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Estimation of the error in the electron temperature determination of the plasma

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Estimation of the error in the electron temperature determination of the plasma

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Abstract. The error of determining the temperature of the electrons of the plasma formation surrounding the spacecraft on the descent trajectory in the radiometric method of diagnostics is considered. It is noted that the error depends on the type of radiometer and coordination of the onboard radiometer antenna. The error is analyzed and its quantification is given

1. Introduction

Spacecraft on the descent trajectory in the Earth's atmosphere are exposed to air plasma formation. Plasma formation occurs due to high-temperature aerodynamic heating of the air surrounding the return spacecraft [1]. The impact of plasma on radio communication on the route aboard the spacecraft-Earth leads to a violation of radio communication due to absorption of electromagnetic radiation power in plasma and reflection from its boundaries [2-4]. To develop methods to combat the violation of radio communication, it is necessary to know the electrical characteristics of plasma for the conditions of spacecraft flight in the atmosphere. Many known methods of diagnostics of plasma parameters cannot be applied for in-situ measurements. Of all currently existing methods of instrumental plasma diagnostics hardware implemented and used almost only two - radiometric and probe [5]. The method of radiometric diagnostics consists in the fact that with the help of onboard antenna and radiometric receiver radio brightness radiation of plasma is measured [6]. To diagnose plasma radiometrically, the model of isothermal homogeneous layer can be used. The conditions of applicability of this model are: within the layer

$$\left.\frac{dA(l)}{dl}\right|_{\lambda=\lambda_m} = const, T_e = const,$$

at the edge of the layer

$$\left.\frac{dA(l)}{dl}\right|_{\lambda=\lambda_m} \to \infty.$$

In these relations, A - the emissivity of the plasma, l -the thickness of the plasma layer, and l is the wavelength at which the diagnosis is made.

This model allows the analysis of plasma diagnostics to be reduced to the analysis of its emissivity. Frequency dependence of emissivity according to peculiarities of interaction of electromagnetic waves with plasma is characterized by four zones: reflection, blackness, translucency and transparency [7].

2. Main part

From the position of analysis of the loss of radio communication on the descent trajectory of the greatest interest is the reflection zone, which takes place for the operating frequency less than the plasma frequency. For this zone, the diagnostic results are conditioned only by the plasma parameters at the boundary. In this case it is possible to determine the radio brightness temperature at the operating frequency of the onboard radio equipment, and through it the temperature of the electrons.

The electron temperature is one of the most important plasma characteristics, because its value determines the concentration of electrons and other electrical characteristics of the plasma, such as, for example, the absolute dielectric permittivity and conductivity of the plasma and the plasma frequency, which determine the passage of electromagnetic waves through the plasma.

The error of determining the radio-luminous plasma temperature is based on the known value of the estimate error of the RMS relative error of the antenna temperature, which can be represented as

$$\delta T_a = (\delta_{fl}^2 + \delta_{dyn}^2 + \delta_c^2 + \delta_T^2 + \delta_R^2)^{1/2},$$

where δ_{fl}^2 - RMS relative fluctuation error of temperature measurement by radiometer, δ_{dyn}^2 - RMS relative dynamic error of radiometer, δ_c^2 - RMS relative error of radiometer calibration, δ_T^2 -RMS relative error of measurement of registered temperature, δ_R^2 - RMS relative error of determination of the reflection coefficient from the plasma boundary.

The fluctuation error of the antenna temperature measurement is due to the radiometer's own noise and can be represented as

$$\delta_{fl} = \frac{\pi T_n}{\sqrt{2\Delta f_{up} t_{lo} K}},$$

where T_n -noise temperature of the radiometer, Δf_{up} -bandwidth of the high-frequency path of the radiometer, t_{lo} -integration time at low frequency, K-coefficient, depending on the type of modulation.

Dynamic temperature measurement error is due to the finite value of integration time

$$\delta_{dyn} = \frac{3}{4}(T_a)'_t \frac{4\tau}{T_{\max}},$$

where $(T_a)'_t$ is the rate of change of antenna temperature, τ the time constant of the radiometer integrator.

Error in determining the reflection coefficient

$$\delta^2{}_R = \sqrt{\delta_c^2 + \delta_T^2}. \quad (1)$$

At $(\frac{\partial T_a}{\partial t}) = 10^3 \, K/s$ we get =0.01%. With the calibration error δ_c =5.5%, the measurement error of the recording equipment δ_T^2 =0.1% from equation (1) we get that the maximum error in antenna temperature determination will be about 7%.

When determining the temperature of electrons in the plasma reflection zone from the measured value of the plasma radio brightness temperature by a radiometer, the RMS relative error of determining the electronic plasma temperature will be written as [8]

$$\delta T_e = \sqrt{\delta^2 T_я + \delta^2 T_R}, \tag{2}$$

where $\delta^2 T_я$ is the RMS relative error of determining the radio-luminous temperature of the plasma.

The calculated ratios for the electron temperature error depend on the radiometer's circuit design.

For a radiometer with frequency and time division, the error of determining the temperature of the electrons can be represented as

$$\delta T_e = \frac{(\delta^2 T_a + \delta^2 R(T_n - T_e)/T_a + R^2 \delta^2 T_n)^{1/2}}{1 - R^2}, \tag{3}$$

where $\delta^2 T_n$ - RMS relative hardware error in determining the noise temperature of the radiometer, T_n - noise temperature of the radiometer.

For a radiometer with feedback in the input circuit

$$\delta^2 T_e = \sqrt{\delta^2 T_n + \delta^2 T_я (1/L^2 K^2)}, \tag{4}$$

where L is the decoupling value of the power divider of the input circuit of the radiometer, K is the transfer coefficient of the input path, taking into account the feedback.
Here the value $\delta^2 T_n$ is written in the form

$$\delta T_n = \frac{R^2}{[n - R^2(n-1)]}, \tag{5}$$

The expression for K can be represented as

$$\delta T_n = \frac{1 - R^2}{[n - R^2(n-1)]}. \tag{6}$$

Figure 1 shows the dependence of the RMS relative error of determination e depending on the energy coefficient of reflection , calculated by expressions (2)-(6).

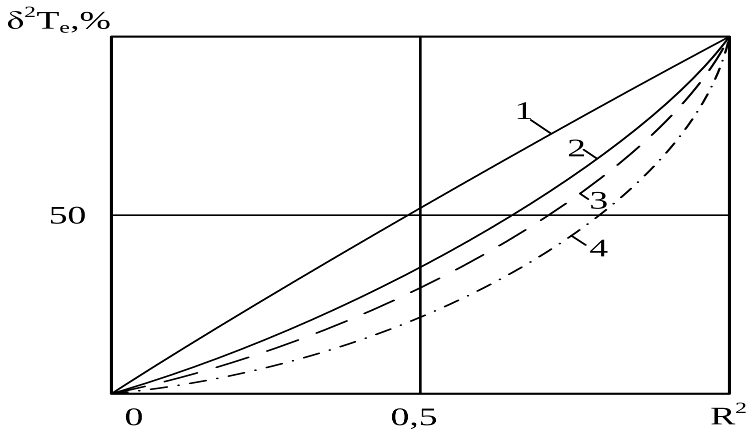

Figure 1. Root-mean-square relative error of determination T_e from R (1-n=1; 2-n=2; 3-n=3,16; 4-n=10).

3. Conclusion

As can be seen from figure 1, for reflection coefficients R<0.5 the error of determining the electronic temperature of the plasma will be determined mainly by the value of $\delta^2 T_a$. At large values R^2 (more than0.8) the error T_e of determination does not exceed 30%, while when using a modulation radiometer the RMS relative error of plasma electronic temperature determination will be 80%.
Figure 2 shows the root-mean-square relative error in determining the electron temperature of the plasma as a function of the power fission coefficient. The figure shows that the optimal value of the division factor is approximately 6.

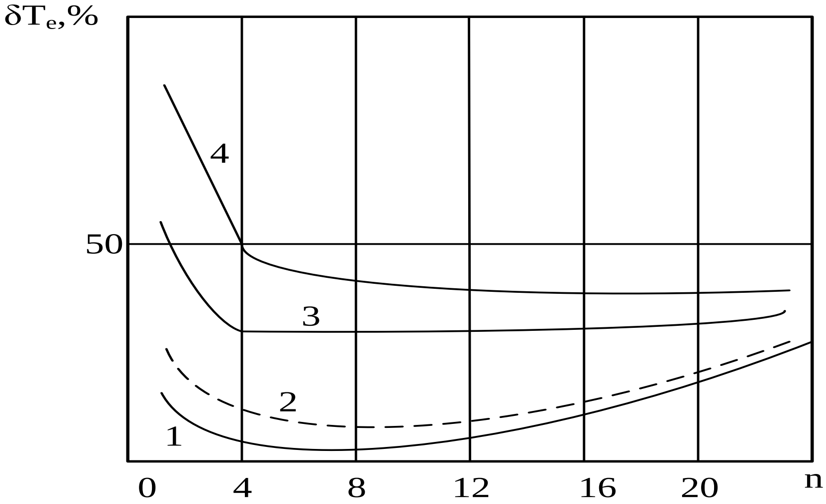

Figure 2. Dependence of the RMS relative error of determining the electronic plasma temperature on the power division factor.

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