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LETTERS TO THE EDITORS

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On the existence and physical meaning of the Zenneck wave

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Abstract. The physical meaning of the Zenneck wave is discussed. It is pointed out that the full spectra of the modal basis functions that we know to exist do not feature such a wave. Aspects concerning setup requirements for proof-of-concept experiments are addressed.

The recently published letter [1] to the *Uspekhi Fizicheskikh Nauk* (*Phys. Usp.*) claims, as did the communication [2] published earlier, that their authors did observe a Zenneck wave above the air–water (this last part is essential) interface.

The following aspects can and must be considered to justify calling this claim into question, as will be shown below.

The Zenneck wave is a rapid surface wave in a longitudinally *infinite* waveguide. The history of the subject of how to excite this wave is generally known (see Refs [1, 3]), so there is no need to spend much time on it. We will point out nevertheless – as an unassailable experimental fact – that so far this wave has never and in no way manifested itself directly or indirectly in the process of the practical mastering of still higher and higher frequencies in the spectrum of electromagnetic waves, even though in the last century this process was extremely intense, and special attempts, even if unsuccessful, were in fact made to excite and detect the Zenneck wave [3, 4]. Quite the opposite is true: all the effects that have been explained or for which various physical applications have been found [3] concerned and still concern the real existence of only waves in open waveguides such as the *slow* surface wave (proper wave of an open waveguide, the wave of its discrete spectrum) or the leaky wave (rapid improper wave of an open waveguide). Nature has shown indifference as to how one chooses the methods to solve the relevant problems in which the Zenneck wave surfaced but then disappeared and so forth, or to numerous discussions of this issue, so that, for instance, A Oliner [3] chose to characterize the issue of whether the Zenneck wave could be excited as esoteric.

Consequently, the claim by the authors of Refs [1, 2] that Zenneck waves were observed conflicts with practical observations of most other researchers and thus needs special attention.

Returning again to the possibility of exciting the Zenneck wave, the authors of Refs [1, 2] are perfectly right in stating that theoreticians have no unified point of view on this issue. If we ignore various finer points in the opinions of experts, we can briefly state this.

The prevalent point of view [3, 5] (we shall refer to it as 'standard') is the opinion that *actual* antennas cannot excite such a wave. As a rule, people mean by this that apertures of real antennas are too small to excite the Zenneck wave whose structure is not very different from that of an ordinary plane wave sliding along the surface of a waveguide. At the same time, it is assumed that the physical meaning of the Zenneck wave itself is a waveguide wave of an open waveguide. In other words, its structure is such that the underlying surface, having certain characteristics of impedance, is capable of channeling this wave along itself regardless of any characteristics of real sources. However, there exists another standpoint that we fully share.

This point of view has been presented several times in the literature and is also quoted in paper [1]. The point is that by virtue of the representation of field by the Sommerfeld integral taken over branching integration contours, the rapid surface wave is never separated out of the integral in the form of a residue of the integrand, when the initial contour of integration is deformed and changes into a saddle one. This argument was used by J R Wait [6] in his discussion with G Barlow (who defended the standard viewpoint) when he hypothesized that the Zenneck wave should be eliminated from the spectrum of normal waves of the open waveguide because its slowing down coefficient is less than unity. In other words, even though this wave satisfies the ordinary boundary condition on transverse infinity, its field structure is such that it cannot be classified as a waveguide wave regardless of any characteristics of the sources. These arguments were later strengthened and expanded in our publications [7–10], where we pointed to the existence of basis functions (which include complex Fresnel integrals) whose spectrum is *a priori* free of such waves of open waveguides as rapid proper and slow improper waves. [1]

It thus follows from the above that the experiment staged by V N Datsko and coworkers [1, 2] seems to confirm the standard viewpoint [2] but rejects Wait's assumption which received proper support and was brought to a certain degree of perfection in our earlier publications [7–10], where we used

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[1] These functions are essentially analytical continuations in a parameter of the familiar analytically closed Sommerfeld solution [11] for the diffraction of a uniform plane wave by an ideally conducting half-plane. A simple generalization of the presentation of this solution that we gave in Ref. [7] makes it highly efficient in solving certain model problems of the theory of open waveguides, in which an infinitely thin waveguiding half-plane (with 'soft' boundary conditions at the facets) is an ideal object for modeling the relevant wave processes.

[2] It remains unclear how it was possible to excite a Zenneck wave using an ordinary antenna with a low aperture and achieve an amplitude sufficient for its reliable separation from the bulk wave at small distances.

independent arguments. However, it would be a big mistake to arrive at hasty conclusions here.

The authors of Refs [1, 2] believe that due to their experiment "the debate between theoreticians has been successfully concluded" [1]. Indeed, physics is an experimental science and as a consequence the requirements demanded of the setting up of a physical experiment are extremely stringent — especially when experts differ in their opinions.

Below is what we think in this regard.

If the authors of the communications [1, 2] have indeed recorded the propagation of a surface wave, not a bulk one, over the water surface, then the phase velocity of its propagation was nevertheless smaller, not greater, than the speed of light — that is, they could have recorded ordinary slow wave at very low velocity reduction but mistakenly confused it with a rapid wave. This opinion is based on the following assumptions.

Elementary calculations show that in the frequency range 0.7–6 GHz in which measurements were conducted in Refs [1, 2] at room temperature and at salt content $S = 35$ g in water (S is the total weight of solid matter in grams per kg of seawater [12]), the theoretical value of the Zenneck wave slowing down coefficient (the ratio of the real part of the longitudinal wave number of the wave to the wave number in air) runs monotonously through the interval 0.999–0.995. [3] We need to emphasize that the experiments of Refs [1, 2] were carried out over water with a salt content (35% [1, 2]) higher by an order of magnitude than that of seawater [12]. Elementary physical arguments show that conductance of seawater will continue to be directly proportional to S [12] at higher values of S for which data is not available [12]. It is therefore possible to evaluate the phase velocity of the Zenneck wave in the experimental conditions of Refs [1, 2]. We find that the phase velocity of the Zenneck wave over water that is supersaturated with salt should, all other conditions being equal, approach the speed of light even more closely (the difference is in the fourth significant figure).

According to Wait's suggestion and the above-presented interpretation, this is not a waveguide wave [4] and it cannot be excited by any type of antenna. However, the experimental setup is then in an unstable state. Even a very small perturbation of the water surface, such as tiny rippling due to microvibrations, would then be sufficient for the situation to change drastically. Rippling, which the experimenters may not have even noticed, forms a sinusoidal velocity-reducing fluting. As a result of this and due to the setup being in a nearly critical regime, a slow surface wave imitating a Zenneck wave may have formed (the higher the saturation of water with salt, the lower the level of microvibrations required for its generation); its propagation velocity is less than the speed of light by a quantity which cannot be controlled with sufficient accuracy (it appears that controlling the third or even the fourth significant figure in the centimeter range of wavelengths is impossible), so that it is easily mistaken for a Zenneck wave.

Unfortunately, we are not aware of any papers which would consider the propagation of a surface wave over a sinusoidally disturbed water surface. It is impossible, therefore, to obtain a quantitative evaluation of the effect of this sort of perturbation on the phase velocity of a surface wave. Nevertheless, the possibility of the reality of an imitation factor of this kind cannot be dismissed. Consequently, a proof-of-concept experiment needs to be conducted not over water but over a solid surface of dry land. Such experiments have been reported [4] and the results have been negative.

The discussion above can be summarized as follows.

The specific issue of the physical meaning of the Zenneck wave is profoundly tied to the general aspects of the theory of propagation of electromagnetic waves. For this reason, we have to treat with caution any claim that rapid surface waves have been observed over a *water surface* and to check that they meet stringent requirements as to accuracy and suppression of imitation factors. Moreover, we should wait, as always in such cases, for confirmation of the observation of the Zenneck wave in independent experiments over a *rigid underlying surface*.

[3] The data required for this evaluation on seawater bulk conductance as a function of salt content and temperature can be found in the book [12].

[4] The field of this wave can, however, be regarded as the field of a nonuniform plane wave which is incident on the above-mentioned interface between two media at a certain angle chosen in such a way that the wave is not reflected from the surface (imaginary Brewster's angle). It is easy to show that the condition of the reflection coefficient of this wave from the surface being zero is identical to the 'dispersion equation' for the Zenneck wave. This interpretation of the physical meaning of the Zenneck wave is perfectly legitimate. Furthermore, the *near-field zone* of any antenna contains a spectrum of nonuniform plane waves and, therefore, this spectrum contains a wave with a suitable wavenumber. The presence of such a wave in the near-field zone of a dipole agrees with the fact of separation of the Zenneck wave contribution to the general field of the emitter in the vicinity of the underlying surface — but only within Sommerfeld's 'numerical distance' [13], which has no relation to the excitation of a wave directed by an open waveguide.

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