Methodical maintenance of radiometric measurements of atmosphere at millimeter waves range

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Abstracts - The methodology of determination of radio-brightness temperature values (T_b) of atmosphere and total vertical absorption of atmosphere by the method of radiometry are described. A qualitative analysis of sources of errors in the considered calibration methods, methods of restoration of intensity of radio-heat radiation and vertical absorption in the atmosphere is carried out. Results of estimates of accuracy of restoration of T_b of the atmosphere are given for the case of use of different combinations of calibration methods of the radiometer and methods of measurement of diffraction coefficients of radiometer's antennas. The possibility of determination of radio brightness of the sky with 3% accuracy at 3 millimeter waves range is shown.

Keywords - radiometry; atmosphere investigation; measurements; retrieving problems.

Radiometric researches of the atmosphere in millimeter wave range (MM WR) are of interest to tasks of the remote sensing (RS) of the environment, radio astronomy, meteorology, climatology and other. In recent years the methods of radiometry are used for statistical accumulation of data on a value of total vertical atmospheric absorption for the decision of auxiliary tasks of development of terrestrial-space communication links and communication networks of 5G format.

In radiometry the intensity of radio-heat radiation accepted from the researched environment can be expressed in the values of radio brightness temperature (T_b) represented in Kelvin degrees (K). The decision of this task carries out by calibration of measuring equipment. The procedure of radiometric monitoring of the atmosphere supposes (in addition to support of calibration of measuring equipment) the subsequent transition from the measured values of antenna temperature of radiometers (T_a) to the radio brightness temperature of observed object of radio-heat radiation. Then these data are used for restoration of values of atmospheric absorption and for retrieving of physical parameters of observed objects in a number of tasks of RS.

Different methods of the decision of these tasks are developed to the now. The choice of a specific calibration method of radiometric equipment and methods of restoration of parameters of the atmosphere carries out, as a rule, on the basis of complex and compromise reviewing of requirements to the accuracy of defined parameters, to simplicity and convenience of procedures of measurements. The final decision of this question is caused by also technical capabilities and existence of emergency devices and additional equipment in the conditions of external expeditions measurements.

I. CALIBRATION PROCEDURE OF THE RADIOMETER.

Calibration of radiometric equipment carries out for the purpose of conversion of the values of signal voltage (V) registered on an output of the radiometer to the values of antenna temperature (K).

The vast majority of the calibration procedures used in practice are based on a method of two matched loadings of antenna, each of which has well known T_b and which has significantly differed one of other value of T_b. Usually one of the matched loadings of the radiometer antenna has a controlled ambient temperature. The distinction of calibration methods is usually connected with a method of support of controlled T_b of a signal from the second loading or an object of own radio thermal radiation in the used WR. Then value of antenna temperature of the researched object is defined experimentally as:

$$T_a = T_o - \frac{T_{b_1} - T_{b_2}}{U_1 - U_2}(U_1 - U_x) \quad (1)$$

where the first multiplicand represents a calibration coefficient (K \Volt), T_0– the thermodynamic temperature of the first loading (K), U_1, U_2, U_x– respectively the level of output signal of the radiometer accepted from the 1st, 2nd calibrating loadings and from the observed (researched) object.

In the work the analysis of influence of calibration accuracy on determination of the sky T_b is carried out for the calibration methods which are based on the usage: a) the matched loading of the horn antenna which is in case of indoor temperature (about 300K) and in case of a boiling temperature of liquid nitrogen (about 78K); b) the radio-frequency radiation of the atmosphere and non-cooled loading of the horn antenna (with use of value of T_b of the atmosphere calculated with according to meteorology data, or measured by means of a reference horn); c) the difference of the signals accepted from the zenith direction of the clear sky and the matched antenna loading with the subsequent summing of this difference with the difference signal between the directions 60° from a zenith and the direction in a zenith. The specified amount of such summing will be in good compliance with the known value of thermodynamic temperature of loading. It is connected to the fact that the radio thermal radiation of the sky in the direction 60° from a zenith with a fine precision is value equal 2Tb of a zenith.

It is possible to show that Ta value of descending radiation of the atmosphere can be written also as:

$$T_a = T_b(1-\beta) + 2.7e^{-\tau} \times (1-\beta) + \overline{T_{ph}} \times \beta \qquad (2)$$

where β - the parameter considering dispersion out of the main lobe of antenna pattern of the antenna system (AS), τ - the optical thickness of the atmosphere, $\bar{T}_{ph}$ – average value of background radiation.

Determination of T_b of the atmosphere from the results of measurement T_a , as a rule, carries out by use of both of these expressions (1-2).

The selected calibration method of radiometric system and implementation of its procedure as well as method of determination of parameters of dispersion of the antenna (β) has significant effect on the accuracy of measurements of radio brightness of investigated objects. We considered influence of above mentioned calibration methods of radiometers and several methods of determination of the dispersing properties of the antenna on measuring accuracy of the atmosphere T_a. Calculation of accuracy of determination of T_b was performed for all competing methods by means of uniform and well-known approach which is based on use of "transfer of errors" equations [1].

The special technique was developed for measurement of parameters of dispersion of the horn antennas. This method is based on use of widely known device, – the artificial moon (AM) in combination with application of a special hollow shading casing (so named a “blende”) made from foam polystyrene which filled with the absorbing material placed into liquid nitrogen. The hollow foam “blende” recovers the antenna directions out of principal lobe of antenna pattern.

Procedures of measurement of antenna temperature of the radiometer in case of layout of the antenna in the radio absorbing shading casing which oriented in a zenith are used in this technique. At the first stage T_a is measured when the main lobe of antenna pattern is superimposed by the radio absorbing disk ($T_{a_{mm}}$). At the second stage the radio absorbing disk superimposes a complete lobe of antenna pattern ($T_{a_{am_c}}$), i.e. the total sector of angles which is not shaded by a “blende”. The expressions of T_a for both of these cases have following appearance:

$$T_{a_{mm}} = T_{o_m}(1-\beta)\eta + T_{O_{bl}}\beta_i\eta + \overline{T_{bz}}\beta_{ni}\eta + T_O(1-\eta) \qquad (3)$$

$$T_{a_{am_c}} = T_{o_m}(1-\beta)\eta + T_{O_{bl}}\beta_i\eta + \overline{T_{om}}\beta_{ni} + T_O(1-\eta) \qquad (4)$$

where: T_{o_m}, $\bar{T}_{0_{bl}}$- thermodynamic temperature of the antenna and the radio absorbing material of AM and a shading casing respectively; $\bar{T}_{bz}$ - the average radio brightness temperature of the sky accepted by a non-isotropic part of the antenna pattern which approximate (with an accuracy of 1%) is equal to the radio brightness temperature of a zenith; β_i, β_{ni} - scattering factors of the isotropic and non-isotropic parts of the antenna pattern respectively, η - an effectiveness factor of antenna.

From the expressions of (3) and (4) is follows that:

$$\beta_{ni}\eta = \frac{T_{a_{am_c}} - T_{amm}}{T_{obl} - T_{bz}} \qquad (5)$$

Now, having written antenna temperatures of a zenith at the “blende” with radio absorber temperature T_o (T_{azT_o}) and temperature of liquid nitrogen ($T_{az_{nit}}$) as:

$$T_{azT_o} = T_{bz}(1-\beta)\eta + T_{O_{bl}}\beta_i\eta + \overline{T_{bz}}\beta_{ni}\eta + T_O(1-\eta) \qquad (6)$$

$$T_{az_{nit}} = T_{bz}(1-\beta)\eta + T_{Oblnit}\beta_i\eta + \overline{T_{bz}}\beta_{ni}\eta + T_O(1-\eta) \qquad (7)$$

we will receive:

$$\beta_i\eta = \frac{T_{azT_o} - T_{az_{nit}}}{T_{obl} - T_{oblnit}} \qquad (8)$$

Besides, from expressions (3) and (6) follows that:

$$(1-\beta)\eta = \frac{T_{amm} - T_{azT_O}}{T_{om} - T_{bz}} \qquad (9)$$

Solving jointly (5), (8), (9)and meaning, as β_{ni}+ β_i= β, it is easy to receive β_{ni}, β_i, β, η values.

Along the different most widespread types of the small aperture antennas [2] which were investigated by means of this method, the smallest value of parameter of dispersion was marked at the horns with flare angle change [3]. The antenna pattern of this type of a horn is created by correction of distribution of amplitude and a phase of a electro-magnetic field in a horn aperture at the expense of specific changing of flare angle. The precision measurements of radio brightness temperature of zenith area of the atmosphere were carried out by this method usage and with use of a method of two loadings. Then, the measurements of β values of two copies of the narrowly targeted Cassegrain antennas were carried out with attraction of the known method of radio-frequency radiation of the wood [4]. The β values for such kind of antennas with 2 m aperture were equal 0.24 and 0.26 in the range of 90 GHz.

It is appropriate to note that from the technological and budgetary points of view the horn with flare angle change is very perspective for its use up to the frequencies of 700 GHz [5-6]. However, for MM and sub-MM WR (up to THz frequencies) the most perspective today is usage low-aperture antennas created on the basis of the open end of the foam-dielectric line [7-9]. The summary properties of antenna pattern (side lobe level, level of cross-polarization radiation and level of dispersion out of the main lobe of antenna pattern) as well as the low-cost and technological effectiveness of this type of the small aperture antennas [10] exceeds the analogs researched by us in the 90 GHz range [2].

Besides the method described above, which use the foam blend cooled up to the nitric temperatures and which give possibility to estimate an impact of β value accuracy on measuring accuracy of Ta atmosphere, we additionally considered the such methods as: a) a method of "the artificial moon" [4]; b) a method of "radio-frequency radiation of the wood" [4]; c) a method of radio-frequency radiation of the central part of a Moon's disk in the "new moon" phase (it might be applicable for super-directive mirror antennas).

The analysis of retrieved data (Table) showed that the maximum accuracy of determination of T_b of the atmosphere (about 3%) can be obtained by measuring a dispersion of antenna using the method of "the artificial moon" and calibrating the radiometer by means of cooling the matched loading of horn antenna up to liquid nitrogen temperatures.

Other combinations of the considered methods provided the lower values of accuracy. For other considered methods of radiometer calibration, this circumstance is connected to inaccuracy of estimates of radio brightness of sources of space radiation (for the Moon, - about 10% inaccuracy and existence of a factor of influence of a Moon phase) as well as it is connected with short precision of calculated determination of radio brightness of the atmosphere according to meteodata (up to 10% for cases of the cloudless atmosphere). Besides, the accuracy of calibration methods and methods of measurement of parameters of dispersion of antennas which use spatial (elevation) reorientation of the antenna is reduced due to change of intensity of the background accepted by back and side lobes of the antenna pattern.

However, in cases when such high accuracy of determination of the measured intensity of the descending radiation of the atmosphere or a source of space radiation is not required, it makes a sense to use simpler and convenient methods of measurements in implementation. For example, to carry out the calibration of radiometers using the radiation of zenith area of the clear sky estimated theoretically on the meteorology data basis. Different combinations of these methods were used by us in practice in programs of observation of continual radiation of the atmosphere.

TABLE I

ASSESSMENT OF ACCURACY OF DETERMINATION OF THE SKY Tb FOR DIFFERENT CALIBRATION METHODS OF THE RADIOMETER (α) AND METHODS OF MEASUREMENT OF PARAMETER OF DIFRACTION (β) OF ANTENNA SYSTEM.

Methods of measurement of parameter β	**calibration methods**	
	method of both loadings (300K, 78K)	method of calculation of the sky Tb
Method of the Moon		10-17%
Method of the artificial Moon	3%	6%
Wood radiation method		9%

II. AN ASSESSMENT OF ACCURACY OF RESTORING TECHNIQUES OF ATMOSPHERIC RADIOBRIGHTNESS TEMPERATURE.

Restoration of values of total vertical absorption in the atmosphere according to radiometric data can be carried out by also different methods. For example, by method of elevation sections [1,4] or by beacon method at the expanse of trans-illumination of the atmosphere by emitted signals of the satellite or powerful source of space radiation. Both of these methods require use of the difficult additional equipment in the form of mechanical system of antennas re-orientation, narrowly targeted antennas and some special software.

It is more convenient to conduct such kind experimental investigations by a radiometric method, relying on connection between the measured T_a with retrieved T_b based on expression:

$$T_a = (T_{batm} + 2.7e^{-\tau})(1-\beta) + \overline{T_{ph}} \times \beta \qquad (10)$$

In a case of such approach, usage the AM method for calibration of the radiometer allows to exclude from reviewing an item of $\bar{T}_{ph}$. In this case the values T_{aatm} and T_{aam} are measured by means of the selected calibration method, and then T_b value is calculated from the system of two equations. Such equation system consist from the previous expression and similar to it for a case when the AM disk superimposes the main lobe of antenna pattern. Here τ value can be evaluated very approximately; for example, one might be calculated according to meteodata, in view of much smaller value of this item. Then a value of τ can be recovered more exactly using the values of T_b defined from the well-known expression:

$$\alpha\Delta n = (T_{bam} - T_{batm})(1-\beta) \quad (11)$$

where α - calibration coefficient from equation (1), Δn – the differences of output signals of radiometer when AM and atmosphere are observed.

For computation of errors of determination of values β, α, T_{batm} by means of the listed methods we wrote the route of appropriate mathematic expressions by means of formulas of "transferred errors". For example, for the most exact combination of methods when calibration is carried out on the basis of the antennas loading which cooled up to the nitric temperatures, and when diffraction parameters of antenna are defined by the AM method, the dispersion of errors of measurements for T_b of atmosphere can be described according to this equation:

$$\sigma_{Tbatm}{}^2 = (\frac{\partial T_{batm}}{\partial \alpha})^2 \sigma_\alpha{}^2 + (\frac{\partial T_{batm}}{\partial \Delta n})^2 \sigma_{\Delta n}{}^2 + (\frac{\partial T_{batm}}{\partial \beta})^2 \sigma_\beta{}^2 + \\ + (\frac{\partial T_{batm}}{\partial T_{am}})^2 \sigma_{T_{oam}}{}^2 + (\frac{\partial T_{batm}}{\partial \tau})^2 \sigma_\tau{}^2$$

here σ_{Tbatm} — dispersion of measurement errors or dispersion of estimation of the corresponding parameters.

Having calculated derivatives and passing to the relative mean squared errors, it is possible to obtain an expression for calculation of errors of determination of T_{batm} value:

$$\delta T_{batm}{}^2 = \frac{\sigma T_{batm}{}^2}{(T_{batm})^2} \quad (12)$$

The quantitative estimates of measurement errors determinate by the specified calculation method (with usage the parameters of the specific radiometric equipment at 94 GHz which were described in [11-12]) consists for parameters: β - 9%, α -1%, T_b – 3%.

CONCLUSION

Thus, as a result of the carried-out work:

- the methodology of determination of T_b values of the atmosphere and its total vertical absorption values obtained by a radiometry method as well as the possible ways of assessment of these procedures which were necessary for implementation of the accompanying parameters is described;

- results of estimates of accuracy of restoration of atmosphere T_b in case of use of different combinations of calibration methods of the radiometer and methods of measurement of diffraction coefficient of antenna are given;

- qualitative analysis of sources of errors in the considered calibration methods and methods of restoration of radio-brightness temperature and complete vertical absorption values in the atmosphere is carried out.

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