# Observation of Zenneck-type waves in microwave propagation experiments

**Article** *in* Journal of Applied Physics · August 2006

DOI: 10.1063/1.2212307 · Source: IEEE Xplore



**9 authors**, including:

Roberto Mignani
Università Degli Studi Roma Tre


Rocco Ruggeri
Italian National Research Council


F. Cardone
Italian National Research Council


Alessandro Agresti
University of Florence

JOURNAL OF APPLIED PHYSICS **100**, 024910 (2006)

# Observation of Zenneck-type waves in microwave propagation experiments

A. Ranfagni, P. Fabeni, and G. P. Pazzi
*Istituto di Fisica Applicata "Nello Carrara," Consiglio Nazionale delle Ricerche, Via Madonna del Piano 10, 50019 Sesto Fiorentino, Italy*

A. M. Ricci and R. Trinci
*Istituto per le Telecomunicazioni e l'Elettronica della Marina Militare "Giancarlo Vallauri" (Mariteleradar), Viale Italia 72, 57100 Livorno, Italy*

R. Mignani
*Dipartimento di Fisica "Edoardo Amaldi," Universitá degli Studi di Roma "Roma Tre," Via della Vasca Navale 84, 00146 Roma, Italy and INFN, Sezione di Roma III, Via della Vasca Navale 84, 00146 Roma, Italy*

R. Ruggeri[a)]
*Istituto dei Sistemi Complessi, Consiglio Nazionale delle Ricerche, Sezione di Firenze, Firenze, Italy*

F. Cardone
*Istituto per lo Studio dei Materiali Nanostrutturati, Consiglio Nazionale delle Ricerche, Via dei Taurini 6, 00185 Roma, Italy*

A. Agresti
*Dipartimento di Fisica dell'Università di Firenze, Firenze, Italy*

(Received 6 March 2006; accepted 5 May 2006; published online 24 July 2006)

The debated question of the superluminal speed of information remains open to different interpretations in spite of recent, apparently conclusive, contributions. A different point of view is here considered, which is based on experimental results of microwave propagation experiments, in far-field conditions. They support the hypothesis of the existence of fast waves of the Zenneck type. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2212307]

## I. INTRODUCTION

Superluminal motions (that is, motions at velocities greater than light velocity $c$ in vacuum) of wave packets and photons have been extensively demonstrated in a variety of situations. However, the question as to whether a wave packet can be considered a signal is much debated and still remains an open question, even in the light of recent contributions,[1,2] which will be here briefly discussed. For the purpose of reinforcing a different point of view on the above said question, much more attention will be here devoted to results of microwave propagation experiments. They concern the direct observation of superluminality in far-field conditions, even if far and near fields are not separable by a sharp frontier.

An answer to the above question was attempted in Ref. 1 with a propagation experiment in a birefringent optical fiber. The results obtained showed that, while the group velocity can indeed exceed the light velocity in the fiber, the signal velocity—identified by the delay of a sharp front—remains constant and equal to $c/n_f$, $n_f$ being the refractive index of the fiber. However, some questions arise as for the meaning to be attributed to these results. In fact, the sharp leading edge, the position of which is indeed practically independent of the pulse attenuation and group delay, has a relative amplitude $r$, i.e., the ratio of the sharp front to the total pulse amplitude (magnified by the logarithmic scale), which is only a small percentage and is comparable with the noise level.

Similar arguments can also be adduced for the results reported in Ref. 2 dealing with a propagation experiment in a "fast-light" optical medium, in which a point of nonanalyticity was introduced on the top of Gaussian pulses for the purpose of realizing the conditions required for having a signal. However, because of limited spectral extension, the transition involved was quite smooth, so that its actual beginning was rather uncertain, making the proof not at all convincing.[3]

For the sake of completeness, we wish to mention that an attempt to solve this question was also made[4] by a computer simulation in order to obtain the rise front of the pulse at the output of an undersized waveguide operating below the cutoff frequency. The result was that, while the complete profile of the pulse showed an evident superluminality, the true initial part remained confined within the luminal limit for an amount of $r$ of only a few percent (say, 1%–2%). Therefore, even in the light of this result, the ever-present noise effects made the proof inconclusive since any conceivable delay measurement to be performed at an $r$ value sufficiently above the noise level (depending also on the sensitivity of the detector) will always give a superluminal result (see Fig. 1), although the instant of detection of the advanced pulse is evidently delayed. This fact induced the authors of Ref. 5, on the basis of an unusual operational procedure of delay measurement, to conclude that the noise effect is that of limiting the signal velocity to values less than $c$.

[a)]Electronic mail: rocco.ruggeri@isc.cnr.it

 

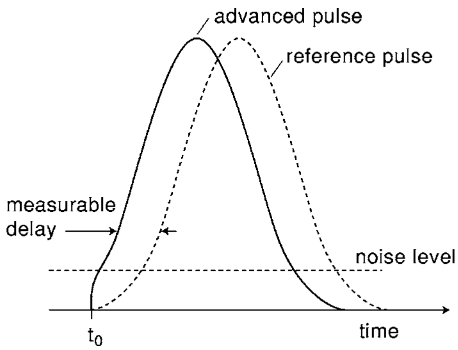


FIG. 1. Sketch of the measurable delay above the noise between the advanced and reference pulse; $t_0=R/c$, where $R$ is the traveled distance.

We wish to recall that according to standard methods,[6] the propagation of a pulse can be described by a contour integral in the complex plane of frequencies. By extending the integration domain to infinity, the forerunner of the signal cannot arrive before a time $t_0=R/c$, where $R$ is the traveled distance. However, by considering a finite spectral extension (in accordance with the physical evidence), the result obtained was that "something" can arrive earlier, at a time $t \leq R/c$.[7]

Tunneling and, more generally, situations in which dispersion is present (as in the cases before considered) are characterized by different velocities, namely, those related to phase, group, and signal propagations. The cases in which the dispersion is absent, or negligible, are different.[8] There, all the components in the spectral extension have the same propagation velocity, and the above-mentioned velocities tend to be coincident. The results obtained (usually for the group velocity) could, presumably, thus be extended to the signal one, even if some caution is required since—as it is evident—the definition of "signal velocity" is not universally shared.[9]

The works quoted in Ref. 8 concern open-air microwave propagation experiments, most of them employing horn antennas operating at different frequencies in the range of 1–10 GHz. The result was that, in all the considered cases, the superluminal behavior was evident in the so-called near field which, according to a selected near-field criterion, is given by $R=2d^2/\lambda$, $R$ being the distance, $d$ the width of the antenna aperture, and $\lambda$ the wavelength.[10]For a given distance, with increasing wavelength, we tend to enter the far-field region, thus confirming the nature of the observed facts (peculiar of the near field). However, if $R$ is maintained constant, the effect does not disappear with increasing $\lambda$, thus leaving open the problem to the possibility of observing superluminal behavior even beyond the near-field limit. The cases till now considered imply that (strong) superluminal effects can be revealed over moderate distances. In the case of tunneling these are typically of the order of some wavelengths, arriving for the cases of Ref. 8 to tens of wavelengths, that is, the order of magnitude of $R$ is that of one or few meters (near-field limit). The question as to whether it is possible to extend these effects over larger distances, let us say over tens or hundreds of meters (still maintaining the same range of frequencies), naturally arises.[11] In Sec. II we present an analysis of the Zennek-type waves, considered as suitable to produce superluminal effects. Section III is devoted to report the results of a microwave propagation experiment and their interpretation on the basis of the model of Sec. II.

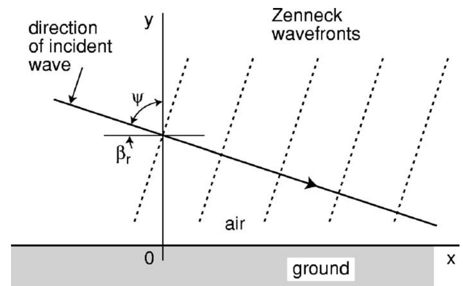


FIG. 2. Zenneck wave incident on a flat surface, after Ref. 15.

## II. ZENNECK WAVES

The possibility of observing superluminal behavior over large distances was theoretically anticipated in Ref. 12 dealing with a plausible extension of this kind of investigation to the domain of radio frequencies (in this case the range of $R$ should be enormously augmented), under the hypothesis that Zenneck waves (a type of fast waves) are generated.[13] These waves, as particular solutions of Maxwell's equations, travel without change of pattern over a flat surface bounding two homogeneous media of different conductivities and permittivities. They are inhomogeneous plane waves because the field decays exponentially over the wave front with increase of distance from the surface.[14] For a system consisting of a launcher antenna with vertical polarization, placed over a flat ground with finite losses, the wave fronts are not perpendicular to the ground plane, and their inclination produces an increase of the propagation velocity along the ground-air interface (see Fig. 2). In general this wave gives rise to both a reflected and a transmitted wave entering the ground plane. For a critical value of the incidence angle (the Brewster angle), there is no reflected wave. This condition, required for a pure Zenneck wave, is verified when, by denoting by $\psi$ the angle of incidence (with respect to the vertical of the ground) and by $\chi$ its imaginary part, we have

$$\tan(\psi - i\chi) = \sqrt{\kappa_r - im}, \qquad (1)$$

where $\kappa_r=\kappa_1/\kappa_0$ is the relative permittivity of the ground with respect to air and $m=\sigma_1/\omega\kappa_0$, $\sigma_1$ being the conductivity of the ground and $\omega=2\pi\nu$ the angular frequency of the wave.[15]

The locus of the Zenneck-wave pole, that is Eq. (1), is represented in the $(\psi,\chi)$ plane of Fig. 3, for different values of $\kappa_r$. In each curve, parameter $m$ varies from smaller values (on the left) to infinity when the curves tend asymptotically to the straight line crossing the abscissae at $\psi=90°$. The latter represents the tangent to the steepest-descent path for an angle of observation of 90° that is, that of an observer staying over the earth plane. The Zenneck pole is always situated beyond; therefore, it is never captured by the path deformation, since the Zenneck pole corresponds to $\psi$ values less than 90°; that is, the corresponding ray is penetrating the

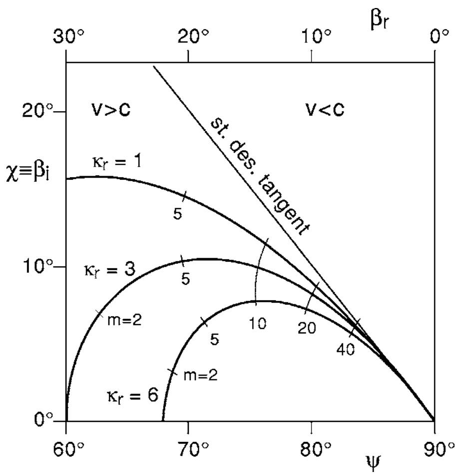


FIG. 3. Loci of the Zenneck-wave pole in the $(\psi,\chi)$ plane for different values of the relative permittivity $\kappa_r$ as a function of the parameter $m$, after Ref. 12. When $m\to\infty$, the curves tends asymptotically to the steepest-descent path, but they are always situated on the $v>c$ side. The scale of the incidence angle $-\beta_r$ is also shown.

ground or, if we prefer, the incidence angle is negative ($-\beta_r$ in Fig. 2). It, however, contributes in the steepest-descent representation as a correction term which is significant if the pole is not too far from the steepest-descent path. The evaluation of this contribution can be made, according to the diffraction theory, along the lines of the analysis reported in Ref. 16. For a pole situated at the angle $\beta=\beta_r+i\beta_i$ in the complex $z$ plane of Fig. 3, we operate the change of variable from $z$ to $s$ according to the relation

$$s^2=-i(1-\cos\beta), \quad (2)$$

where we have to put

$$\cos\beta=\cos\beta_r\cosh\beta_i-i\sin\beta_r\sinh\beta_i. \quad (3)$$

Clearly, if the pole would be situated exactly on the steepest-descent path, which satisfies the condition $\cos\beta_r\cosh\beta_i=1$, $s^2$ turns out to be positive and $s$ real measures of the displacement from the saddle point situated in the origin; otherwise, $s$ is complex and according to the nomenclature of Ref. 16 is named $s\equiv b=b_r+ib_i$. The amplitude relative to the pole contribution results are given, apart from a multiplicative constant, by the function $w(z)$, where the quantity $z$ in the argument is given by $z_b=b\sqrt{2\pi R/\lambda}$, where $\lambda$ is wavelength. The function $w(z)$ is given in Ref. 17; however, when the argument is sufficiently large, say, $|z_b|\gtrsim 3$, its absolute value can be evaluated according to the simplified expression

$$|w(z)|\simeq\frac{1}{\sqrt{\pi}|z_b|}. \quad (4)$$

Under the assumption that $\epsilon=(1+\kappa_r)/2m\ll 1$, relation (1) can be simplified as $\beta\equiv\beta_r+i\beta_i\simeq[(1+\epsilon)+i(1-\epsilon)]/\sqrt{2m}$, where $-\beta_r=\psi-90°$ is the incidence angle (with respect to the ground plane) and the imaginary part $\beta_i\equiv\chi$. For a frequency $\nu\simeq 10$ GHz, we have $m\simeq 2\sigma_1$; assuming for $\sigma_1$ a plausible value of the order of 10 mhos/m and $\kappa_r=6$,[18] it turns out that $\beta_r=10.6°$ and $\beta_i=7.4°$. With these values, the effect over the observed propagation velocity $v=c/(\cos\beta_r\times\cosh\beta_i)$, given by $\Delta v/c=v/c-1\simeq 10^{-2}$,[12] is modest but observable provided that the range $R$ of propagation is sufficiently large; for $R=100$ m we should have $\Delta\tau=10^{-2}R/c\simeq 3$ ns of time advance with respect to the luminal delay. It seems therefore conceivable to perform an experimental test on this effect.

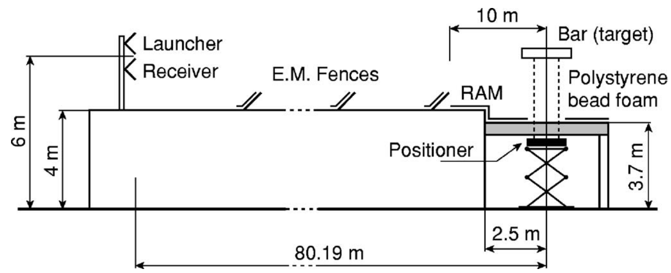


FIG. 4. Scheme of the adopted experimental setup for microwave propagation.

## III. EXPERIMENTS

The geometry of the experimental setup is sketched in Fig. 4. Two identical horn antennas (Flam & Russel model 6414), one as a launcher and the other as a receiver (a radar system), were mounted side by side to achieve vertical polarization in a quasimonostatic configuration. They were positioned at a height of about 2 m over a metallized (sputtered zinc) surface plane having a keyhole shape formed by a circle (20 m in diameter) and a rectangle (60 m longer side). The metallized surface, 4 m high above ground level, at the wavelengths of the experiment was considered as specular (not diffusive). The target, a rectangular-section steel rod 6 m long and with a cross section of $6\times 3$ cm$^2$ (thickness of 2 mm), was positioned, shorter side, over a Styrofoam pylon [almost transparent to electromagnetic (e.m.) waves in the band of the experiment] whose azimuthal angle was controllable by an Orbit positioner. The height of the pylon (and consequently the height of the rod) was adjustable with respect to the fixed height of the antennas. The rod during the experiment was positioned transversally with respect to the line of sight of radar antennas and its signal maximized through fine adjustments of its azimuthal position. The distance of antennas-center of pylon was about 80 m. A pulsed (high pulse repetition frequency) radar employing a frequency modulated continuous wave stepped (FMCWS) system, with power boosted by a solid state amplifier, was used to transmit and receive a series of short (100 ns was selected) and spectrally pure electromagnetic impulses, "wave packets," equally spaced by 9375 kHz at 800 individual different frequencies covering the experiment band: 7.5–15 GHz. This band permitted us to achieve, in the down-range coordinate, a synthetic pulse having a theoretical spatial resolution of about 4 cm in a range ambiguity window of 16 m in extent. The receiver was physically range gated on the target, having introduced a pulse delay of 535 ns (80.19 m), and opened for about 100 ns (about 15 m) to remove alias signals and clutter falling in the selected temporal window. To further reduce spurious signals and clutter in the temporal window a software gate was opened around the rod. To minimize the influence of the "multipath" (four paths) due to e.m. energy reflecting on the plane surface and interfering with

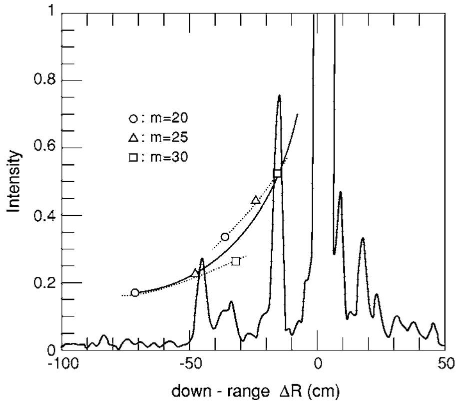


FIG. 5. A 1D radar image obtained in an outdoor test range according to the experimental setup whose geometry is sketched in Fig. 3. In addition to the main specular reflection peak, others anticipated and delayed secondary peaks exist with intensity of the order of $10^{-3}$ with respect to the specular one. The anticipating peaks, in the range of $\Delta R \simeq -0.5$ m, are interpreted to be due to a Zenneck-type wave (see Table I), whose intensity (in arbitrary units) is described by the overimposed curve. Dotted curves link data relative to one-way (upper data) and double-way (lower data) traveling waves.

the direct ray, a certain number of "electromagnetic traps" (fences) and radar absorbing material (RAM) were strategically positioned along the antennas-rod path. Multipath caused by refraction/diffusion onto overlooking atmospheric layers was considered negligible, taking into consideration experiment geometry. Received echoes, conveniently processed, allowed the reconstruction, in the time domain, of a spatially resolved one-dimensional (1D) (down-range) radar image. A 1D radar image is shown in Fig. 5 where the $x$ axis has been converted into a spatial scale. We note that, in addition to the main energetic signal positioned at $\Delta R = 0$ and corresponding to the (direct) specular reflection, others exist. They are complex signals having relative magnitudes of about 27–35 dB lower than the absolute maximum corresponding to the (direct) specular one. Some of them anticipate the specular reflection and are in the range of distance $\Delta R \simeq -0.5$ m or $\Delta\tau \simeq -3.3$ ns, ignoring, for the moment, their relative intensities and exact positions.

As far as the origin of these secondary complex signals are concerned, the following effects have been analyzed and cannot be considered as their causes: (i) isolation between antennas, (ii) finite spectral extent of the total band (7.5 GHz), number of emitted frequencies (800) and their physical duration (100 ns), (iii) sidelobes of the antennas, (iv) multipath effects, (v) secondary lobes of filter gates, (vi) atmospheric absortion-emission-diffusion.[19] In Table I, the results of an analysis performed according to the computational model for the Zenneck wave of Sec. II are summarized. The computations have been made for some values of the parameter $m$ and for two values of $R$, namely, 80 and 160 m, depending on the fact that the Zenneck wave is considered to operate only on one way between launcher and target, or on a double way including the return to the receiver. By the evaluation of $\Delta v/c$, we determine the time anticipation $\Delta\tau$ and the corresponding spatial position $\Delta R$. Then, by means of Eq. (4), we find the wave amplitude as proportional to $|w(z_b)|$ and, finally, the wave intensity $I \propto |w(z_b)|^2$ as reported in the last column of Table I, once this has been normalized to a given value: the amplitude corresponding to $|z_b| = 25.7$ has been selected for convenience of representation. The results obtained are reported in Fig. 5 where they are approximately described by a single average curve, even if for each value of $m$ we should have slightly different curves. From an inspection of Fig. 5, we note that the value of $m = 20$, as first estimated in Sec. II is not suitable to fit the main secondary peaks of intensity as shown in Fig. 5. Values of $m$ slightly augmented, that is, $m = 25-30$, are required for a best fitting of the two main secondary peaks, the principal of which, at $\Delta R = -16$ cm, is attributed to a single-way traveling wave, while the minor one, at $\Delta R = -48$ cm, is attributed to a double-way traveling wave.

TABLE I. Parameter values for evaluating the variation of position $\Delta R$ and the intensity $I$ for one-way and double-way traveling Zenneck waves.

| $m$ ($k_r = 6$) | $\beta_r$ (deg) | $\beta_i$ (deg) | $R$ (m) | $\Delta v/c$ ($10^{-3}$) | $-\Delta\tau$ (ns) | $-\Delta R$ (cm) | $\lvert z_b \rvert$ | $\lvert w(z_b) \rvert$ ($10^{-3}$) | $I$ ($10^{-3}$) |
|---|---|---|---|---|---|---|---|---|---|
| 20 | 10.60 | 7.45 | 80 | 9 | 2.43 | 36 | 20.6 | 27.4 | 34.2 |
| ⋯ | ⋯ | ⋯ | 160 | ⋯ | 4.85 | 72 | 29.2 | 19.3 | 17.0 |
| 25 | 9.22 | 6.95 | 80 | 6 | 1.61 | 24 | 18.1 | 31.2 | 44.4 |
| ⋯ | ⋯ | ⋯ | 160 | ⋯ | 3.20 | 48 | 25.7 | 21.9 | 21.9 |
| 30 | 8.25 | 6.53 | 80 | 4 | 1.07 | 16 | 16.5 | 34.2 | 53.4 |
| ⋯ | ⋯ | ⋯ | 160 | ⋯ | 2.13 | 32 | 23.4 | 24.1 | 26.5 |

Therefore, the hypothesis of the Zenneck wave for the anticipated peaks of the scattered wave appears, for the plausibility of the involved quantities, as a reasonable one. Of course, even if the condition for a pure Zenneck wave is not perfectly satisfied (in this case the reflected wave should not be totally frustrated), the required values of $m$ appear to be of the right order of magnitude. Analogously, according to the adopted geometry, the delay suffered by a reflected, not totally frustrated wave turns out to be of the same order of nanoseconds: the retarded peaks in Fig. 5 likely have this origin.[20]

The effect of a wave of Zenneck-type has to be considered as a secondary fact with respect to the ordinary wave which, naturally, propagates with velocity $v = c$. The velocity of a Zenneck-type wave (or more generally of a complex wave) is given, as said before, by $c/(\cos\beta_r \times \cosh\beta_i)$, with a small but, in this case, well evidenced superluminal behavior.

These waves are nothing but a special case of complex waves,[21] which were the basis for the interpretation of the results in Ref. 8 where the ground plane was irrelevant. This signifies that the interpretation given for the results obtained in near field is still tenable. This is an important point since it, while attenuating the possible role of the Zenneck waves, puts the interpretational key on a larger basis. In other words, the existence of Zenneck waves offers one (plausible) possibility for interpreting the observed superluminal behavior without excluding, however, that other ways could be considered ever in the framework of "anomalous" waves. The smallness [in terms of the magnitude proportional to the square of the field intensity ($E^2$) of the scattered/diffracted signal] of the revealed effect (distinctly above the noise level) is justified, given the large distance which makes the ordinary (luminal) wave decidedly dominant. However, the instrumentation, electromagnetic environment, data acquisition, and processing as the coherent integration allowed us to evidence even very small effects as those here reported.

In consideration of these results, which demonstrate the existence of signal forerunners exhibiting superluminal behavior even beyond the conventional limits of the near field, we can conclude—even independently of the possible interpretations—that the question as to whether superluminality can be extended or not to information velocity, at least in relation to the situations above described, characterized by the absence or by the presence of weak dispersion, is far from being answered definitively.


[1]N. Brunner, V. Scarani, M. Wegmüller, M. Legré, and N. Gising, Phys. Rev. Lett. **93**, 203902 (2004).
[2]A similar, but less convincing result, was reported by M. D. Stenner, D. J. Gauthier, and M. A. Neifeld, Nature (London) **425**, 695 (2003); 429 (2004).
[3]See for information W. Heitman and G. Nimtz, Phys. Lett. A **196**, 154 (1994); G. Nimtz, Nature (London) 429 (2004).
[4]M. Bini, D. Andreuccetti, R. Olmi, and N. Rubino, *Proceedings of the 11th National Meeting on Electromagnetism, Florence, 1–4 October 1996* (IROE of the Italian National Research Council, Florence, Italy, 1996), p. 717.
[5]A. Kuzmich, A. Dogariu, L. J. Wang, P. W. Milonni, and R. Y. Chiao, Phys. Rev. Lett. **86**, 3925 (2001).
[6]L. Brillouin, *Wave Propagation and Group Velocity* (Academic, New York, 1960).
[7]A. Ranfagni and D. Mugnai, Phys. Rev. E **52**, 1128 (1995).
[8]A. Ranfagni, P. Fabeni, G. P. Pazzi, and D. Mugnai, Phys. Rev. E **48**, 1453 (1993); A. Ranfagni and D. Mugnai, *ibid.* **54**, 5692 (1996); D. Mugnai, A. Ranfagni, and R. Ruggeri, Phys. Rev. Lett. **84**, 4830 (2000); Phys. Rev. E **69**, 027601 (2004).
[9]As mentioned before in relation to Refs. 1–5, this is a delicate and controversial point. See also R. L. Smith, Am. J. Phys. **38**, 978 (1970).
[10]F. Terman and J. M. Pettit, *Electronic Measurements* (McGraw-Hill, New York, 1952), p. 418.
[11]For an answer to this question see also E. Recami, Physica A **252**, 586 (1998); S. Longhi, P. Laporta, M. Belmonte, and E. Recami, Phys. Rev. E **65**, 046610 (2002).
[12]A. Ranfagni and D. Mugnai, Phys. Rev. E **58**, 6742 (1998).
[13]J. Zenneck, Ann. Phys. **23**, 846 (1907).
[14]An old long-debated question is related to the presence or not of Zenneck waves in the surface wave of broadcasting. See for information J. A. Stratton, *Electromagnetic Theory* (Mc Graw-Hill, New York, 1941), pp. 573–578.
[15]For a detailed analysis, see the classical work by H. M. Barlow and A. L. Cullen, Proc. Inst. Electr. Eng. **100**, 329 (1953).
[16]L. B. Felsen and N. Marcuvitz, *Radiation and Scattering of Waves* (Prentice-Hall, Englewood Cliffs, NJ, 1993), pp. 399–410.
[17]M. Abramowitz and I. Stegun, *Handbook of Mathematical Functions* (Dover, New York, 1970), p. 297.
[18]These values are obtainable by a partial metallization of the ground surface.
[19](i) The isolation between launcher and receiver horn antenna was measured to be higher than 60 dB for both horizontal and vertical polarizations; moreover, the radar was temporally gated in transmission and in reception. (ii) A spectral extension of $2\Delta\nu=7.5$ GHz causes a cell having a thoretical spatial resolution of 2 cm, whereas the effect of the frequency discretization gives rise to an alias free-range window of 16 m. (iii) Antenna secondary lobes are of the order of 30 dB below the main lobe maximum and are in the interval of 20°–30° off axis depending on frequency value. Even if assumed as admissible, their contributions would produce an effect of about 6%–15%, which is an order of magnitude greater than the observed one, $\sim$1%. (iv) The multipath deeply affects measurements performed close to reflective surfaces as in the Lloyd experiment. The effect is explicated as a constructive and destructive interference: affected signals will result modulated in amplitude. With the aid of the fences and RAM, the multipath was minimized. Taking into account the geometry of the experiment, the influence of the reflections caused by off-main lobe and sidelobes rays impinging on structures (fences) and over the surface plane cannot anticipate (spatially/temporally) a main lobe ray. Direct ray (main lobe) represents the shortest path distance antenna-rod-antenna. (v) Selected temporal gating window had performance close to "Blackman" type. First sidelobe level is 45 dB lower than maximum. (vi) Atmospheric absorption-diffusion-refraction can be ignored for the two-path distance geometry at the experiment frequencies.
[20]No symmetric (with respect to specular reflection) secondary delayed complex signals are evident on the graph of Fig. 5; this instead might happen if mathematical processes had polluted the data.
[21]T. Tamir and A. A. Oliner, Proc. Inst. Electr. Eng. **110**, 310 (1963). Many other contributions on this matter can be found in the literature; see, for information V. I. Baibakov and Yu. Kistovich, Sov. Phys. Tech. Phys. **27**, 846 (1982).