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RADIO ASTRONOMY
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ESTIMATING THE LEVEL OF TROPOSPHERIC ABSORPTION AT MICROWAVE FREQUENCIES AND OPERATIONAL PARAMETERS OF PERTINENT AERONOMIC AND RADIO ASTRONOMICAL INSTRUMENTS IN THE "MAXIMUM CONFIDENCE" TECHNIQUE

Subject and Purpose. *The work has been aimed at the development and practical implementation of a new method for processing the results of aeronomic and radio astronomical observations that are performed with the help of a total-power radiometer for a variety of elevation angles of the objects. The method proposed makes it possible evaluating the absorption coefficient in the troposphere and current basic parameters of the measuring system. The subject of research is the tropospheric zenith opacity* τ*, the scattering coefficient* β *of the antenna system, and noise temperature of the radio receiver together with the antenna.*

Methods and Methodology. *The method is based on a new approach to mathematical processing of the observational results. In contrast to the widely used dual-parameter least squares method, we propose to vary one of the parameters, while determining its most probable value as such corresponding to minimal mean square deviations as functions of the parameter's value. The estimates obtained within this procedure are regarded as the most probable values of the atmospheric absorption constant (troposphere opacity in the zenith direction), the scattering coefficient of the antenna system, and the noise temperature of the radio receiver (together with the antenna). The technique proposed has been named the "maximum confidence" method.*

Results. *The method developed was first demonstrated and verified on a mathematical model. The same way the experimental data obtained in the 3-mm range of wavelengths, with different receivers and meteorological circumstances were processed. The effectiveness of the "maximum confidence" method proposed by the authors has been proven.*

Conclusions. *A new method of processing the data of aeronomic observations allows us to increase the accuracy of measurements of the tropospheric zenith opacity. In addition, it gives possibility to determine the scattering coefficient of the antenna and to monitor the noise temperature of the radio receiver. The latter has its own importance as a method of determining the parameters of the receiving system during real operation rather than separately on specialized measuring stands.*

Keywords: *aeronomy, radio astronomy, atmospheric profiles, millimeter waves.*

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Introduction

The task of observational aeronomy is to obtain information about the current state and dynamics of processes in various layers of the stratosphere. Primary information on these processes can be obtained from measured parameters of radiation spectra of atmospheric impurities of low concentration (like CO, O_3, or ClO), as observable at 100 GHz and higher frequencies. For obvious reasons, such research can be most conveniently carried out from the surface of the Earth. The apparent disadvantage of the approach is that the spectra are to be recorded through the troposphere where the millimeter wavelength electromagnetic radiation experiences noticeable absorption. Under poor weather conditions (which are a typical case for many of the geolocations of interest, like the so-called "weather factories"), the attenuation can reach 3 dB or more. The same problem is typical for radio astronomy, should the telescope be located in an unfavorable astroclimatic zone. The attenuation along the line of sight is usually determined with the help of so-called atmospheric profiles, by measuring the brightness temperature of the sky at a variety of elevation angles. The brightness temperature data set that has been obtained is processed within the framework of the accepted model of the troposphere, yielding an estimate of the attenuation level.

The most common model of the troposphere is a single-layer horizontal formation of an isothermal character [1—3]. This approach permits minimizing the number of parameters necessary for characterizing variations of a signal passing through the troposphere.

The atmospheric profiles are usually obtained with modulation radiometers. For purely aeronomic purposes, the commonnly used radiometer (radio spectrometers) are such whose antenna apertures do not exceed 50 cm. In radio astronomy, the radio telescopes located at low altitudes above sea level [4], may sometimes be equipped with separate, small-sized radiometers. The absolute brightness temperature measurements require calibration which is usually done per two thermostatically controlled loads of significantly different temperatures. As a result, the receiving device becomes power-consuming, rather cumbersome and failing optimization from the point of its time measurement cyclogram [5].

Recently, due to the significantly improved operating stability of receiving devices, it is the full power radiometers that are increasingly used in practice. When getting atmospheric profiles with such radiometers, it is possible to significantly simplify the calibration procedure by using the proper noise of the receiving system as one of the calibration sources [5]. Such calibration simplifies the measurements process without impairing its accuracy.

In principle, the information about tropospheric attenuation and parameters of the receiver and the antenna is contained in the output signal of the recording system based on a compensation radiometer. The task of this work is to construct a technique for extracting such data, and the authors' approach is reported below.

1. General

The antenna temperature $T_{ant}(\Theta)$, if recorded as observed from the ground, without account of receiver noise, can be written as [1]:

$$T_{ant}(\Theta) = \left(T_{em} + T_{bg}\right)e^{-\frac{\tau}{\sin\Theta}} + T_{eff}\left(1 - e^{-\frac{\tau}{\sin\Theta}}\right), \tag{1}$$

where T_{em} is the temperature of the spectral line of a small atmospheric impurity at the upper edge of the troposphere; T_{bg} — temperature of the cosmic microwave background radiation (2.7 K outside the atmosphere); T_{eff} — the effective temperature of the troposphere; Θ — the elevation angle at which the observations are made, and τ — the tropospheric zenith opacity (the level of attenuation in the troposphere at $\Theta = 90°$).

Let us note that Eq. (1) is correct only in the case when the instantaneous operating frequency bandwidth of the radiometer is noticeably lower than the spectral line width. If the radiometer bandwidth were greater than the spectral line-width, then, remaining in terms of temperatures, the T_{em} should be included with a weight factor in the form of the ratio of the effective line width to the instantaneous bandwidth of the radiometer. But, in any case, the relation $(T_{em} + T_{bg}) << T_{eff}$ is valid, because T_{eff} is 50...250 K at frequencies above 100 GHz, depending on the current state of the troposphere. Accordingly, Eq. (1) simplifies:

$$T_{ant}(\Theta) = T_{eff}\left(1 - e^{-\frac{\tau}{\sin\Theta}}\right). \qquad (2)$$

To calculate the radiation properties of the troposphere, it is enough to know the physical temperature at the Earth's surface T_{gr}, the effective temperature of the troposphere T_{eff} and the tropospheric zenith opacity τ [1]. A lot of work has been devoted to determining the effective temperature of the troposphere, ranging from those based on purely empirical considerations, where figures like $T_{eff} = 0.95T_{gr}$ or $T_{eff} = T_{gr} - 15$ were assumed [1], and to complex statistical calculations [2]. The results differ by a few percent despite the great complexity of direct verification with the use of instrumental data either from weather balloons or from satellites. However, this representation (as well as Eqs. (1) and (2) only works in the case of clear weather conditions, without clouds and hydrometeors.

The function $T_{ant}(\Theta)$ is plotted in Fig. 1 for two values of τ. The significant nonlinearity of $T_{ant}(\Theta)$ is obvious.

In practice, the most interesting range of elevation angles is 25 to 65 degrees. At larger angles, the sky temperature changes little. Below 25°, the non-flatness of the troposphere, interference from local objects and, along the side lobes, ground radiation are affected. This is well illustrated by the dependence (Fig. 2) of T_{ant} on the so-called the atmospheric airmass $M(\Theta) = 1/\sin\Theta$.

It is advisable to make measurements at the largest possible M range and for as many angles as possible, so that averaging can be carried out effectively. In real conditions, the number of points (elevation angles) is taken in the range of 4 to 7. The limiting factors are the width of the antenna radiation pattern (a few degrees) and the degree of stability of weather conditions during estimation of the tropospheric profile. An important feature of the total-power radiometer is its high fluctuation sensitivity which allows one to minimize the time interval for taking the profile.

From Eq. (2) and the estimate for the atmospheric air mass M it follows

$$\tau = -\frac{1}{M}\left(1 - \frac{T_{ant}}{T_{eff}}\right). \qquad (3)$$

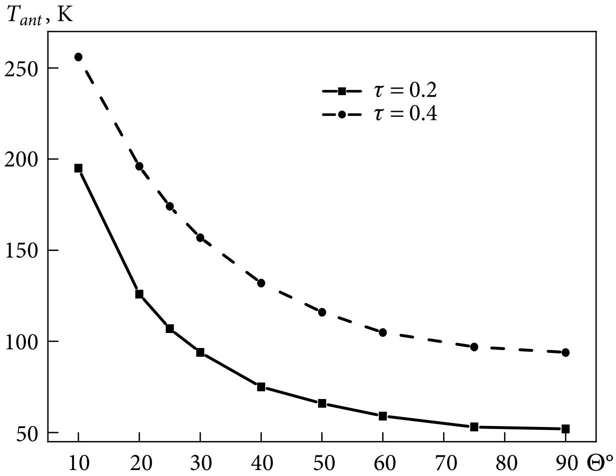

Fig. 1. The calculated sky temperature as seen by the antenna, as a function of the elevation angle, for two values of τ. The temperature of the near-surface atmospheric layer is 300 K

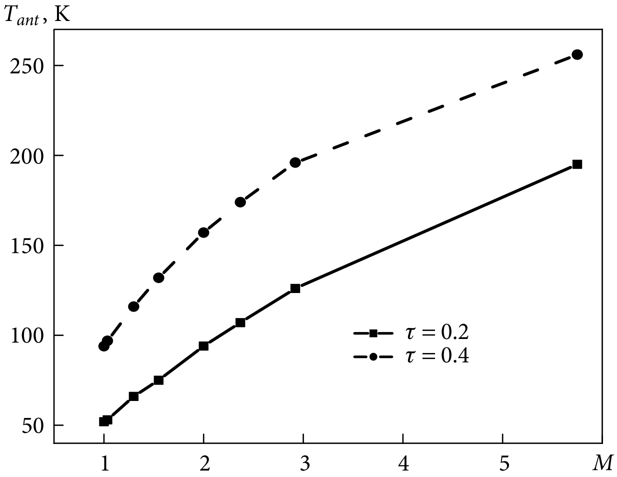

Fig. 2. Calculated sky temperature as seen by the antenna, as a function of the number M of atmospheric air masses considered, for a variety of troposphere opacity values τ measured toward the zenith

Usually, the processing of the results of atmospheric profiles is carried with the use of Eqs. (2) and (3), within the generalized least squares method [6]. This technique makes it possible to obtain statistically averaged data on the condition of the atmosphere, in particular, on the tropospheric zenith opacity. In the approximation of a single-layer troposphere model, $\tau(\Theta) = const$ and, according to Eq. (3), the same values should be obtained for different elevation angles. In practice, the values of τ at different elevation angles have a scatter, both because of the presence of measurement errors and the simplified model representation of the troposphere as a planar, single-layer isothermal formation. By processing the data from multiple profiles, we were able to modify the processing technique in such a way as to improve the accuracy of determining τ and, at the same time, to obtain additional information on parameters of the receiving system.

Typically, in the course of measurements aimed at obtaining atmospheric profiles, the receiver and its horn feed of the aeronomical set-up are positioned horizontally. A rotating mirror (or an optical system of a more complex composition) may be placed in front of the horn to provide a possibility of changing the direction of signal reception, in the range from the horizon to zenith, and carry out calibrations [7]. At the same time, the presence of side lobes of the radiation pattern introduces some additional radiation from the environment. The latter is characterized, similar as in the case of losses in transmitting antennas, by some scattering coefficient β [8]. By definition, $\beta = (P - P_{main}) / P$, where P is the total power received by the antenna, P_{main} is the power received within the principal lobe of the radiation pattern. The scattering coefficient magnitude can, in principle, be either measured or calculated.

Measurements of the scattering coefficient are a very costly procedure. Mathematical modeling (and measurements as well) can provide the necessary accuracy, however under idealized conditions that are not identical to such of aeronomical practice. An accurate knowledge of the scattering coefficient is badly needed for determining not just T_{rec}, but the actual value of the structure's noise temperature. The technique presented below allows us to determining the tropospheric attenuation coefficient, antenna scattering coefficient and noise temperature of the receiver without performing specific heterogeneous tests.

2. Idea of the "maximum confidence" method

Following the Nyquist theorem, we can write down an expression for the signal at the output of the sky observing receiver as

$$U = ck_b \Delta f \left[T_{rec} + \beta T_{eff} + (1-\beta) T_{ant}(\Theta) \right], \qquad (4)$$

where k_b is the Boltzmann constant; Δf — the instantaneous operating frequency band of the receiver; T_{rec} — the noise temperature of the receiver; c — the transmission coefficient of the reception / amplification path, including the quadratic video detector.

When atmospheric profiles are obtained, an additional calibration measurement is made, specifically: an absorbing load with a known temperature T_l is placed directly in front of the receiver horn. The recorded signal is in this case

$$U_{cal} = ck_b \Delta f \left(T_{rec} + T_l \right). \qquad (5)$$

As shown in [5], the radiation of the surface layer of the troposphere can serve as a calibration signal (rather than the thermal radiation of the load).

The output signal is designated as U, since it is actually the voltage that is measured which is proportional to the output signal power, with taking into account the output square-law detector. One more note: here and below we operate with the root-mean-square values of noise-like signals, ignoring their fluctuating component as insignificant even with an accumulation time of about a few seconds.

The quantity $T_{sys} = T_{rec} + \beta T_{eff}$ can be considered as the noise temperature of the receiving system, including the antenna. The receiver noise temperature T_{rec} is a fairly stable value and is measured by the generally accepted method of alternately placing in front of the horn some aperture-type absorbing loads with different temperatures [8]. The measurement error T_{rec} is about 10%. The procedure is performed rarely, normally 1—3 times per year. As for determining the system noise temperature T_{sys}, parameters β and τ, we propose to search for their current values at the time of observations by varying the scattering coefficient and calculating the corresponding attenuation coefficient in the troposphere over the widest possible range of elevation angles.

The values of the tropospheric zenith opacity, taken for the same scattering coefficient and different elevation angles have a scatter (see above), although, according to the model of a single-layer troposphere $\tau = const$. Let us write down the average value of $\overline{\tau}$ and the value of the standard deviation S for each measured scattering coefficient,

$$S = \sqrt{\frac{\sum_{i=1}^{n} (\tau_i - \overline{\tau})^2}{n}}, \qquad (6)$$

where n is the number of measurements at different angles.

The estimate for τ taken as closest to the true value will be that at which the standard deviation (S) is at its minimum. This method of tropospheric profile processing can be called the "maximum confidence method", of which the details and verification are described below.

3. Verification of the maximum confidence method using emulated atmospheric profiles

By specifying parameters of the receiving system and the atmosphere (specifically, T_{gr}, T_{rec}, τ, and β) and making use of Eqs. (2)—(6), we have been able to construct an emulated atmospheric profile. In this case, similar as with the real profile, we obtain 5 to 7 pairs of values of U and Θ, that is, discrete readings of the $U=f(\Theta)$ function. Next, the calculated results are to be processed within the procedure which is the subject of testing, in order to determine the values of τ and β. By comparing the magnitudes that have been found with those set at the beginning, we can evaluate correctness of the methodology used.

Let us take $T_{gr} = 300$ K, $T_{rec} = 500$ K, $\tau = 0.3$ and $\beta = 0.29$. Then, according Eqs. (1), (3) and (5), the initial data for the processing (with the elevation angle coordinate varying between 25 and 60 degrees) will be represented by seven pairs of the U and Θ values, plus one calibration pair. Setting $T_{rec} = 500$ K, we calculate τ using (3) for $\beta = 0.1\ldots0.4$, taking into account calibration (5) and obtain 7 values of τ as a function of Θ for each value of the scattering coefficient. Then, for each β, we determine the average value ($\overline{\tau}$) and the standard deviation from the average S according to (6). Next, we determine the scaled value $\delta = 10^3 S$ (for convenient view, since S is small) as a function of the scattering coefficient β. These calculated dependencies are shown in Fig. 3.

The calculation results (Fig. 3) show that the minimum point in the dependence of the standard deviation corresponds to $\beta_{mf} = 0.29$, while the minimum itself is quite sharp. This value of β corresponds to $\tau = 0.3$. Thus, we call the determined values of β and τ the most confident and denote them as β_{mf} and τ_{mf}, respectively. Both of the values found correspond exactly to the specified ones, therefore, the technique works correctly. Similar emulations were carried out for different values of τ and β with the same success.

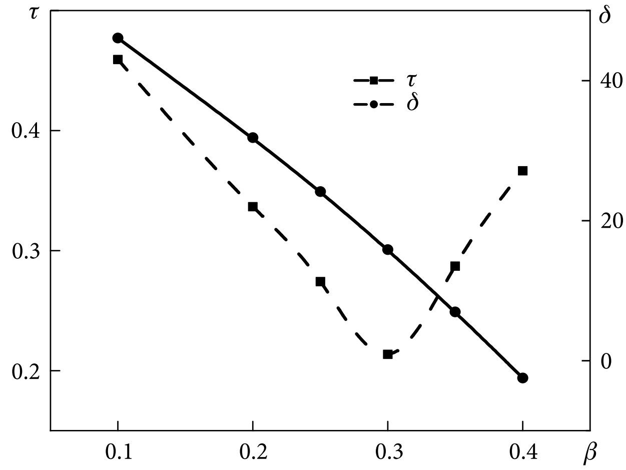

Fig. 3. The tropospheric zenith opacity τ and standard deviation along the profile ($\delta = 10^3\ S$) versus the scattering coefficient β ($T_{rec} = 500$ K, $T_{sys} = 590$ K, $\beta_{mf} = 0.29$, $\tau_{mf} = 0.3$)

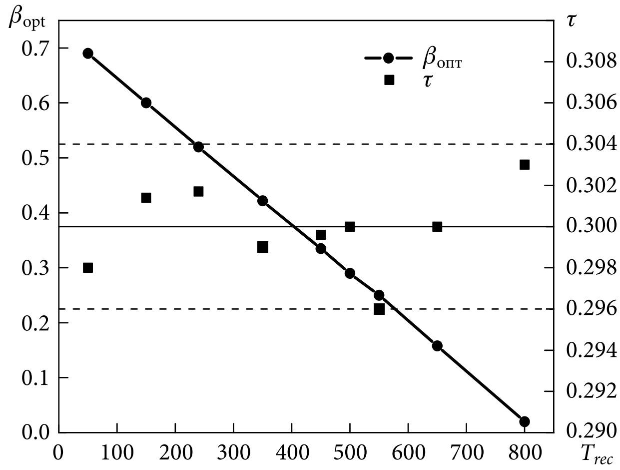

Fig. 4. Highest confidence estimates for the tropospheric zenith opacity τ_{mf} and the scattering coefficient β_{mf} of the antenna system as dependent on noise temperature T_{rec} of the receiver

Using the theoretical model, it is possible to determine how the error in measuring the noise temperature of the receiver affects the accuracy of determining τ and β. The fact is that according to the generally accepted hot and cold load method, the noise temperature of the receiver in the millimeter range is determined with an accuracy of no better than 10% [9]. In the framework of our approach, emulated profiles were processed, while varying the values of the receiver noise temperature in the range from 50 to 800 K. The results are shown in Fig. 4 in the form of dependences of τ_{mf} and β_{mf} on T_{rec}. As one would expect, the noise temperature of the receiver has virtually no effect on τ. The error in determining τ

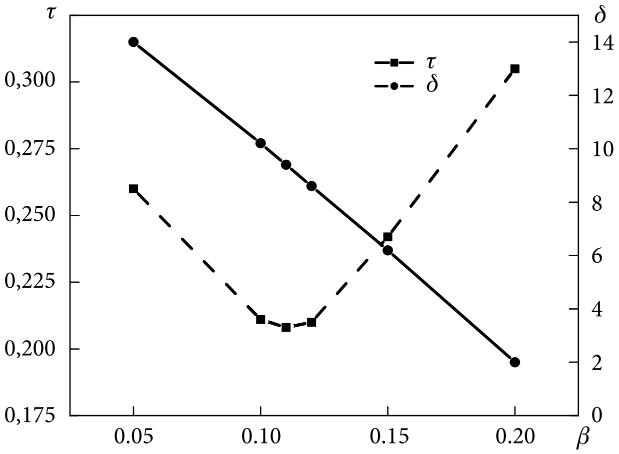

Fig. 5. The tropospheric zenith opacity τ and standard deviation δ versus the scattering coefficient β (after results of March 10, 2019 measurements, with T_{rec} = 300 K, T_{sys} = 330 K, β_{mf} = 0.11, τ_{mf} = 0.269)

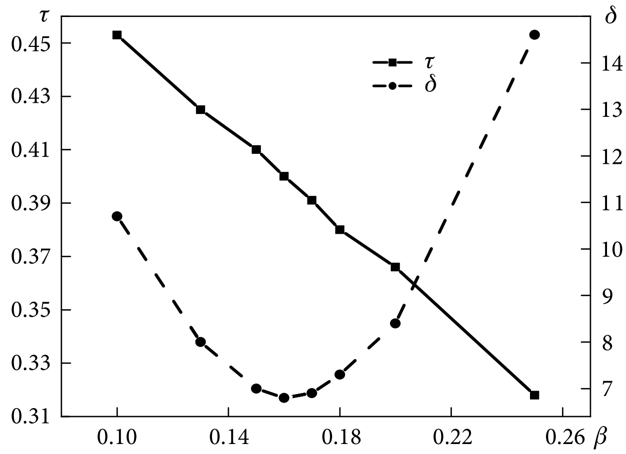

Fig.7. The tropospheric zenith opacity τ and standard deviation δ versus the scattering coefficient β (from the measurements of November 13, 2019: T_{rec} = 2300 K, T_{sys} = 2350 K, β_{mf} = 0.16, τ_{mf} = 0.4)

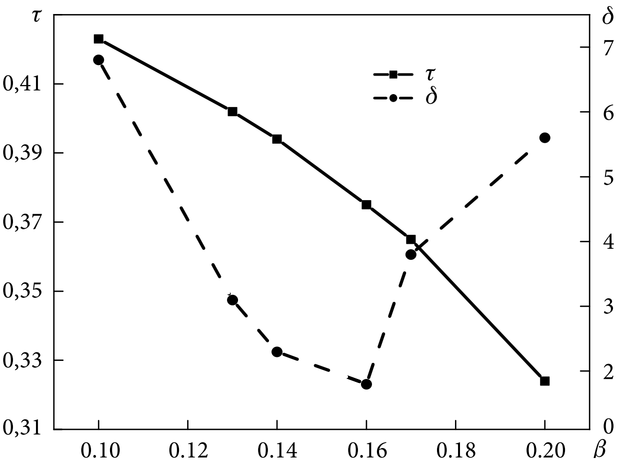

Fig.6. The tropospheric zenith opacity τ and standard deviation δ versus the scattering coefficient β (after results of October 2, 2019 measurements , with T_{rec} = 1100 K, T_{sys} = 1150 K, β_{mf} = 0.15, τ_{mf} = 0.38)

does not exceed 1% in the interval T_{rec} = 250…600 K (dashed lines in Fig. 4), while T_{rec} and β_{mf} are related by a linear dependence. Accordingly, if T_{rec} was not measured separately, then within the framework of the proposed approach it is possible to obtain its upper estimate.

Thus, if a profile is obtained to determine τ, then it is quite enough to know the noise temperature of the receiver very approximately; an error of 50% is quite satisfactory. If the profile is made to determine the scattering coefficient of the antenna system, then it is desirable to know the noise temperature of the receiver quite accurately (10%). Taking into account the fact that the scattering coefficient of a particular antenna is very stable, T_{rec} can be monitored as often as desired without using aperture loads.

4. Real profiles: Processing within the maximum confidence method and discussion

To test the proposed technique and determine its practical suitability, experiments were carried out using 3 receivers of a design similar to the previously described device [10]. The noise temperature of the receivers equaled 300, 1100 and 2300 K and the fluctuation sensitivity of the radiometer in its total power mode was 10, 50 and 100 mK, respectively. The local oscillator frequency in all of the receivers was the same, namely 113.76 GHz [11], which provided for the ability to receive radiation from the stratospheric CO (115.3 GHz). All radiometers were used with mirror-horn antennas with a radiation pattern width of 4°, elevation angle range was from 30 to 55°.

Experimental data with a receiver with T_{rec} = 300 K were obtained on March 10, 2019. The results of processing data along the profile at the scattering coefficient β being varied from 0.05 to 0.2 are shown in Fig. 5.

The dependence of the standard deviation on β demonstrates a rather distinct minimum, which indicates that the temperature of the receiving system for β_{mf} = 0.11 was 330 K at τ_{mf} = 0.269.

Experimental data on the profile with a receiver with T_{rec} = 1100 K were obtained on October 2, 2019.

The results of data processing for the scattering coefficient β being varied from 0.1 to 0.25 are shown in Fig. 6

Due to the higher noise temperature, the minimum in the dependence of the standard deviation upon β is less distinct than in Fig. 5 while offering quite unambiguous data for determining the temperature of the receiving system and the value of the tropospheric zenith opacity $\tau_{mf} = 0.374$.

The experimental data on the profile obtained with the receiver with $T_{rec} = 2300$ K date to November 13, 2019. The results of data processing, with the scattering coefficient β being varied from 0.1 to 0.25 are shown in Fig. 7.

The graphs shown in Fig. 7 show that even in the case when the noise temperature of the receiving system is an order of magnitude greater than the noise temperature of the sky, the proposed technique makes it possible to quite accurately determine the value of τ and obtain information about the real noise temperature of the receiving system that has been used for monitoring the atmosphere.

In practical applications, the search for the minimum (Figs. 5—7) is carried out through a polynomial approximation. Here we limited ourselves to graphical representations, since the main goal was to demonstrate capabilities of the proposed method.

For different receivers (1100 and 2300 K) and under different weather conditions, but with identical antennas, the values obtained as the most confident estimates for the scattering coefficient proved to be the same. The smaller value of β_{mf} for the 300 K receiving system owes to the twice larger area of the output reflective mirror. These facts, along with the results of mathematical modeling, are indicative of correctness of the approach proposed.

Conclusions

The modeling and the experimental studies that have been carried out suggest that the method proposed for processing atmospheric profiles, with the aim of determining parameters of both the atmosphere and the equipment employed, is quite suitable for practical use. It enables selection of the most confident values from the range of possible values of β, τ and T_{rec}, and, accordingly, allows increasing the estimation accuracy for the tropospheric zenith opacity. In addition, it permits monitoring the noise temperature of the receiving system and the scattering coefficient of its antenna without resorting to any calibration devices of high complexity. The method proposed seems to prove useful for solving many various problems of practical aeronomy and radio astronomy.

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ВИЗНАЧЕННЯ РІВНЯ ТРОПОСФЕРНОГО ПОГЛИНАННЯ В МІКРОХВИЛЬОВОМУ РАДІОДІАПАЗОНІ ТА ОЦІНКИ РОБОЧИХ ПАРАМЕТРІВ ВІДПОВІДНИХ АЕРОНОМІЧНИХ І РАДІОАСТРОНОМІЧНИХ ІНСТРУМЕНТІВ МЕТОДОМ «МАКСИМАЛЬНОЇ ДОСТОВІРНОСТІ»

Предмет і мета роботи. Метою роботи є розробка та практичне впровадження нового методу обробки результатів аерономічних і радіоастрономічних спостережень, що виконуються за допомогою радіометра повної потужності під різними кутами місця. Запропонований метод дозволяє визначати сталу поглинання в тропосфері та діючі базові параметри вимірювальної системи. Предметом досліджень є стала тропосферного поглинання τ, коефіцієнт розсіювання антенної системи β та шумова температура радіоприймача разом з антеною.

Методи та методологія. Метод базується на новому підході до математичної обробки результатів спостережень. На відміну від широковідомого методу найменших квадратів одночасно за двома параметрами ми пропонуємо один із параметрів варіювати, а його найбільш імовірну величину визначати через точку мінімуму на залежності середньоквадратичних відхилень від величини самого параметра. Визначені за такої процедури величини сталої атмосферного поглинання, коефіцієнта розсіювання антенної системи та шумової температури радіоприймача (разом з антеною) ми називаємо найбільш імовірними, а запропонований метод в цілому — методом «максимальної достовірності».

Результати. Метод, що розроблено, спершу демонструється та верифікується на математичній моделі. Таку саме обробку проведено за експериментальними даними, котрі було одержано в 3-мм діапазоні довжин хвиль, з різними приймачами і за різних метеорологічних обставин. Ефективність запропонованого авторами методу «максимальної достовірності» доведено.

Висновки. Новий метод обробки даних аерономічних спостережень дозволяє підвищити точність вимірювань сталої поглинання атмосфери й коефіцієнта розсіювання антени, а також моніторити шумову температуру радіоприймача. Останнє має власну значимість як метод визначення параметрів приймальної системи під час реальної експлуатації без застосування спеціалізованих вимірювальних стендів.

Ключові слова: *аерономія, радіоастрономія, атмосферні розрізи, міліметрові хвилі.*