Measurement of wave electric field in space plasmas: the antenna effective length at resonance

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Abstract. We show that the effective length of a dipole antenna grows by more than an order of magnitude close to the plasma resonance in a streaming solar wind. This finding is to be used in interpretation of wave electric field measurements in space plasmas.

Keywords: double sphere dipole, effective length, resonance conditions

The study of effective length of the double sphere dipole antenna under resonance conditions is related to the reception of quasi-regular signals (quasi-harmonic waves) coming to the receiving antenna from a distant source and it allows for meaningful conversion of the voltage measured on the antenna terminals to the electric field of incident waves. The general treatment was given by Chugunov, 2001, [2] and was successfully applied to two point measurements (transmitter↔receiver, James, 2000, [4]) of waves around the lower oblique resonance in the ionosphere (Chugunov et al., 2003, [3]).

The rms voltage on a receiving antenna is expressed as

$$V^2 = \frac{2}{\pi}\Delta\omega \int \frac{(2\pi)^3 W_k^{inc}(\omega,\vec{k})}{k^2} dR_k , \qquad (1)$$

where $dR_k = \frac{(2\pi)^5}{\omega - \vec{k}\vec{u}} \left|\vec{k}\vec{j}_0(\vec{k})\right|^2 \delta(\varepsilon_l(\omega - \vec{k}\vec{u},\vec{k}))\, dk d\Omega = \frac{\omega}{\omega - \vec{k}\vec{u}} dR_k^* ,$

dR_k^* is a differential resistance of radiation in the resonant mode, and the longitudinal plasma dielectric function

$\varepsilon_l(\omega - \vec{k}\vec{u},\vec{k}) = (k_\alpha \varepsilon_{\alpha\beta} k_\beta)/k^2 = 0$

gives the dispersion equation of electrostatic waves, in our case leading to

$(\omega - k_z u)^2 - k_z^2 v_T^2 - k_\perp^2 v_T^2 - \omega_p^2 = 0$, $\vec{j}_0(\vec{k})$ is the Fourier component of the current density distribution of unit amplitude on the antenna, $d\Omega = \sin\vartheta\, d\vartheta\, d\varphi$ – is the solid angle, $\Delta\omega$ receiver bandwidth, ω_p is the plasma resonance frequency, v_T the electron thermal velocity and u the solar wind drift velocity directed along z-axis.

The formula is valid for any incident radiation of spectral energy density $W_k^{inc}(\omega,\vec{k})$.

In case of a quasi-harmonic wave coming from a source to the receiver we have

$$W_k^{inc}(\omega,\vec{k})\Delta\omega = \frac{\Pi_{gr}^{inc}}{\Delta\Omega_{gr} \cos \vec{k}\,\hat{}\,\vec{v}_{gr}} .$$

The Poynting vector Π_{gr}^{inc} is directed along the radius vector from the emitter point to the receiver point, $\vec{k}\,\hat{}\,\vec{v}_{gr}$ is the angle between the wave vector $\vec{k}_*$ and $\vec{v}_{gr}$, the group velocity , and $\Delta\Omega_{gr}$ is the solid angle in the direction of group velocity.

With some comments the rms open circuit voltage V induced on the terminals of a dipole antenna can be written as $V = EL_{eff}$ with E the amplitude of the incident wave and L_{eff} the effective length. It should be borne in mind that this deceptively simple relation reflects both the dependence of the effective length on the antenna field pattern (normalized) and on vector relation of the incident wave electric field vector and a unit vector giving the dipole orientation. Moreover, the plasma dispersive properties, especially in the vicinity of a resonance, have a profound effect on the re-radiated field pattern of quasi-potential modes.

To help the understanding of physical reasons for the change in effective length we show Figs.1-3. The wave number surfaces (normalized by the Debye length) for Langmuir waves in a streaming plasma are elliptic, with slightly longer axis along the stream velocity u (z-axis). They exist also below the local plasma frequency, with cutoff at $\omega_p(1\text{-}M^2)^{1/2}$, M= u/v_T ~1/3. Note two critical points: at the plasma frequency, to the waves radiated downstream belongs a wide spectrum of wave vectors, the situation reminiscent of that at conical refraction (Born & Wolf, 1959), and for allowed lower frequencies a point exists where two waves coalesce, the wave normal is at right angle to the group velocity, as on the resonance cone in magnetized plasmas. It is also a boundary between backward (obtuse angle between the wave vector and group velocity) and forward (acute angle between these two vectors) waves.

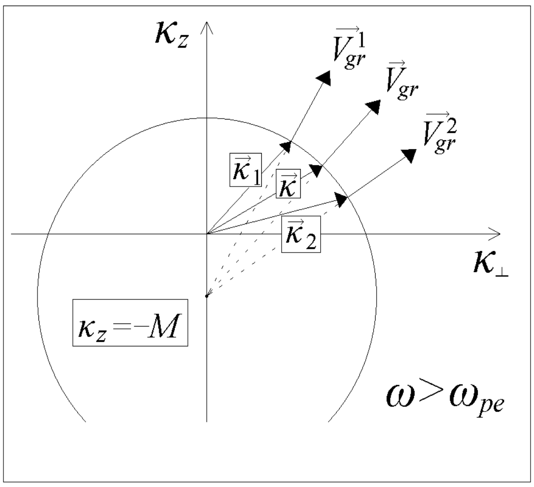

Fig. 1 Wave number surface above the resonance

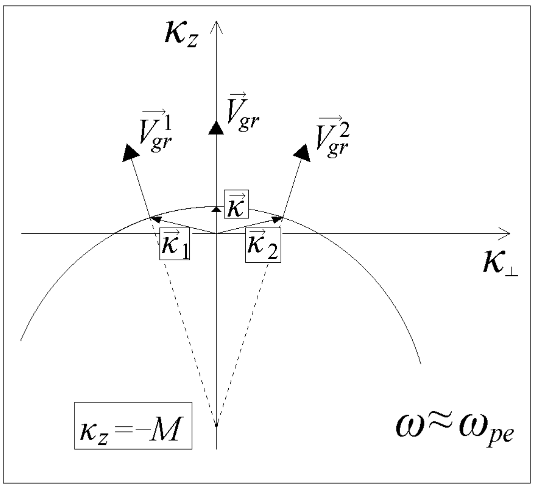

Fig. 2 Wave number surface very close to the resonance

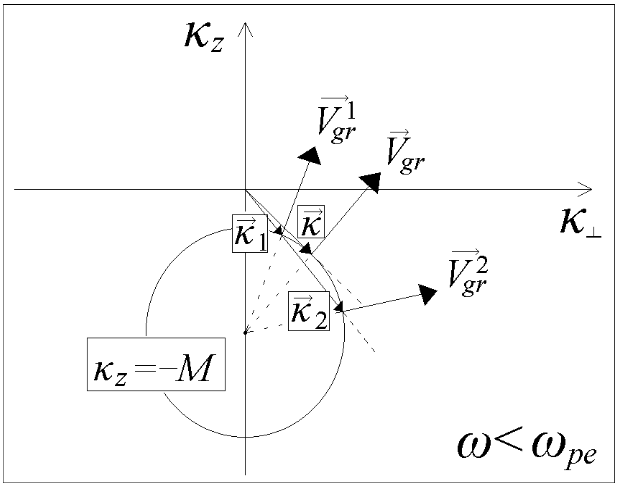

Fig.3. Wave number surface below the resonance

The waves corresponding to these two critical points contribute strongly to the antenna response to the received waves, which is manifest by the growth of its effective length.

The next two figures 4 and 5 show the effective length computed from the above formula (1) as a function of frequency at the vicinity of the plasma resonance at 31 kHz, with M=1/3, so that the cutoff is at 29.4 kHz. Here we keep the antenna orientation fixed in space, but the angles of the incident signal are presented as a parameter. The growth of the effective length by more than an order of magnitude is apparent close to the plasma frequency. The geometrical length of the double sphere dipole is 44 m. We do not show here how the curves connect at the resonance, as there the antenna finite aperture comes into play. This depends on the angle at which the receiving antenna is seen from the source of incoming waves, which is not known in the present situation. The different curves correspond to different angles of arrival of the quasi-harmonic waves.

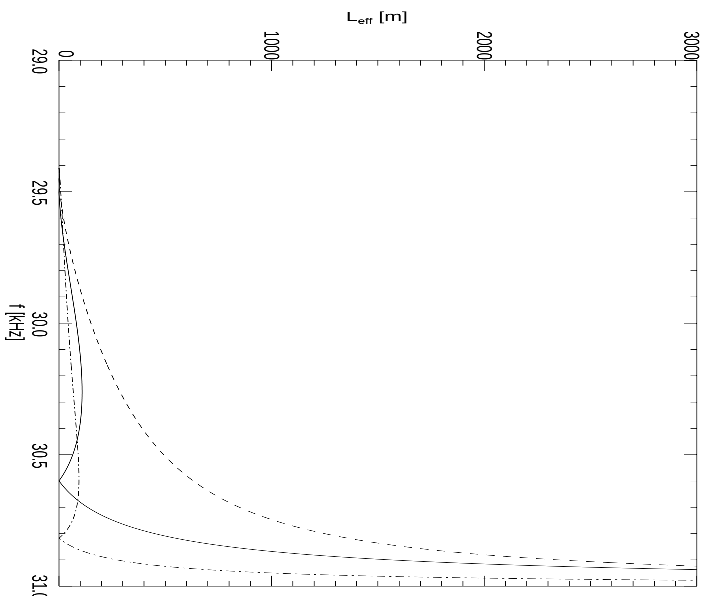

Fig. 4 Effective length below the resonance

The full line in the fig.4 (frequencies below the plasma resonance) tracks the directions given by the point on the wave number surface, cf. fig.3, where two waves coalesce , the wave group velocity is perpendicular to the phase velocity. The dashed line, ---, shows the backward waves (obtuse angle between phase and group velocity) coming at a smaller angle of arrival, the dot-dashed -.-.- line represents the forward waves coming with greater angles of arrival . These angles depend on plasma frequency, cf. wave number surfaces below the plasma resonance. Above the plasma frequency, in the fig. 5, the angles of arrival remain fixed, --- line is for waves coming under a small angle downstream, -.-.- is for a greater angle and that with -…-…- for waves propagating under a small angle upstream. All these waves are forward waves (acute angle between the phase and group velocity). The full line at the bottom of the figure is traced for the case of non-streaming plasma, for comparison.

The figures show convincingly that a quasi-harmonic wave coming downstream with a frequency very close to the local plasma resonance is registered at the receiver by a strongly enhanced voltage. This finding is being used for interpretation of wave observations in a streaming plasma of the solar wind performed in space projects.

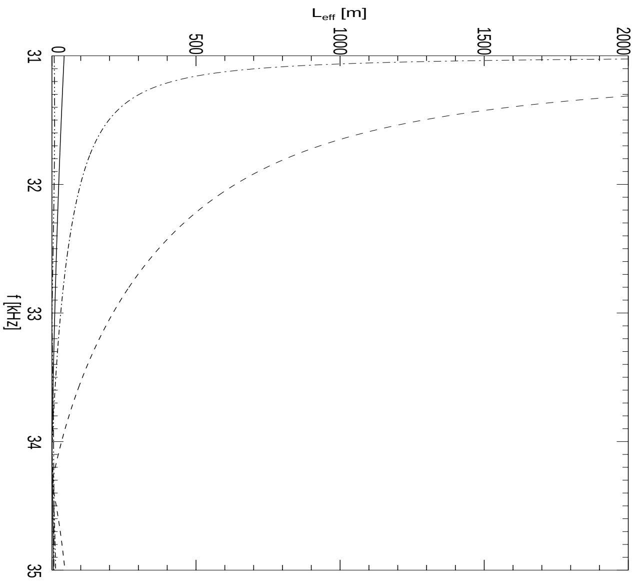

Fig.5 Effective length above the resonance

In general we may conclude that the growth of the antenna effective length by more than an order of magnitude under resonance conditions must be taken into account in interpretations of observations of quasi-harmonic waves coming from a distant source., or in any other case of reception of waves in such circumstances.

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