{T_0}^2} = \frac{T_{Atm}}{\left(T_{Atm} + T_0 - T_{sys}\right)^2}\sigma_{T_0}. \tag{7}$$

The relative error $e^{\tau AM}$ can be defined as the ratio of $\sigma_{e^{\tau AM}}$ to $e^{\tau AM}$.

$$\delta_{e^{\tau AM}} = \frac{\sigma_{e^{\tau AM}}}{e^{\tau AM}} = \frac{\sigma_{T_0}}{T_{Atm} + T_0 - T_{sys}}. \tag{8}$$

The relative error of $e^{\tau AM}$ more clearly characterizes the influence of the uncertainty of the T_0 and zenith opacity on the source flux density. Applying the formula for indirect measurement errors to Eq. (2), it is easy to show that

$$\delta_S = \sqrt{\delta_{T_a}^2 + \delta_{DPFU(El)}^2 + \delta_{e^{\tau AM}}^2}, \tag{9}$$

where δ_S is the relative error of the source flux density, δ_{T_a} is the relative error T_a arising during calibration, $\delta_{DPFU(El)}$ is the relative error $DPFU\,(El)$.

Using Eqs. (7) and (8), we calculated the error $e^{\tau AM}$, which is typical for observations. In doing so, the following assumptions were made:

(i) $T_0 \approx 22$ K. This is the averaged noise temperature T_0 for the observation period from September 2019 to January 2020 (Figs. 3b, 4b).

(ii) $T_{ground} \approx 8$ ℃. T_{ground} was assumed to be the average annual temperature in Ventspils in 2019. At the same time, $T_{Atm} \simeq T_{ground} - 17 \approx 264$ K.

(iii) $T_{sys} \approx 30$ K. This system noise temperature is typical for observations in good weather at an elevation ∼40°.

Under these assumptions, as well as for $\sigma_{T_0} \approx 1$ K, using Eqs. (7) and (8), we calculate the values of $\sigma_{e^{\tau AM}} \approx 0.004$ and $\delta_{e^{\tau AM}} \approx 0.39\%$.

The parameters T_0, T_{ground}, T_{sys} have limitations. Figures 3 and 4 show that 20 K $< T_0 <$ 25 K. T_{ground} is defined as the maximum and minimum annual temperature. For Ventspils in 2019 –10 ℃ $< T_{ground} <$ +31 ℃. T_{sys} at high elevation can drop to 27 K. In bad weather and low elevation, it is possible to raise T_{sys} to not more than 50 K. By varying the parameters T_0, T_{ground}, T_{sys} within the indicated limits, it is easy to show that at $\sigma_{T_0} \approx 1$ K, in any case, $\delta_{e^{\tau AM}}$ does not exceed 0.5%. This value is quite enough for making observations.

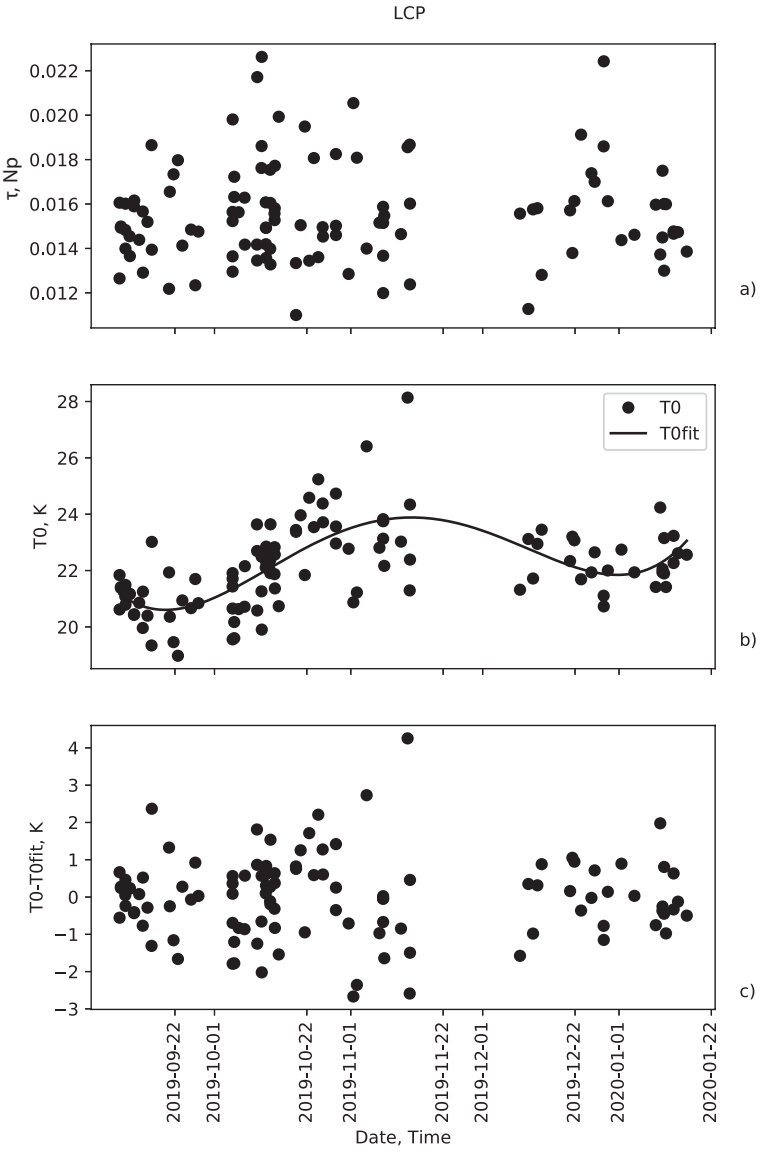


Figure 3 Time dependence of the zenith opacity τ (3a), noise temperature T_0 and its approximation T_0fit (3b) and difference between T_0 and T_0fit for left-hand circular polarizations (3c).

6 Verification of the method of correction of atmospheric opacity

Unfortunately, when performing real observations, $DPFU\,(El)$ errors and pointing errors are larger than those of the atmospheric opacity correction method in C-band. Therefore, the accuracy of the method is difficult to check. But we can compare the

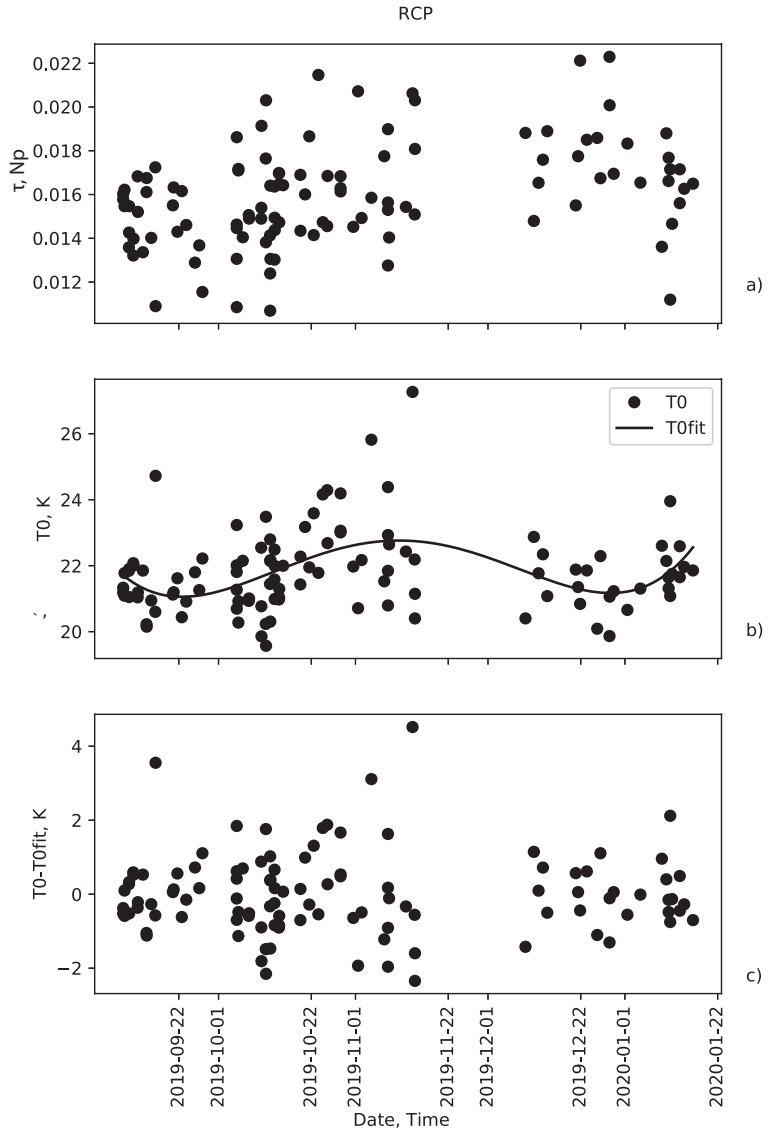


Figure 4 Time dependence of the zenith opacity τ (4a), noise temperature T_0 and its approximation T_0fit (4b) and difference between T_0 and T_0fit for right-hand circular polarizations (4c).

data using the method and without it. To do this, we made the scans of the source 3C123 in different weather. Observations were held on August 16, 2021 at a frequency of 6.8 GHz for left-hand circular polarizations. On this day, the cloudiness quickly varied with time in the RT-16 area. First, in the absence of clouds, we made the sky dip and clarified T_0 values. The T_0 value was 24.5 K. Then several scans 3C123 were carried out at different degrees of cloudiness. During the observations, the elevation

Table 1 System temperatures, antenna temperatures and zenith opacities obtained from 3C123 scans.

N	T_{sys}, K	T_a, K	$e^{\tau AM}$	τ, Np	T_a^*, K
1	43.6	0.49	1.075	0.044	0.53
2	40.6	0.49	1.063	0.036	0.52
3	34.3	0.52	1.037	0.021	0.54
4	32.1	0.53	1.029	0.016	0.55

has not changed significantly and has a value $\sim 36^{\circ}$. The results are presented in Table 1. During the experiment, a significant change in the system noise temperature T_{sys} was registered. In these circumstances, this can be explained only by the change in τ, since under constant weather conditions, T_{sys} changes insignificantly.

The T_{sys} was obtained using a noise diode. T_a values are obtained by fitting the Gaussian function. τ is calculated using Eq. (6). T_a^* is calculated by formula (1).

The relative errors of the antenna temperatures are calculated according to the data from Table 1. The relative error of the antenna temperature of the source is $\delta_{T_a} = \frac{\sigma_{T_a}}{\overline{T_a}} 100 = 4.1\%$. The relative error of the antenna temperature of the source, adjusted to the atmospheric opacity is $\delta_{T_a^*} = \frac{\sigma_{T_a^*}}{\overline{T_a^*}} 100 = 2.4\%$. It is shown that $\delta_{T_a^*} < \delta_{T_a}$. This indicates that T_0 and τ are defined without significant errors. But this experiment does not prove that the relative error of T_a^* caused by the uncertainty T_0 does not exceed 0.5%. It remains only a theoretical result.

7 Conclusions

The method (Kraus (2007)) was applied to correct the zenith opacity in the C-band at the RT-16 radio telescope of the Irbene observatory. Preliminary measurements of the noise temperature T_0 were carried out and its time dependence was found. This allows the zenith opacity to be determined during observations. T_0 errors were found. The relative error of $\delta_{e^{\tau AM}}$ is estimated. $\delta_{e^{\tau AM}}$ is directly related to the error of the source flux density. It is shown that $\delta_{e^{\tau AM}}$ does not exceed 0.5%, which is quite acceptable for astronomical observations.

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