Use and Application of Precursor Waveforms

H. D. Griffiths, C.J. Baker, A. Fernandez, J.B. Davies and A.L. Cullen
University College London
Dept. Electronic and Electrical Engineering
Torrington Place, London WC1E 7JE, UK

Abstract:

In this paper we introduce the phenomenon of precursor waveforms. These are short lived Electro-Magnetic pulses such that their duration is less than that of typical values of the Debye relaxation time. This alters their propagation characteristics and potentially reduces their attenuation through dielectric materials. This is very attractive for a number of radar applications where it is an advantage to 'see-through' otherwise opaque media. Here we present the theory underlying this concept, comment on its validity and discuss the advantages and disadvantages of ensuing applications.

Keywords: Precursor waveforms, FOPEN, UWB radar

1. Introduction

Precursor waveforms are effects due to the response of materials due to the ultrafast rise and fall times of short pulses. The phenomenon has been studied since the earliest days of Electro-Magnetics [1], and in more recent years it has been suggested that since the theory predicts that the attenuation of the Brillouin precursor is proportional to $1/r^{1/2}$ as compared with exponential decay (as is the case with conventional propagation), then it might be possible to obtain lower-loss propagation through foliage – in other words, better foliage penetration (FOPEN) properties than conventional radar waveforms.

In the late 1980s, a study was commissioned by the Defense Advanced Research Projects Agency (DARPA) in the USA, into Ultra-Wideband Technology, since it had been suggested that such technology might offer a counter-stealth capability. The panel undertaking the study included many well-known names from the US radar research community. The report was published in July 1990 [2], and concluded, amongst other things, that impulse radar '… is not inherently anti-stealth', '… has no special LPI characteristics', and '… does not offer a major new military capability, nor correspondingly does it present the threat of a serious technology surprise'. The report caused concern in some quarters, owing to its impact on emerging stealth technologies, and an investigation of the panel and its activities was undertaken. This investigation concluded that '… the panel's report was credible and the panel balanced'. An account of the panel's work and of the investigation was published in the IEEE AESS Magazine [3].

In the last few years a number of research studies (mostly theoretical) have been funded in the USA by the US Air Force Office of Scientific Research (AFOSR), and a number of claims have been made [4, 5] which, if true, would seem to be significant. However, there is clearly some difficulty in reconciling the various claims. At this stage it is far from clear whether the effect is exploitable, and if it is, whether it depends at all critically on the properties of foliage, and what form a practical system would have to take to be at all useful. It was therefore appropriate to undertake a short precursor study to attempt to answer these questions. The principal objectives of the present study were therefore:

- To understand the precursor waveform phenomenon
- To understand the performance limitations of precursor waveforms
- To identify the most promising applications areas for precursor waveforms.
- If appropriate, to recommend the form of a research programme to corroborate the study findings

The structure of this paper is as follows. Section 2 presents a brief theoretical description of the precursor phenomenon; Section 3 presents a review of the various publications and their claims, and Section 4 draws some conclusions.

2. The Precursor Phenomenon

If a unit step function modulated signal

$$\begin{array}{cl} 0 & \text{for } t < 0 \\ \sin\left(\omega\left(t - z/c\right)\right) & \text{for } t > 0 \end{array}$$

is incident on a block of material $z > 0$, then strictly the leading edge travels with the velocity of light c, though with zero power. This is because of the material's finite relaxation times, so that the material's polarization does not respond instantly to a transient electric field.

As a realistic example, consider an incident pulse with centre frequency ω_c equal to a resonance frequency ω_{res} of the presumed homogeneous material, and with bandwidth somewhat greater than the absorption bandwidth $\Delta f_{res.}$ In this case (again because of finite relaxation times) analysis shows that frequencies closely above or below ω_{res} travel faster than the carrier frequency ω_c. The resulting pulse will therefore have its central frequencies attenuated (by absorption) and moreover will be preceded by its adjacent frequencies. At any depth of penetration into the material, the first measurable 'signal' to arrive is termed the 'Sommerfeld Precursor' (arising from spectral frequencies above ω_c) followed by the separate 'Brillouin Precursor' (from frequencies below ω_c) - and finally the main core of the pulse of frequencies around ω_c. (Figure 1). These precursors have been observed experimentally, both at optical frequencies and at microwave frequencies (Figure 2) [1].

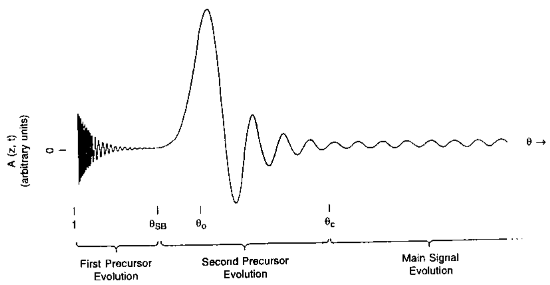
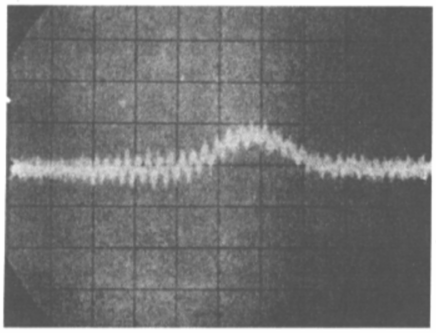
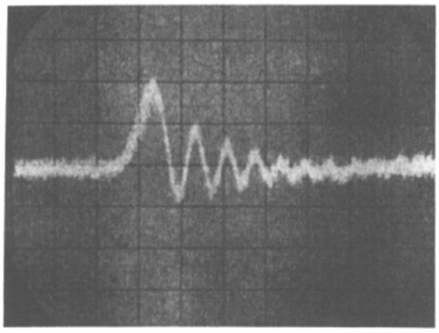


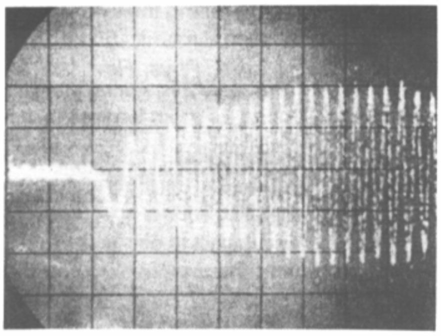
Figure 1. Dynamic behaviour of the propagated field due to an input step-function-modulated signal with applied signal frequency $\omega < \omega_{SB}$. Brillouin's original choice of parameters for a highly absorptive and dispersive medium were $\omega_0 = 4.0 \times 10^{16}$/s; $\omega_p^2 = 20.0 \times 10^{32}/s^2$; and $\gamma = 0.28 \times 10^{16}$/s. Therefore ω_{SB} is 7.22×10^{16}/s for that choice. These parameters are in the optical realm, but the same relations apply for parameters in the RF regime, i.e. for $\omega_c < \omega_{SB}$ the precursors are as shown. $\theta = ct/z$, i.e. time normalised to distance and the speed of light. For $0 < \omega_c < \omega_{SB}$ the two precursor fields evolve prior to the main signal arrival. For $\omega_c \geq \omega_{SB}$, only the first precursor field evolves prior to the signal arrival, with the second precursor field occurring during the signal evolution (after Sherman and Oughstun [6]; also reproduced in [7]).



20 Gauss
(a)



100 Gauss
(b)



200 Gauss
(c)

Figure 2. Pulsed sine wave response (5ns/div) with carrier frequency of 0.625 GHz of ferrimagnetically filled coaxial line. The characteristic frequencies ω_0 and $(a^2+\omega_0^2)^{1/2}$ are both dependent on an externally applied magnetic field permitting isolation of the signal components. Sommerfeld and Brillouin precursors are visible in (a); the Brillouin precursor in (b); and the Brillouin precursor and the signal in (c) (after Pleshko and Palócz [8]; also reproduced in [7].

3. Discussion

As discussed in the previous section there is good evidence, both theoretical and experimental indicating that precursor waveforms can be created that have less than exponential decay properties. However, here we more concerned with the utility of such waveforms for remote sensing applications where penetration of otherwise opaque media is an advantage. There are a number of elements that must be considered if such a system is to be designed. The first is the requirement for transmitted power that enables useful detection ranges. If we assume merely free space propagation then we can equate parameters to those of an equivalent, conventional radar also operating in free space. For example, we might expect conventional radar to have an average power of approximately 0.1 W for relatively short range (less than 30 km) applications. To achieve an equivalent average power in an ultra short pulse system with a pulse magnitude 10 kW and duration of 0.1 ps requires a PRF of 10 kHz and integration of over a second. There are, of course, many assumptions implied by this simplistic calculation. Nevertheless, it is quite clear that there are immense challenges in designing a system that has useful range for remote sensing applications due to the very small power levels that exist inherently in short pulses. Equally, though, it should be noted that very short range operation (i.e. tens of metres) is much more feasible and may offer alternative applications.

However, as the main advantage of precursors is their potential for reduced attenuation then their propagation properties through the various media of interest (e.g. foliage etc) will be a key factor in determining utility. This seems to be the area of greatest uncertainty. The theoretical work has used the Debye and Lorentz models for the propagation medium, and it is not clear whether these models may accurately represent the behaviour of foliage canopies in practice, nor how this may depend on parameters such as foliage density or moisture content. We can, however, compare with experimental evidence that has been reported in the open literature for more traditional forms of foliage penetration radar and in particular SAR [e.g. 9, 10 and 11]. These demonstrate that hard (i.e. metallic based) objects can be observed through a forest canopy consisting of a variety of types at differing growth periods. Moreover, high power, relatively wideband waveforms can be generated at low carrier frequencies quite straightforwardly. Thus any consideration of the practical usage of precursors should be compared directly with this form of system, i.e. any attenuation advantage of precursors should be offset against the levels of average power that can be more easily generated with conventional wideband SAR.

The next aspect to consider in producing a practical system is the technology required. This includes the generation of either very short duration or very fast leading edge pulses, a means of impedance matching them to free space, and a method of detecting the resulting scattered precursors. This implies very significant challenges and possibly the development of new forms of technology. However, as there remains much to be done to validate the theory and principles underlying precursors we shall not consider technology aspects further.

4. Conclusions

In this paper we have introduced the phenomenon and theory of precursors. There is no doubt that the phenomenon exists, but the theory illustrates that there is a delicate balance between the specification of the waveform and the properties of the medium through which it must propagate. This has led to much debate as to the range of validity and the utility to which precursors can be put. For example, proponents of the idea, in particular K. E. Oughstun and colleagues [12], have had details of their analyses and predictions seriously challenged by T. M. Roberts [13]. Doubt is also cast on the practicality by D. L. Black [14]. There persist some confusion and contradictions in the literature, making an unequivocal judgment difficult on the issue. However, we have found no evidence to suggest that the original conclusions drawn by DARPA in the late 1980s are in any way incorrect.

5. References

[1] Brillouin, L., ‘Uber die Fortpflanzung des Licht in disperdierenden Medien’, *Ann. Phys*., **44**, 203, 1914.

[2] ‘Assessment of Ultra-Wideband (UWB) Technology’, DTIC No. ADB146160, 13 July 1990. The Executive Summary of the report was published in *IEEE AESS Magazine*, pp45 – 49, November 1990.

[3] Fowler, C.A., ‘The UWB (impulse radar) caper *or* “punishment of the innocent”’, *IEEE AESS Magazine*, pp3 – 5, December 1992.

[4] Albanese, R., Medina, R. and Penn, J. ‘Precursors, foliage, artificial dielectrics and radiative transport’, AFOSR Electromagnetics Workshop, San Antonio, 17 – 19 January 2002.

[5] Olson, T. ‘Precursor-based HRR for foliage penetration: a 10 – 15 dB win’, AFOSR Electromagnetics Workshop, San Antonio, 8 – 10 January 2004.

[6] Sherman, G.C. and Oughstun, K.E., ‘Description of pulse dynamics in

Lorentz media in terms of the energy velocity and attenuation of time-harmonic waves', *Phys. Rev. Lett.* **47**, 1451-1454, 1981.

[7] Barrett, T.W., 'Energy transfer through media and sensing of the media', Chapter 7 in *Introduction to Ultra-Wideband Radar Systems* (J.D. Taylor ed.), CRC Press, 1995.

[8] Pleshko, P. and Palócz, I., 'Experimental observation of Sommerfeld and Brillouin precursors in the microwave domain', *Phys. Rev. Lett.*, **22**, pp1201-1204, 1969.

[9] Gustavsson, A., Ulander, L.M.H., Martineau, P., du Plessis, O., Frölind, P.-O., Jonsson, T., Larsson, B., Le Coz, D. and Stenström, G., 'Some results on detection of targets deployed in hide under foliage', Proc., *EUSAR 2002* Conference, Cologne, pp57–60, 4 – 6 June 2002.

[10] Ulander, L.M.H. and Hellsten, H., 'System analysis of ultra-wideband VHF SAR', Proc. *RADAR'97* Conference, Edinburgh, IEE Conf. Publ. No. 449, pp104–108, 14 –16 October 1997.

[11] Binder, B.T., Toups, S., Ayasli, S. and Adams, E.M., 'SAR foliage phenomenology of tropical rain forests and northern US forest', Proc. IEEE International Radar Conference *RADAR'95*, Washington DC, pp158–163, 8 – 11 May 1995.

[12] Oughstun, K.E. and Sherman, G.C., *Electromagnetic pulse propagation in causal dielectrics*, Springer-Verlag 1994.

[13] Roberts, T.M., 'Radiated pulses decay exponentially in materials in the far fields of antennas', *Electronics Letters* **38**, No 14, July 2002.

[14] Black, D.L., 'An overview of impulse radar phenomenon', *ASD/ENACR Wright-Patterson AFB, OH 45433-6503.*