V. I. Baĭbakov, V. N. Datsko, and Yu. V. Kistovich. Experimental discovery of Zenneck's surface electromagnetic waves. In the classical experiments of H. Hertz the hundredth anniversary of which is being celebrated now, electromagnetic waves were observed propagating in free space. The results of these experiments soon won worldwide fame and acceptance. The history of investigating surface electromagnetic waves (SEW) unfolded not in this straightforward, but in a truly dramatic manner.

1. In 1899, A. Sommerfeld examined the problem of an axial current in a long straight wire and obtained solutions of the Maxwell equations whose amplitude falls off rapidly with distance from the surface of the wire. These solutions were interpreted by him as SEW, possibly by analogy with the surface acoustic waves of Reyleigh. In 1901, G. Marconi realized radio transmission across the Atlantic Ocean at a frequency of 30 kHz in connection with which it was supposed that in his experiments a new type of radio wave— a surface wave (SW) was excited. In 1907, J. Zenneck showed thar Maxwell's equations with appropriate boundary conditions admit a solution which can be termed a surface wave. The disperion relation for SW propagating along the boundary between media with dielectric permetivities ε and ε_0 is of the form

$$k^2 = k_0^2 \frac{\varepsilon_0 \varepsilon}{\varepsilon_0 + \varepsilon},$$

where $k_0 = \omega/c$, k and ω are the propagation vector and the frequency of the wave, and c is the velocity of light in vacuum.

The wave is "tied" to the surface, its phase velocity is somewhat higher than the velocity of light in vacuum and depends on the properties of the substrate. Zenneck considered that the field of a real radiator at great distances from it will be of the form of the wave found by him. But from his work it only follows that the SW can exist, but the field is not in any way associated with the antenna, i.e., the principal essence of the problem of the radiation has not been established.

2. The problem of excitation of the electromagnetic (EM) field by a vertical dipole situated above a flat conducting surface is the classical problem of radio physics. It was first examined in 1909 by A. Sommerfeld who found that in the radiation of the dipole both bulk EM waves and SW are present. He considered that at great distances from the source the Zenneck SW wave predominates, and thus he had established the connection SW with the source of radiation. The concept of the Zenneck SW supported by the authority of Sommerfeld for a long time was almost generally accepted. But beginning with 1919 in the papers by Wehl, Van der Pol, V. A. Fock and others this conclusion was disputed and acknowledged to be erroneous. Efforts to excite Zenneck's SW under natural conditions above the surface of land, fresh and sea water also ended unsuccessfully. One of such efforts was the large-scale experiment carried out in 1934–1941 in our country directed by Academicians L. I. Mandel' shtam and N. D. Papaleksi. Since then the opinion has become firmly established in Soviet radio physics that excitation of Zenneck's SW by real radiators is impossible and that the very concept of a surface wave is erroneous. This opinion has been included in textbooks on radio physics and is predominant today.

3. However, in recent years SEW have been observed experimentally in different laboratories of the world. According to present-day theoretical concepts two cases are possible:

a) $\varepsilon < 0$ is a real quantity, and then so-called Fano waves exist at the boundary with a phase velocity $v < c$ observed in a gas-discharge plasma (surface plasmons) and in semiconductors and metals. At the present time they are being actively investigated and are used in the spectroscopy of surfaces.

b) $\varepsilon = \varepsilon' + i\varepsilon''$ is a complex quantity, $\varepsilon'' > 0$. At the separation boundary a Zenneck wave arises with phase velocity $v > c$. Prior to our work of 1980–1982 the Zenneck wave had not been experimentally observed.

4. Any real source of an EM field situated at the separation boundary between two media excites both surface and bulk waves and their separation turns out to be a complicated experimental problem. In our experiments the Zenneck SW was observed under laboratory conditions on the surface of water of different salinity (mostly of 35%) in the frequency of 0.7–6 GHz. Methods were developed of exciting and investigating standing and traveling surface waves.

In the traveling wave regime using a radiator of special construction we succeeded in "tearing away" the bulk radiation from the surface and to direct it upwards at large angles to the horizon, thereby freeing the SW from the admixture of the bulk field. In the radiation from such a source situated above the surface of water the presence of a wave was recorded which propagated along the surface, whose amplitude falls off with the distance to the radiator as $1/\rho^{1/2}$, which corresponds to the divergence of the SW. Measurements of the vertical structure of the field in this wave showed that the field falls off exponentially with distance from the surface. The measured dependence of the height of localization on the frequency and on the salinity of the water turned out to be in good agreement with theoretical calculations. Moreover transformation of the SW into bulk radiation on inhomogeneities of the wave-guiding surface was observed. In the standing wave regime the Zenneck SW was excited in a rectangular resonator under the conditions of its dimensional resonance. In the course of this an unambiguous separation of the SW from the bulk waves was realized and its vertical phase-amplitude structure was measured which turned out to be in complete agreement with theory. In addition the frequency dependence of the damping of the SW was measured and also the dependence of the phase velocity on the value of the surface impedence of the water.

5. An analysis was carried out of the results of the singlė experiment known to us (Hansen, USA, 1974) on the propagation of EM waves of decameter range (5–30 MHz), excited by special antennas over the ocean surface along a trajectory 237 km in length. In contrast to Hansen who found an inexplicable anomaly in the propagation of the EM field we have reached the conclusion that in his experiment a mixture of bulk and surface waves was excited, with the trajectory itself "choosing" the less damped waves. We have shown that at frequencies below a certain critical frequency which depends on the salinity (15 MHz in Hansen's case), the Zenneck SW is damped considerably less than the "terrestrial beam." Consequently at a frequency above 15 MHz the propagation of the EM field was due to the "terrestrial beam," while at frequencies below 15 MHz it was due to the Zenneck SW, and this explains the anomaly. The data on the relative damping of the SW obtained from Hansen's work agrees well with the results of our own laboratory measurements.

6. The existence of the Zenneck SW was for a long time disputed primarily because of the absence of experimental data. The observation of SW under natural conditions requires specific means and methods of measurement, which must be developed beforehand in the laboratory, where the excitation and identification of this wave does not present special difficulties. At the present time the existence of the Zenneck SW has been demonstrated by direct experiments, and therefore it is necessary to reexamine the outdated opinions and to embark on investigations, particularly under natural conditions over the sea surface, with the aim of developing new channels of radio communication and new radar methods.

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