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Diagnostics of CME cavity using data of multiwave measurements of behind-the-limb solar radio bursts

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Abstract. Mathematical modeling of the behind-the-limb radio bursts propagation characteristics at the second harmonic of the local plasma frequency of the solar corona was performed for analytical models of the electron density of the circumsolar plasma and CMEs. The features of the bursts trajectories are studied depending on the parameters of the CMEs and the initial coordinates of solar radio sources. The conditions for the strong effect of CME on radio bursts are determined. The possibility of determining the CME cavity's parameters from the data of multiwave measurements of the group delays of behind-the-limb radio bursts is shown.

Keywords: mathematical modeling, geometrical optics approximation, behind-limb source, near-Sun plasma

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Материалы конференции
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Диагностика полости КВМ по данным многоволновых измерений залимбовых солнечных радиовсплесков

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Аннотация. Для аналитических моделей электронной концентрации околосолнечной плазмы и КВМ выполнено математическое моделирование характеристик распространения залимбовых радиовсплесков на второй гармонике локальной плазменной частоты короны. Изучены особенности траекторий всплесков в зависимости от параметров КВМ и начальных координат солнечных радиоисточников. Определены условия существенного воздействия КВМ на распространение радиовсплесков. Показана возможность определения параметров полости CME по данным многоволновых измерений групповых задержек залимбового всплеска.

Ключевые слова: математическое моделирование, приближение геометрической оптики, залимбовый источник, околосолнечная плазма

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Introduction

The mechanisms of generation and propagation of coronal mass ejections (CMEs) are of great interest. Passing through the interplanetary medium, these plasma disturbances can have a significant effect on the condition of near-earth space and can be the cause of the magnetosphere deformation, geomagnetic storms and other phenomena [1]. CME observations are usually carried out with white light coronagraphs installed on spacecraft board. In particular, the source of such data is the LASCO coronagraph that located on spacecraft named SOHO [2]. Coronographs provide two-dimensional CME's images, which allow direct determination of some characteristics of plasma ejections in the celestial plane, for example, the angular size of the ejection in latitude and the velocity of its elements. At the same time, the determination of the electron density in CME from two-dimensional images (that was obtained at one point) is possible only with the use of a priori assumptions about the structure of the plasma ejection [3]. In addition, white light coronagraphs are used in the STEREO space mission (SECCHI). These devices make it possible to study the processes of solar activity in a 3D image, which contributes to the determination of additional parameters, including the propagation direction of the plasma emission. However, these devices are located far enough from the solar photosphere. Great hopes are pinned on the next-generation satellites: SolO and Parker Solar Probe. These devices will be located near the solar photosphere, which will allow studying the processes of solar activity in more detail. The results of distant radio sounding by sources of natural origin are used to research the Sun atmosphere. One of the possibilities for studying CMEs can be observations of the Sun's own radio emission passing through the corona. There is a well-known type of solar radio emission called bursts. The bursts are generated at the second harmonic of the local plasma frequency of the solar corona. The radio bursts with the sources located on the opposite side of the Sun (in relation to the observer in the Earth's orbit) are of great interest. It is noted that ground based observations of the behind-the-limb (BTL) bursts were possible in the presence of CMEs from active regions near the solar limb in the frequency range of 25–44 MHz [4]. Physical interpretation this effect had been considered in [5, 6].

In this work, mathematical modeling of the coronal plasma formation's effect on the solar radio emission's propagation is carried out and the possibility of estimation of the CME cavity parameters by the characteristics of radio bursts from sources located on the reverse side of the Sun is shown.

Numerical simulation of characteristics of radio emission propagation in a disturbed solar corona

Calculations of the CMEs' effect on the propagation of solar radio emission were carried out in the approximation of geometric optics [7]. It was assumed that the source of the radio burst is isotropic, point-like and radiates at the second harmonic of the local plasma frequency of the corona. A two-dimensional case was considered. A polar heliocentric coordinate system was used. The geometry of the case is shown in Fig. 1. The small circle (continuous line) represents the Sun's photosphere. The middle circle (dash-dotted line) is the area of background concentration near the solar photosphere, extending to level $R = R_m$ relative to the center of the Sun. The large circle (dashed line) is responsible for the Earth's orbit with a radius $R_z = 1\text{AU}$. The dotted curve characterizes the trajectory connecting the source and receiver of the radio burst.

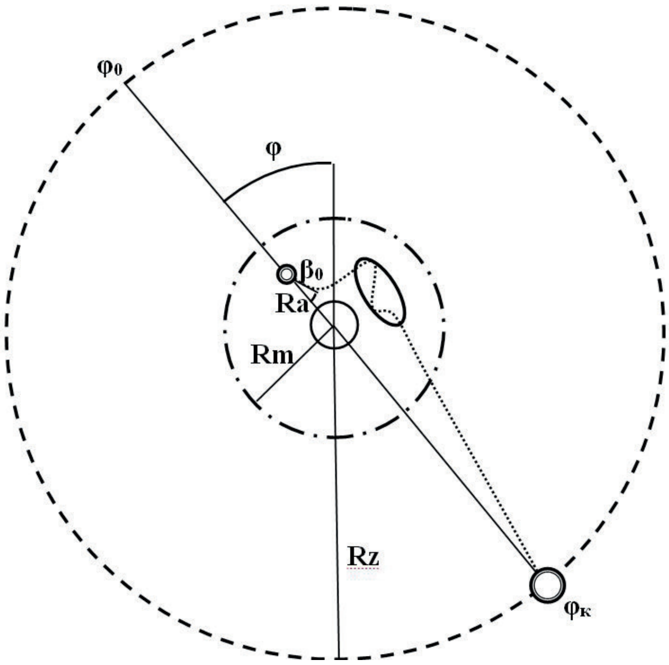

Fig. 1. Geometric diagram of radiation propagation from a BTL radio burst
R_a is the radial coordinate of the position of the radio emission source relative to the center of the Sun,
φ_0 is the angular coordinate of the radio burst source relative to the Sun, φ_k is the receiver angular coordinate,
β is the radiation angle

To calculate the trajectory characteristics of radio emission in the disturbed solar corona, we used the system of ray equations [8]:

$$\frac{dR}{d\phi}=R\cot\beta;\quad \frac{d\beta}{d\phi}=\frac{1}{2\varepsilon}\left(\frac{\partial\varepsilon}{\partial\phi}\cot\beta-R\frac{\partial\varepsilon}{\partial R}\right)-1, \tag{1}$$

where: $\varepsilon(R, \varphi) = \varepsilon_0(R) + \varepsilon_1(R, \varphi)$ is dielectric constant of the medium, ε_0, ε_1 characterize the regular condition and disturbed condition of the corona, φ is independent variable (angle relative to the center of the coordinate system associated with the Sun), $\beta(\varphi)$ is beam refraction angle, $R(\varphi)$ is the current radial coordinate of the beam. We used the following equation a model of the dielectric constant of the regular corona [9]:

$$\varepsilon_0=1-\left(\frac{f_{pl}}{f}\right)^2\left(\frac{R_m}{R}\right)^2, \tag{2}$$

where: $R_m=5R_s$; f_{pl} is plasma frequency at level R_m; f is operating frequency. Coronal plasma formation was described using the function:

$$\varepsilon_1=\mu\exp\left[-\left(\frac{\varphi-\varphi_l}{a}\right)^2-\left(\frac{R-R_l}{b}\right)^2\right], \tag{3}$$

where R_l, φ_l are radial and angular coordinates of the CME localization center, a, b are radial and angular scales of CME, μ is parameter characterizing the electron concentration of plasma inside the CME cavity.

Based on system (1), numerical modeling of the CME effects on the solar radio bursts trajectory characteristics was carried out. The following initial conditions were set. It was assumed that the source of radio emission is at an altitude $R_a = 3\ R_s$, where $R_s \approx 7\cdot10^5$ km is the solar photosphere radius, $\varphi_0 = 0$ rad, $\beta_n = 2.07$ rad is the initial radiation angle. The radiation of BTL radio sources was considered in the frequency range of 25–44 MHz. CME parameters were: $a = 0.06\ R_s$, $b = 0.15$ rad, $\mu = 1$. The localization center of the coronal disturbance had coordinates $\varphi_l = 0.8$ rad, $R_l = 3\ R_s$. Fig. 2 shows the dependences of the refraction angles of radio emission on the angular variable, calculated using the system of Eqs. (1), for regular (Fig. 2,*a*) and disturbed (Fig. 2,*b*) conditions. It follows from the obtained graphs disturbance of depleted electron density appears in the solar corona, the overall propagation path of radio bursts also increases in the entire range of the considered operating frequencies. At the same time, non-monotonic sections appear in the dependences of the refraction angles. This unusual behavior of the curves is associated with the emerging possibility of leakage of decameter radio bursts at low frequencies over long distances.

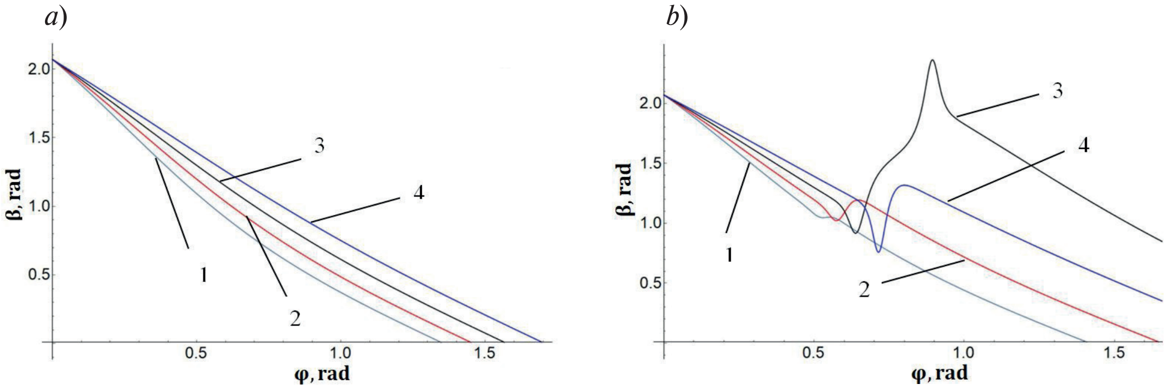

Fig. 2. Refraction angles of decameter radio bursts at different operating frequencies in the absence (*a*) and in the presence (*b*) of a cavity with a reduced electron concentration

Fig. 3 shows the results of calculations of the corresponding trajectories of radio bursts:

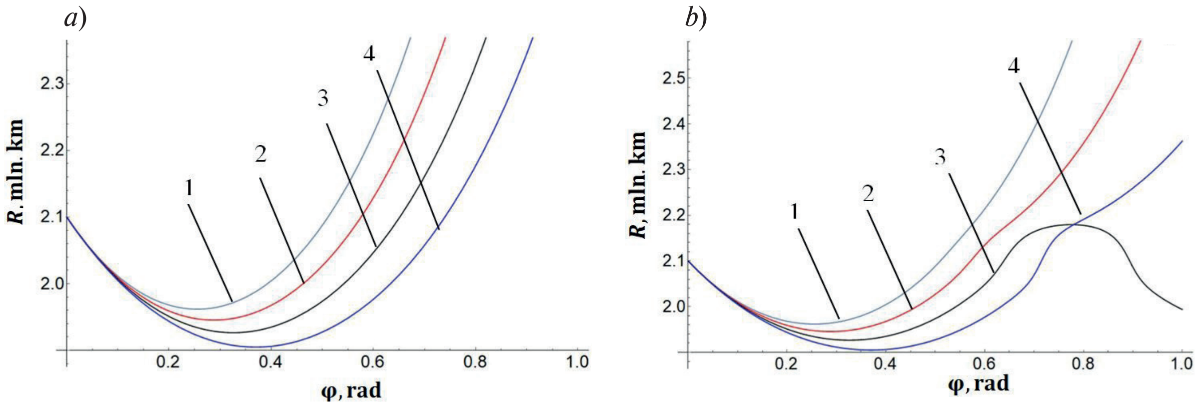

Fig. 3. Trajectories of radio bursts at different operating frequencies in the absence (*a*) and in the presence (*b*) of a cavity with depleted electron density

As follows from Fig. 3, the appearance of a CME-type coronal plasma formation contributes to a significant curvature of the radio burst trajectory and an increase in its propagation path. The trajectory of the radio burst, the angle of refraction of which manifested itself in an unusual way, becomes much longer due to the propagation of radio emission in the CME. In the presence of CME in the corona, along with the variation of the trajectory of the radio burst, its group delay changes. The additional equation was introduced into system (1) to calculate this delay:

$$\frac{d\tau}{d\phi}=\frac{R}{c\sqrt{\varepsilon}\sin\beta},\tag{4}$$

where c is speed of light.

Mathematical modeling of the radio bursts group delays at various frequencies was performed, based on Eqs. (1), (4), The coordinates of the radio burst source and the receiver relative to the Sun were: $\varphi_0 = 0$ rad, $\varphi_k = 1.995$ rad. The following dependence was considered as a model of the disturbed solar corona:

$$\varepsilon = 1-\left(\frac{f_{pl}}{f}\right)^2\left(\frac{R_m}{R}\right)^2\left(1-\mu\exp\left[-\left(\frac{\varphi-\varphi_l}{a}\right)^2-\left(\frac{R-R_l}{b}\right)^2\right]\right),\tag{5}$$

where $f_{pl} = 14$ MHz, $R_m = 5\ R_s$, $a = 0.05\ R_s$, $b = 0.4$ rad, $\varphi_l = 0.7$ rad, $R_l = 3\ R_s$.

The ranging was carried out at the observation point of the ray trajectories for different transmission frequencies in the process of numerically calculating the frequency dependence of the radio bursts' group delay in the disturbed corona. Fig. 4 shows the results of calculations of the difference between the group delays of radio bursts at different frequencies and the delay at a frequency $f = 25$ MHz.

It is easy to see that at low frequencies (26–30 MHz), when refraction is most significant, there is a strong difference in the group delays of radio bursts at different frequencies. At high frequencies (30–36 MHz) this dependence becomes slower and reaches the saturation level. The calculated group delay difference can be used to reconstruct the CME parameters from the measured relative delays of radio bursts at different frequencies along the path between the emitting source and the observer. It is possible to equalize the calculated and measured dependences on the frequency of the radio bursts' group delays using the regular corona model and information on the CME's spatial parameters from the data of optical observations, by fitting the parameter μ. This will determine the contrast parameter of the CME cavity.

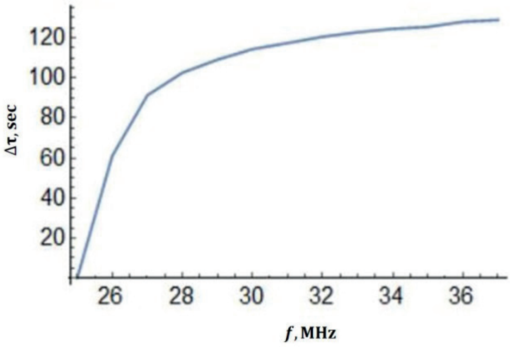

Fig. 4. Difference in the group delays of radio bursts
in a disturbed corona at different frequencies

Conclusion

The mathematical modeling of the characteristics of the BTL solar radio bursts propagation through the solar corona was carried out. The conditions for the significant effect of coronal plasma formations on the trajectories of radio bursts are determined. The possibility of reliable ground-based observations of the radio emission beyond the limb in the presence of CME is shown. The possibility of determining the parameters of the CME cavity from the data of multiwave measurements of the solar radio bursts' group delays is shown. The developed apparatus for mathematical modeling can be used to interpret the experimental data of the CME BTL transmission from spacecraft. It is also applicable in the analysis of observational data of planetary radar signals and radio emission from discrete space sources passing through the heliosphere.

REFERENCES

1. **Zeleny L.M., Veselovsky I.S.**, Plasma Heliogeophysics. Moscow: Fizmatlit, 2008, p 672.
2. **Aschwanden M.J.,** Physics of the Solar Corona. An Introduction with Problems and Solutions. London: Springer, 2005, p 908.
3. **Thernisien A.F.R., Howard R.A., Vourlidas A.,** Modeling of flux rope coronal mass ejections. The Astrophysical Journal, 2006, 652, p 763–773.
4. **Brazhenko A.I., Melnik V.N., Konovalenko A.A., Dorovskyy V.V., Frantsuzenko A.V., Rucker H.O., Panchenko M.I., Stanislavsky A.A.,** An unusual Solar burst decameter vawe-length. 1. Observations. Radio Physics and Radio Astronomy, 2012, V.17, №2, p 90–105.
5. **Brazhenko A.I., Melnik V.N., Konovalenko A.A., Dorovskyy V.V., Frantsuzenko A.V., Rucker H.O., Panchenko M.I., Stanislavsky A.A.**, An unusual Solar burst decameter vawe-length. 2. Interpretation. Radio Physics and Radio Astronomy, 2012, V.17, №3, p 199–206.
6. **Stanislavsky A.A.,** The role of radio wave propagation effects in the solar corona to interpret the behind-limb bursts Radioastronomy and Astrophysics, 2016, 21**,** p 3–13.
7. **Ginzburg V.L.,** Propagation of Electromagnetic Waves in Plasma. New-York: Gordon and Breach Pub., 1961, p 684.
8. **Kravtsov Yu.A., Orlov Yu.I.,** Geometrical Optics of Inhomogeneous Medium. Berlin: Springer-Verlag, 1990, p 312.
9. **Yakovlev O.I.**, Space Radio Science. Boca Raton: CRC Press, 2002, p 320.

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