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# Unified interpretation of superluminal behaviors in wave propagation

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**Abstract**

By using two approaches, we demonstrate that superluminal behaviors in wave propagation can be attributed to mechanisms acting in the near-field limit. One approach is based on complex waves, while the other relies on a path-integral treatment of stochastic motion. The results of the two approaches are comparable, and suitable for interpreting the data obtained in microwave experiments; these experiments, over a wide range of distances, show a time advance which, in any case, is limited to nanoseconds.


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Superluminal propagation of wave packets (and photons) has been extensively demonstrated in a variety of situations. However, the question as to whether a wave packet can be considered as a signal has been debated for a long time, and is still open. In the cases in which dispersion is absent (or negligible), all the components of the spectral extension have the same propagation velocity; therefore, phase-, group- and signal-velocity tend to coincide. The experimental results, which usually concern the group velocity, could presumably be extended to signal velocity, although caution is needed because a univocal definition of the latter is lacking, and this remains a delicate and controversial point [1].

In the several considered cases of microwave propagation experiments [2–5], the observed time-advance of the "signal" with respect to the normal (luminal) propagation (superluminal effect), turned out to be always of the order of nanoseconds, although the length of propagation $R$ ranged between 20 cm and 80 m. This time-advance corresponds to an (apparent) shortening of $R$ of the order of at most one meter. Therefore, the space where the effect occurs is, presumably, only that of the *near field* which, for the frequency range considered (1.2–15 GHz), is just of the order of one or a few meters (also depending on the dimensions of the antennas). This fact does not prejudice the validity and the interest of the results, though it puts their relevance into a different perspective.

The interpretation of the results obtained in all the cases that we present here, is based on the existence of mechanisms which are peculiar to the near field. More specifically, we will consider a model based on complex waves, and one based on a path-integral approach to a stochastic process, which can be both traced back to similar effects. Before presenting them, let us briefly comment on the experimental results collected in Fig. 1.

A set of data refers to measurements performed at 9.5 GHz, for several values of the range (from 21 to 111 cm) separating the launcher and receiver horn antennas [2]. They clearly show that the time advance, which is about 1 ns for the shorter distances, tends to become negligible when the range becomes greater than about one meter, i.e. a value which almost coincides with the near-field limit given by $R = 2D^2/\lambda$, $D$ being the width of the antenna and $\lambda$ the wavelength [4]. Two addi-

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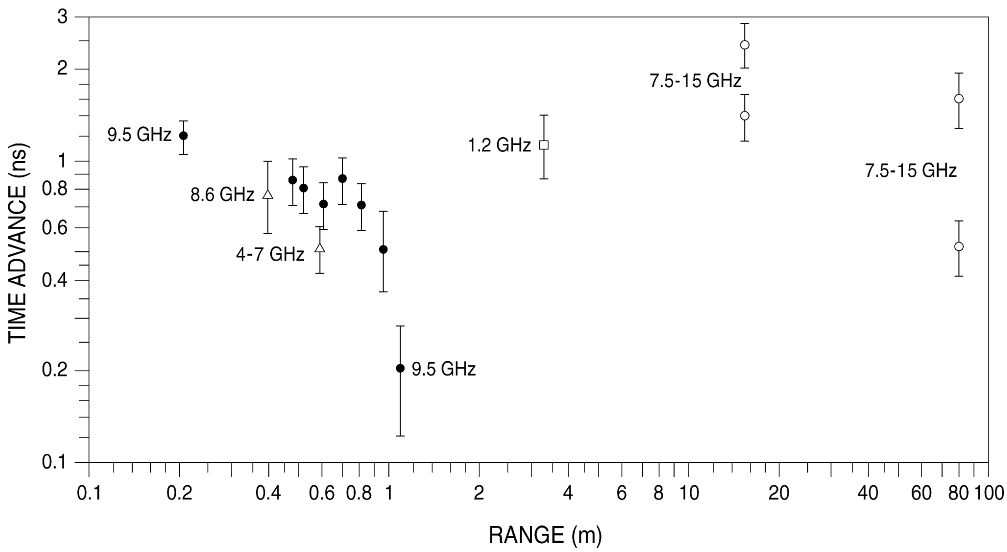


Fig. 1. Time advance data, with respective fiducial bars, with respect to luminal flight-time, as obtained in several microwave propagation experiments, performed at different range values, and at frequencies between 1.2 and 15 GHz.

tional sets of data obtained at 8.6 and 4–7 GHz, for a range of 40 and 60 cm respectively, essentially confirm this behavior [3]. A result of 1.1 ns, obtained with two big horn antennas at 1.2 GHz for a range of 340 cm, confirms the previous tendency: the time-advance became negligible when the range was increased up to 585 cm, a value appreciably larger than the near-field limit which, in this case, is estimated to be 462 cm [4].

More recently, experiments were performed by employing a much more sophisticated procedure, i.e. by a radar system [5], which allows the detection of small forerunners of the signal, even well beyond the near-field limit. The data reported in Fig. 1 for ranges of 16 and 80 m, are comparable with those relative to the much smaller range-values presented above. These results, obtained with a set of frequencies (800 values) in the 7.5–15 GHz, are obtained as the ratio of the space advances to the speed of light, i.e. $\Delta R/c$. Actually, the distances for a double-way travelling wave are twice those reported in Fig. 1, i.e. 32 and 160 m, respectively. The reason why, contrary to the previous experiments, in this case it is possible to observe the superluminal effect even in the far-field limit, will be explained later. In what follows, we will describe the two models mentioned above.

*Complex waves*. According to a detailed analysis reported in Refs. [2,4], the field radiated by the horn launcher can be expressed by a contour integral in the complex plane of the $z$ angle:

$$\int A(z)\exp\bigl[ik\rho\cos(z-\alpha)\bigr]\,dz,$$

where $A(z)$ is the amplitude, $k = 2\pi/\lambda$, $\rho$ and $\alpha$ are the polar coordinates of the observation point (the origin is put at the center of the launcher mouth). This gives rise to the sum of two distinct contributions, namely:

$$\sqrt{\frac{\lambda}{\rho}}A(\alpha)\exp\left[i\left(k\rho-\frac{\pi}{4}\right)\right]$$
$$+\,2\pi i\,\mathrm{res}\bigl[A(z\to\beta)\bigr]\exp\bigl[ik\rho\cos(\beta-\alpha)\bigr]. \tag{1}$$

The first term represents the "normal" contribution (a cylindrical wave in this case) propagating with the phase velocity $\omega/k \equiv c$. The second term, due to the presence of a pole singularity at the complex angle $\beta = \beta_r + i\beta_i$, is a complex wave with amplitude determined by $\mathrm{res}[A(z\to\beta)] = \bar{A}(\beta)$ and which, for $\beta_r - \alpha < 0$, attenuates as $\exp[k\rho\sin(\beta_r-\alpha)\sinh\beta_i]$. Its propagation velocity along a path at an angle $\alpha$ (phase-path velocity) is given by:

$$v_{pp} = \frac{c}{\cos(\beta_r-\alpha)\cosh\beta_i}, \tag{2}$$

which, depending on the position of the pole $\beta$ and on the observation angle, can be greater than the light velocity $c$. As for the relative importance of these two contributions, it is clear that for small distances, and for $\beta_i \to 0$ or $\alpha \to \beta_r$, the complex wave can prevail over the normal contribution. However, by increasing the range coordinate $\rho$, the tendency is inverted and the complex-wave contribution becomes negligible. This will happen, approximately, when we reach the conventional limit of the near field. It should be remarked that in non-dispersive situations, like the ones characterizing the experiments mentioned, relation (2) can be assumed to hold also for the group- (and presumably also for the signal-) velocity. This is the reason why by measuring the delay time of pulses in propagation experiments, for moderate distances we obtain clear evidence of superluminal behavior, while normal (luminal) delay is obtained at increasing distance.

It is remarkable that relation (2), for $\alpha = \beta_i = 0$, holds true also in the case of Bessel beams [3a], when $\beta_r$ is identified with the cone angle $\theta$ of the beam.[1] Similarly, for $\alpha = 0$, Eq. (2) pro-

[1] We wish to mention that, according to a vectorial analysis of Bessel beams [D. Mugnai, I. Mochi, Phys. Rev. E 73 (2005) 016605], the mean energy velocity turned out to be (quite surprisingly) equal to the light speed, even when the group velocity is superluminal. However, since the result was obtained in

vides the propagation velocity also for a Zenneck wave, even if in this case the time advance is attributed to the presence of a lossy ground plane acting over the complete range (80 m) of the experiment [5b]. However, the fact that comparable results were obtained when the range was limited to 16 m and in the absence of ground-plane effects [5a], suggests that the hypothesis of a Zenneck wave (which is a special case of complex wave) could again be traced back to the more general case of the complex-wave model, though operating mainly over a limited range (i.e. within the near-field limits). However, the sophisticated measurement methods adopted [5] allowed the identification of even very small forerunners of the signal, about 30 dB lower than the absolute maximum corresponding to the "luminal" contribution, when the range takes on the values of Ref. [5].

Therefore, it seems that the complex-wave model is suitable to give a unified interpretation of the observed superluminal behavior in the various considered cases of microwave propagation experiments. However, there exists also a completely different method, based on path integrals, that can be considered as capable of explaining the observed facts.

*Path-integral approach*. Along the lines of a path-integral treatment of the telegrapher's equation [6], a model for tunneling processes was derived [7] by interpreting the tunneling as a stochastic process in complex time [8]. The salient features of this analysis can be summarized as follows. The average time (duration) of the tunneling process can be expressed as

$$\langle t\rangle = \frac{1}{2a}\left[1-\cos\left(2a\frac{L}{v}\right)\right] + \frac{i}{2a}\sin\left(2a\frac{L}{v}\right), \tag{3}$$

where $a$ is the dissipative parameter entering the telegrapher's equation [6], $L$ is the traveled distance (not necessarily equivalent to the range $R$ in the experiments), and $v$ the "unperturbed" velocity. For small values of the argument $2aL/v$, Eq. (3) can be simplified as

$$\langle t\rangle \simeq a\left(\frac{L}{v}\right)^2 + i\frac{L}{v}. \tag{4}$$

This means that, in this approximation, the tunneling time is a complex quantity, whose imaginary part is nearly coincident with the semiclassical (imaginary) time, while the real part is typically a small quantity (second order in $L/v$) which can give rise to superluminal behavior. Considering near-field propagation in terms of a stochastic process (as early proposed for tunneling), is motivated by the fact that in both cases complex (or evanescent) waves are involved [9].

In the attempt of perfecting this model, still within the framework of path-integral methods, a transition-element analysis can be adopted [10]. Here we limit ourselves to summarizing the essential aspects of this approach, and the results obtained. The transition element (a sort of average) of the trajectory $\langle\tilde{x}\rangle$ can be obtained by differentiating the transition element of $\Delta S$, namely $[\exp(i\Delta S/\hbar)]\langle 1\rangle_S$, where $\Delta S$ is the variation of the action as given by dissipative effects, and $\langle 1\rangle_S$ is the propagator (see Eq. (7-68) in Ref. [10]). Expanding $[\exp(i\Delta S/\hbar)]$ in power series to first order, we have that

$$\langle\tilde{x}\rangle \simeq \bar{x}(t)\left(1+\frac{i}{\hbar}\Delta S\right)\langle 1\rangle_S, \tag{5}$$

where $\bar{x}(t)$ is the classical trajectory and the propagator can be related to the wave attenuation of the complex-wave model, that is $\langle 1\rangle_S \propto \exp[k\rho\sin(\beta_r-\alpha)\sinh\beta_i]$, when the proper substitutions are made. The equation of motion adopted is similar to that of a damped harmonic oscillator, to which our case can be traced back by taking again the telegrapher's equation as a starting point of the analysis [6,7]. In consideration of the "forbidden" character of the process (near-field propagation as a tunneling event), the analytical continuation into a complex plane needs to be considered; a continuation which can also be obtained by replacing the damping parameter $a$ with $ia$ [11]. The equation of motion then becomes (now $t$ is real)

$$\ddot{x}(t) + 2ia\dot{x}(t) + \omega^2 x(t) = 0$$

which, with the boundary conditions $x(0) = 0$ and $\dot{x}(0) = v$, has the classical solution given by

$$\bar{x}(t) = \frac{v}{\tilde{\omega}}\sin(\tilde{\omega}t)\exp(-iat),$$

where $\tilde{\omega} = (\omega^2 + a^2)^{1/2}$.

By means of a functional analysis (here omitted for brevity), it can be shown that in the limit of high values of $\omega$ the real part of the transition element of the time is given by [12]:

$$\mathrm{Re}\langle t\rangle \simeq \frac{L}{v}\left[1-\frac{a}{2\tilde{\omega}}\left(\frac{v}{c}\right)^2\cos\left(2a\frac{L}{v}\right)\right]\langle 1\rangle_S. \tag{6}$$

This result becomes comparable with the real part in Eq. (3) under the assumptions that: $L \approx v/2a$, the quantity $(a/2\tilde{\omega})(v/c)^2$ is of the order of unity, and $\langle 1\rangle_S \approx 1$. However, by identifying $v$ with $c$, the first term, $L/v$, becomes representative of the "normal" delay, while the second one, for $\cos(2aL/v) > 0$,[2] represents a time advance due to the stochastic nature of the motion, comparable to the effect of complex waves in the previous model.

The correspondence between the two models can be further evidenced by considering the phase variation in the second term of Eq. (1), with respect to the normal contribution. By recovering also the time dependence $\exp(-i\omega t)$, we have for the time advance the following relationship:

$$\Delta t = \frac{k\rho}{\omega}\big[1-\cos(\beta_r-\alpha)\big]. \tag{7}$$

By identifying $\rho$ with $L$, $\omega/k$ with $v$, and $\beta_r - \alpha$ with $2aL/v$, this is roughly comparable with Eq. (6). However, one should

the far-field approximation, it does not conflict with our interpretation, which attributes the origin of superluminality to the near field. Moreover, it should be considered that the velocity of energy transport (or ray velocity), when defined as the ratio of the pointing vector to the energy density, $v_e = \mathbf{S}/W$, does not correspond to the propagation of a real observable physical quantity, see Ref. [1a].

[2] This assumption can be satisfied for moderate values of the argument $2aL/v$. A different interpretation of Eq. (6) is given in Ref. [3b], where the dissipation is considered frequency-dependent by identifying the parameter $a$ with $\omega$.

Table 1
Measured time advances $\Delta t$ for different values of the range $R$; parameter values which fit the results: $\beta_r$, $\beta_i$, $\alpha$ according to Eq. (2) under the assumption that the mechanism producing time advance is operating over the complete range; ratio of the signal velocity to the light velocity $v_s/c$ and the quantity $A$ which represents the second term in the parenthesis of Eq. (6), by assuming $v = c$, and $\langle 1\rangle_S \approx 1$

| $R$ (m) | $\Delta t$ (ns) | $\beta_r$ (deg) | $\beta_i$ (deg) | $\alpha$ (deg) | $v_s/c$ | $A$ | Refs. |
|---|---|---|---|---|---|---|---|
| 0.72 | 0.85 | $\pm 27$ | 33.5 | $\mp 30$ | 1.55 | 0.35 | [2] |
| 0.83 | 0.70 | $\pm 11$ | 11.5 | $\mp 30$ | 1.30 | 0.23 | [2] |
| 3.40 | 1.10 | $\sim 0$ | $\sim 0$ | $\mp 25$ | 1.1 | 0.09 | [4] |
| 80 | 1.61 | 9.22 | 6.95 | 0 | 1.006 | $6\times 10^{-3}$ | [5b] |
| 80 | 0.53 | 8.25 | 6.53 | 0 | 1.004 | $4\times 10^{-3}$ | [5b] |

note that while Eq. (7) for $\beta_r - \alpha = 0$ gives a time advance $\Delta t = 0$ (in agreement with the real part of Eqs. (3) and (4), which tend to zero for $a \to 0$), for $a \to 0$ Eq. (6) tends to yield the normal delay $L/v$. Therefore, the equivalence between Eqs. (6) and (7) holds true only under the assumptions mentioned above, following Eq. (6). In other words, while Eq. (7) (and the real part in Eq. (3)) represents the time advance due to the complexity of the waves or to the stochastic character of the motion, Eq. (6) can provide a complete description of the time, where the normal delay results to be shortened by dissipative effects. Note that the normal delay in Eq. (3) is represented by the imaginary part which, for $a \to 0$, tends to give just $L/v$.[3]

On the basis of the two models discussed above, it seems appropriate to conclude that the superluminal behavior observed in microwave propagation experiments can be attributed to mechanisms operating within the limits of the near field. Similar conclusions have been reached in Ref. [1b], although on the basis of different mechanisms. The same can be said about a more recent work [13], where the evanescent modes are identified with virtual photons, and the resulting modelization is relative to the properties of frustrated total internal reflection of double prisms. The mechanisms we have considered, namely complex waves and stochastic motion, already employed for interpreting tunneling processes, proved to be capable of explaining, at least qualitatively, the observed effects in microwave propagation. A quantitative agreement can be obtained on the basis of a plausible selection of values for the involved parameters, see Table 1. These effects consist in time advances of the signal which always resulted to be of the order of one nanosecond, independently of the range of the experiment, over a wide interval of values, from less than one meter (where the effect results even greater than 100%) to about 100 meters (where the effect is less than 1%). A further extension of the range of the experiments could still show interesting aspects, but it would likely meet with increasing difficulties for detecting superluminality, which could be practically non-observable.

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