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Search for ElectroMagnetic Earthquake Precursors

Modification of ion concentration profiles and the lower hybrid resonance frequency above seismically active regions

Deliverable 3.2

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Summary

In the first part of this research reported in the first deliverable to WP3 we have suggested a method of revealing unusual variations of ionospheric parameters possibly related to a gathering earthquake by monitoring the amplitudes of VLF transmitter signals with specially chosen frequencies and locations. This method relies upon two facts: a) the different character of quasi-resonance VLF wave propagation in the cases when the wave frequency f is smaller than $(f_{\text{LHR}})_{\text{max}}$ (which causes the wave to be reflected) or larger than $(f_{\text{LHR}})_{\text{max}}$ (no LHR reflection), where $(f_{\text{LHR}})_{\text{max}}$ is the maximum LHR frequency in the upper ionosphere along the wave path, and b) significant modification of LHR frequency profile, including the value of LHR maximum, in response to relatively small variations of ionospheric parameters, in particular, absolute and relative contents of ion species on a "base level" in the ionosphere. Here we discuss how the electric field above a seismically active region, which often accompanies a gathering earthquake, can lead to variation of the LHR frequency profile above the seismic region.

1 Introduction and link with the first deliverable

In recent decades, the problem of earthquake prediction from its geophysical precursors has been the focus of many studies. Geophysical phenomena such as the anomalous increase in the critical frequency f_0F2, unexpected variations in the amplitude and spectrum of ELF and VLF emissions observed on the ground and on satellites over seismic regions have been considered as possible precursors of an earthquake (see the references to the 1st deliverable).

In the first part of the present research, reported in the first deliverable to WP3, we have suggested a new method of monitoring unusual variations of plasma parameters in the lower ionosphere possibly related to gathering earthquakes. The method relies upon peculiarities of VLF transmitter signal propagation in the magnetosphere and upper ionosphere. While propagating along a magnetospheric trajectory in non-ducted mode, the wave (VLF signal) enters the quasi-resonance regime of propagation and is reflected from the region if its frequency f is equal to the LHR frequency f_{LHR} (Kimura, 1966; Alekhin and Shklyar, 1980; Shklyar et al, 2004). This happens if the wave propagates from the magnetosphere to the ionosphere, i.e. in the direction of increasing f_{LHR}, provided that $f < (f_{\text{LHR}})_{\text{max}}$, where $(f_{\text{LHR}})_{\text{max}}$ is the maximum LHR frequency in the upper ionosphere along the wave path. In this case, the wave will not be registered on a low-altitude satellite like DEMETER, orbiting below the LHR maximum. If, however, $f > (f_{\text{LHR}})_{\text{max}}$, the signal will be registered on low-altitude satellites.

As we show below, the LHR frequency profile, including the value of LHR maximum, is very sensitive to variations of ionospheric parameters, in particular, to absolute and relative concentrations of ion species on a "base level" in the ionosphere. In this way, the amplitude of VLF transmitter signal, which depends crucially on the relation between f and $(f_{\text{LHR}})_{\text{max}}$, becomes very sensitive to variations of ionospheric parameters.

Since there is no convincing evidence in the literature concerning the variations of the LHR frequency before earthquakes, we have studied this subject based on DEMETER data, which has been reported in the first deliverable to the WP3 of the Project. As a result, we have suggested a method of revealing unusual variations of ionospheric parameters possibly related to a gathering earthquake, by monitoring the amplitudes of VLF transmitter signals with specially chosen frequencies and locations. In the second part of our study reported here we discuss a possible reason and the mechanism for the variation of the LHR frequency profile above seismic region.

2 Diffusive equilibrium model and qualitative features of ion distribution in the upper ionosphere

The thermal plasma distribution in the Earth's ionosphere is determined by many different physical and chemical processes. This distribution is nonstationary and depends on many factors, in particular, season, time, location, solar activity, *etc* (Angerami and Thomas, 1964; Bailey and Sellek, 1990). All sophisticated mathematical models of the thermal plasma distribution are numerical, since, accounting for the main physical and chemical processes, the distribution of plasma is described by a complicated set of nonlinear equations (see, for instance, Bailey and Sellek, 1990, and references therein). In the frame of such elaborate models, it is rather difficult to investigate the influence of particular factors on the distribution of different plasma components. For this purpose, simpler models are usually used, which lead to a qualitative understanding of the role of different factors. In this study we use a simplified model which permits us to understand some important qualitative features of the topside ion distribution along the geomagnetic field line, which is necessary for our purposes, namely, analysis of the LHR frequency in the topside ionosphere.

Since the curvature of the ambient magnetic field is of principal importance, we use a dipolar L, Φ, M coordinates system in our consideration. With the dipole centre located at the origin of the Cartesian coordinate system x, y, z, the expressions for dipole coordinates through Cartesian ones have the form

$$L(x,\ y,\ z) = \frac{1}{R_e}\frac{r^3}{(x^2+y^2)}\ ; \qquad \Phi(x,\ y,\ z) = \mathrm{atan}(y/x)\ ; \quad M(x,\ y,\ z) = R_e^2\,\frac{z}{r^3}\ ; \tag{1}$$

$$r \equiv (x^2+y^2+z^2)^{1/2}$$

The dipole coordinate L has a constant value on a given field line, and is equal to the distance from the dipole center to the top of the field line at the equator, measured in units of the Earth's radius R_e. This coordinate is also called McIlwain's parameter. The curvilinear axes corresponding to the coordinate M coincides with the lines of force of the dipole magnetic field. Thus, in this coordinate system, the ambient magnetic field only has a component along M. The coordinate M is measured along the line of force from the equator, so that at the equator, $M = 0$. The coordinate Φ is the azimuth angle, i.e. the angle which the corresponding meridian plane, containing the point (x, y, z) and dipole axis, forms with the (x, z)-plane. The corresponding Lamé coefficients, which are essential quantities characterizing a curvilinear coordinate system, are as follows

$$h_{\mathrm{L}} = \frac{R_e}{(1+\Lambda)(1+4\Lambda)^{1/2}}\ ; \quad h_{\Phi} = \frac{R_e L}{(1+\Lambda)^{3/2}}\ ; \quad h_{\mathrm{M}} = \frac{R_e L^3}{(1+\Lambda)^{5/2}(1+4\Lambda)^{1/2}}\ . \tag{2}$$

The quantity Λ entering in (2) is defined as

$$\Lambda = \frac{z^2}{x^2+y^2} \equiv Z^2 = \tan^2\lambda\ , \tag{3}$$

where λ is geomagnetic latitude. In dipole coordinates, the magnitude of the magnetic field is expressed as

$$B_0(L, M) = \frac{B_e}{L^3}(1+\Lambda)^{5/2}(1+4\Lambda)^{1/2} \equiv \frac{B_e R_e}{h_{\mathrm{M}}}\ , \tag{4}$$

where B_e is the magnitude of magnetic field on the Earth's surface at the equator ($\Lambda = \lambda = 0$). We see that Lamé coefficients and the magnetic field strength are more easily expressed through L, Λ (or L, λ) than through L, M, although, the last two coordinates form an orthogonal coordinate system. The coordinate systems are related through the following equation:

$$M^2 L^4 = \Lambda(1+\Lambda)^3 \;, \tag{5}$$

which determines Λ as the function of M and L.

The equations of diffusive equilibrium which determine the variation of electron density n_e and ion densities n_i along a given geomagnetic field line have the form (Angerami and Thomas, 1964; Bailey and Sellek, 1990):

$$\begin{aligned} \nabla_{\|} n_e &= -\frac{eE_{\|}}{T_e} n_e \;; \\ \nabla_{\|} n_i &= -\frac{m_i g_{\|} - eE_{\|}}{T_p} n_i \;, \end{aligned} \tag{6}$$

where m_e and m_i are electron and ion mass, respectively, $g_{\|}$ is the parallel component of gravitational acceleration, $E_{\|}$ is the polarization electric field, and T_e and T_p are, respectively, the electron and ion temperature in units of eV, the ion temperature is assumed to be equal for all ion components. The quasineutrality condition

$$n_e = \sum_i n_i$$

implies the following expression for $E_{\|}$:

$$E_{\|} = \frac{g_{\|}}{eT_p} \frac{\sum_i n_i m_i}{\frac{\sum_i n_i}{T_p} + \frac{n_e}{T_e}} \;. \tag{7}$$

Substituting these definitions into equations (6) we obtain:

$$\begin{aligned} \frac{dn_e}{dZ} &= -\frac{eE_{\|}}{T_e} \frac{LR_e(1+4\Lambda)^{1/2}}{(1+\Lambda)^2} n_e \;; \\ \frac{dn_i}{dZ} &= -\frac{m_i g_{\|} - eE_{\|}}{T_p} \frac{LR_e(1+4\Lambda)^{1/2}}{(1+\Lambda)^2} n_i \;, \end{aligned} \tag{8}$$

where $E_{\|}$ is determined in (7).

The equations of diffusive equilibrium represent the balance of the sum (equal to zero) of parallel (along the ambient geomagnetic field) components of all forces, namely pressure, gravity and polarization electric field acting upon a given plasma component in a volume element (e.g. Angerami and Thomas, 1964). As is well known, a small parallel electric field, called the polarization field, inevitably appears due to the different mobility of "fast" electrons and "slow" ions. This field balances the difference in the effects of gravity on electrons and ions and keeps the plasma distribution quasi-neutral (see below). In fact, one can neglect the gravity force acting on electrons in comparison with the pressure and electric force, as was done in this study. The quasineutrality condition written above is nothing more than an approximate solution of the Poisson equation for the conditions when the Debye radius is much less than a characteristic scale of the electric field variation.

Equations (8) and (7) form a closed set of equations the solution of which is determined by the values of the concentration of all plasma components at the base altitude. We should underline that it automatically gives the value of the polarization field at this height, and that, in general, the polarization electric field is always positive in the region where diffusive equilibrium with quasi-neutrality holds. From the equation for electron density it follows that n_e always decreases with height. It is then clear that the equations of diffusive equilibrium are not applicable below the ionospheric maximum of the electron density.

An important feature resulting from equations (8) and (7) consists in the following. If the base concentration of all ions and electrons increases (decreases) by some factor, and the temperature profiles remain unchanged, the electron and ion concentration at any point will increase (decrease) by the same factor. Thus, the shape of the concentration profiles is determined only by relative concentrations at the base level, which determines the relative concentrations along the whole profile. For this reason, in numerical calculations we can always set to 1 the electron density on the base level without loss of generality. The real values of concentrations are then obtained by multiplying the calculated values by the electron concentration on the base level. We should stress that the effective ion mass which is an essential factor defining the LHR frequency (see below) depends only on relative concentrations of different species of ions.

We will remind that the variation of LHR frequency profile before an earthquake is the key point in the suggested method of earthquake monitoring. For the sake of convenience, we repeat the definition of the LHR frequency. This will also show how the electron and ion distributions come into play. The LHR frequency $f_{\rm LHR}$ is defined as:

$$f_{\rm LHR}^2 = \frac{1}{M_{\rm eff}} \frac{f_c^2 f_p^2}{f_p^2 + f_c^2} \ , \tag{9}$$

where f_c, f_p are the electron cyclotron and plasma frequencies, respectively, and $M_{\rm eff}$ is the dimensionless effective ion mass determined by the relation

$$\frac{1}{M_{\rm eff}} = \frac{m_e}{n_e} \sum_{\rm ions} \frac{n_i}{m_i} \ . \tag{10}$$

Here, as above, n_e, m_e are the electron density and mass, respectively, n_i, m_i are the same for ions of species i, and summation is assumed over all ion species. The characteristic scale of electron cyclotron frequency variations in the upper ionosphere is of the order of thousand kilometers. Equation (9) then shows that the LHR frequency profile at the heights of low-orbiting ($\sim 500 - 1500$ km) satellites is mainly determined by the behaviour of electron density $n_e \propto f_p^2$ and effective ion mass $M_{\rm eff}$. It is worth mentioning that when $f_p^2 \gg f_c^2$, which is often fulfilled in the upper ionosphere, the LHR frequency is determined only by $M_{\rm eff}$ and f_c. The shapes of the electron and ion density distributions and the profiles of LHR frequency obtained from the solutions of equations (8) and (7) are shown in Figs. 1-8 for various sets of relative ion concentrations at the base level 400 km. The electron density at the base level is the same in all cases, while the contents of H^+, He^+, and O^+ differ as noted in the figure captions. The calculations were performed for the magnetic field line $L = 1.42$ which crosses the height 400 km (used as the base level) at the latitude $\lambda = 30^o$. An electron temperature of $4250K$ and ion temperature $1830K$ were used in calculations. We see essential variations of both maximum LHR frequency and the height of this maximum with the variations of ion (especially of light ion) fractional contents at the base level. Note the most significant changes in the light ion concentration at the heights close to transition point where the concentrations of light and heavy ions are of the same order.

3 Variation of plasma tube contents due to seismic-related electric field

As has been shown above, the LHR frequency profile is quite sensitive to perturbations of the relative density of different plasma species. For instance, if the total number of particles in different magnetic tubes depends on longitude, then both the concentration and LHR profiles along the field line and the latitudinal profiles along a satellite orbit may show strong variations with longitude. In this Section, we investigate the $[\mathbf{E} \times \mathbf{B}_0]$ drift as a possible cause of plasma density perturbations.

In a stationary state which assumes, in particular, the absence of particle drift, the concentration of different plasma species along the geomagnetic field line is determined by the partial balance of the pressure, gravity and the parallel polarization electric field forces. The corresponding relation is simply the equation for the first moment of the distribution function. In this case, the continuity equation gives no new information, since it reduces to the condition of zero average velocity, assuming the absence of any flux. On the other hand, the continuity equation is important for the description of a non-stationary process that modifies the electron and ion distributions.

Since thermal plasma is strongly magnetized, the curvature of the ambient geomagnetic field may play a significant role. We will denote the dipolar coordinates L, Φ, M by X_k, $(k = 1, 2, 3)$, assuming $X_1 = L, X_2 = \Phi,$ and $X_3 = M$. The continuity equation for each particle species has the form:

$$\frac{\partial n_{e,i}}{\partial t} + \mathrm{div}(n_{e,i}\mathbf{V}_{e,i}) = 0 \ , \tag{11}$$

where $n_{e,i}$ is the electron (e) and ion (i) density, $\mathbf{V}_{e,i}$ is the average velocity for electrons and ions of the type i determined by

$$\mathbf{V}_{e,i} = \int \mathbf{v} f_{e,i}(t, \mathbf{r}, \mathbf{v}) d\mathbf{v} \ , \tag{12}$$

Figure 1: Plasma component concentrations (x-axis) vs height along the geomagnetic field line (y-axis) for the following concentrations at the base level: $n^0_{H+} = 2.5 \cdot 10^3$ cm^{-3}, $n^0_{He^+} = 0.5 \cdot 10^3$ cm^{-3}, $n^0_{O^+} = 7 \cdot 10^3$ cm^{-3}, $n^0_e = 10^4$ cm^{-3}.

Figure 2: Height profile of the LHR frequency for the concentrations shown in Fig. 1.

Figure 3: Plasma component concentrations (x-axis) vs height along the geomagnetic field line (y-axis) for the following concentrations at the base level: $n^0_{H+} = 0.5 \cdot 10^3$ cm^{-3}, $n^0_{He^+} = 0.5 \cdot 10^3$ cm^{-3}, $n^0_{O^+} = 9 \cdot 10^3$ cm^{-3}, $n^0_e = 10^4$ cm^{-3}.

Figure 4: Height profile of the LHR frequency for the concentrations shown in Fig. 3.

Figure 5: Plasma component concentrations (x-axis) vs height along the geomagnetic field line (y-axis) for the following concentrations at the base level: $n^0_{H^+} = 2.5 \cdot 10^3$ cm^{-3}, $n^0_{He^+} = 2.5 \cdot 10^3$ cm^{-3}, $n^0_{O^+} = 5 \cdot 10^3$ cm^{-3}, $n^0_e = 10^4$ cm^{-3}.

Figure 6: Height profile of the LHR frequency for the concentrations shown in Fig. 5.

Figure 7: Plasma component concentrations (x-axis) vs height along the geomagnetic field line (y-axis) for the following concentrations at the base level: $n^0_{H+} = 0.5 \cdot 10^3$ cm^{-3}, $n^0_{He^+} = 2.5 \cdot 10^3$ cm^{-3}, $n^0_{O^+} = 7 \cdot 10^3$ cm^{-3}, $n^0_e = 10^4$ cm^{-3}.

Figure 8: Height profile of the LHR frequency for the concentrations shown in Fig. 7.

$f_{e,i}(t, \mathbf{r}, \mathbf{v})$ is the distribution function of electrons (e) and ions (i). The continuity equation (11) is obtained by integrating the kinetic equations over all velocities, the collision integral $St(f_\alpha)$ giving zero contribution since the collisions do not change the number of particles. It should be stressed that, although the form of the continuity equation does not depend on the collision integral, the distribution function itself and, thus, the average velocities $\mathbf{V}_{e,i}$ (12) entering (11) are essentially determined by the collisions.

Now, let us consider the following model problem. Let a stationary distribution of plasma particles in the ionosphere be perturbed by an electric field arising from the region of the forthcoming earthquake. We describe this field by the potential U, so that $\mathbf{E} = -\nabla U$. While analysing the plasma motion under the influence of the field $\mathbf{E}$ we can neglect its parallel component, which is rapidly removed by a small shift of charges along the magnetic field, thus we can suppose that $U = U(L, \Phi)$. We should underline that the last statement concerns only the field connected with the earthquake which is assumed to be much larger than the polarization electric field. Needless to say, the latter remains also in perturbed conditions.

In a collisionless plasma, the transverse electric field $\mathbf{E}_\perp = -\nabla_\perp U$ leads to the drift of all plasma components with the velocity

$$\mathbf{V}_d = c\frac{[\mathbf{E} \times \mathbf{B}_0]}{B_0^2} \ , \tag{13}$$

in cgs units, or, in components:

$$V_{dL} = -\frac{c}{B_0 h_\Phi}\frac{\partial U}{\partial \Phi} \ , \quad V_{d\Phi} = \frac{c}{B_0 h_L}\frac{\partial U}{\partial L} \tag{14}$$

Substituting (14) into (11) we obtain the continuity equation in the form

$$\frac{\partial n_{e,i}}{\partial t} + \frac{V_{dL}}{h_L}\frac{\partial n_{e,i}}{\partial L} + \frac{V_{d\Phi}}{h_\Phi}\frac{\partial n_\alpha}{\partial \Phi} = 0 \ , \tag{15}$$

where $V_{dL}, V_{d\Phi}$ are determined by (14). The terms containing the derivatives of the drift velocity over the coordinates are cancelled because of the relations (14). Equation (15) is similar to the one-dimensional kinetic equation in which the role of conjugate variables is played by the coordinates L, Φ, the role of the Hamiltonian from which the equations of motion can be derived is played by the function $-cU/B_0$, and the role of the phase volume, which is conserved along the particle phase trajectory, is played by the volume in the plane (L, Φ). Due to the similarity mentioned above, we can write a general solution of equation (15) based on Liouville's theorem

$$n(t, L, \Phi) = n_0[L_0(t, L, \Phi),\ \Phi_0(t, L, \Phi)]\ , \tag{16}$$

where $n_0(L, \Phi)$ is the initial density, that is $n(t = 0, L, \Phi)$, and $L_0(t, L, \Phi),\ \Phi_0(t, L, \Phi)$ are initial coordinates expressed as functions of current coordinates and time from the equations of motion

$$\frac{dL}{dt} = \frac{V_{dL}}{h_L}\ , \frac{d\Phi}{dt} = \frac{V_{d\Phi}}{h_\Phi}\ . \tag{17}$$

Proceeding to the solution of the model problem, we notice that the electric field, as well as the drift velocities, should be localized in some region of the (L, Φ)-plane close to the epicenter of the forthcoming earthquake. Let us suppose that the initial density n_0 does not depend on Φ, *i.e.* $n_0 = n_0(L)$, and in the restricted region under consideration the density $n_0(L)$ is, for example, a monotonically decreasing function (which is natural to assume if the positive direction of L corresponds to the increase of the radial distance from the Earth). Let there be a dominant direction of the L-drift in the region of the forthcoming earthquake. Evidently, this direction depends on the sign of the Φ-component of the electric field, $\overline{V}_{dL} \propto E_\Phi$, where the bar denotes the average value. Using (16), (17) we obtain

$$n(t, L, \Phi) = n_0 \left[L - \frac{\overline{V}_{dL}(t, L, \Phi) t}{h_L} \right]\ . \tag{18}$$

It follows from (18) that, in the region where a dominant direction of the drift exists, the particle density varies according to

$$\frac{\partial n}{\partial t} \simeq -n_0^{'} \left[L - \frac{\overline{V}_{dL} t}{h_L} \right] \frac{\overline{V}_{dL}}{h_L}\ , \tag{19}$$

where $n_0^{'}$ is the derivative of the initial density over the coordinate L: $n_0^{'} = dn_0/dL$. We see that the character of the density variation with time is determined by the sign of

$\overline{V}_{dL} \propto E_\Phi$. Let, for instance, $\overline{V}_{dL} > 0$. Since according to our assumption $n_0^{'} < 0$, it follows from (19) that the particle density increases over part of the region of localised electric field. It could be shown that in this case the particle density slightly decreases in the region adjacent to that of the electric field localization. In the case $\overline{V}_{dL} \propto E_\Phi < 0$ and $n_0^{'} < 0$, the situation is reversed *i.e.* the particle density decreases in the region of the field localization and increases in the adjacent region.

4 Modification of thermal plasma distribution and the lower hybrid resonance frequency in the topside ionosphere

The results given above suggest a possible mechanism for the modification of thermal plasma concentration profiles over a seismically active region. Let us suppose that, in the process of earthquake preparation, a large scale quasi-static electric field arises from the seismic region as is suggested by some observations (e.g., Chmyrev et al., 1989). The transverse component of this field penetrates to ionospheric heights and gives rise to the drift of all plasma species across the geomagnetic field. This process is non-stationary, and takes place during a limited time. Due to this transverse drift, plasma redistribution takes place in some region over a forthcoming earthquake. As a result, both the total and relative number of electrons and ions change in this region. Under quite general assumptions regarding the radial plasma distribution in the ionosphere and the character of the electric field, the plasma drift leads to a significant variation of the base concentration and the total number of electrons and ions on some magnetic tube connected to the seismic region; the variation of plasma parameters in the adjacent region is smaller and of the opposite sign. As has been shown above, the most crucial changes take place in the light ion distribution at heights close to the transition point where the concentrations of light and heavy ions are of the same order. Thus, when crossing a seismically active region, a satellite may measure a latitudinal profile of the light ion distribution which significantly differs from the corresponding profiles at other longitudes beyond the region of the earthquake preparation. As we have seen above, the same is true for the maximum value of the LHR frequency and the height at which this maximum is situated.

We should underline that the transverse electric field and related particle drift constitute only one possible mechanism for the modification of plasma distribution, in particular, of the light ion and LHR frequency profiles. The important point is the variation of the number of particles above some level or similarly the variation of the base concentrations of the plasma components. Such variations could take place under the influence of various factors connected with the earthquake preparation. Here we mention another possible scenario, following the model of lithosphere-ionosphere interaction that has been put forward by Martynenko *et al.* (1996) for the explanation of anomalous changes in VLF signal characteristics. We believe that the same processes may play a part in the problem investigated in the present study.

According to the Martynenko et al. 1986 model, radioactive gas releases during the time preceding the earthquake increase the atmospheric conductivity. This changes the current flowing between the ionosphere and the Earth and, thus, the electric field at the lower boundary of the ionosphere. Since the effective collision frequency ν_{eff} depends on the magnitude of the electric field $\mathbf{E}$, the variation of $\mathbf{E}$ changes ν_{eff}, which in turn changes the ionization balance and, thus, plasma parameters in the lower ionosphere. We may then speculate that these perturbations “propagate” upwards through the ionosphere and slightly modify the total number of charged particles along a plasma tube. As we have shown above, this can significantly change the plasma concentration profiles, especially of light ions in the region near the transition point, and, thus, the LHR frequency profile, including the value of its maximum.

5 Summary and conclusions

In the present study, we have suggested a possible mechanism of variation of ion distribution and the LHR frequency profiles above seismically active regions. We have shown that such variations can take place due to particle transversal drift caused by large-scale electric field arising above the region of gathering earthquake. We have undertaken a detailed analysis of the corresponding processes. As has been shown earlier, in the first part of the study in the frame of WP3, the corresponding variations in the LHR frequency profiles can be detected my monitoring the changes in amplitudes of VLF transmitter signals observed over seismic regions at the heights below the LHR maximum, if the transmitter frequency is close to the maximum in the LHR frequency profile.

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