Scattering of Brillouin Precursor Fields from Objects inside Water

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Introduction

In a dispersive medium, the appearance of the steady-state part of the signal is preceded by oscillations known as precursors. This is due to the interrelated effects of phase dispersion and frequency dependent attenuation. The propagation properties of the precursors are different from the steady-state part of the pulse which makes them suitable for many applications. An example of these interesting properties is the non-exponential attenuation rate of the Brillouin precursors inside a Debye medium.

For a Debye-type dielectric, eventually, the dynamical field evolution of a modulated pulse with a temporal support $T$ where, $T \gg 1/f_c$ ($f_c$ is the modulation frequency of the pulse) will be dominated by the Brillouin precursor, as the pulse propagates inside the medium. The peak amplitude in the Brillouin precursor decays as the square root of the inverse of the propagation distance, as opposed to the exponential decay of the steady-state part of the pulse. Exploiting this property, Oughstun has suggested that an input pulse consisting of two mutually delayed and $\pi$ phase shifted Brillouin precursors would be a “near optimal” excitation in terms of the attenuation inside triply distilled water [1].

Evidently, this optimized pulse is promising for remote sensing applications, aimed at detecting objects inside lossy dispersive media such as moist soil and water. In such cases, the optimized pulse can overcome the high loss of the medium and contribute to the detection of objects further inside the dispersive medium.

In the following, Finite-Difference Time-Domain (FDTD) simulations are employed to evaluate the usefulness of the optimized pulse for remote sensing applications, by modeling its scattering from objects inside water. It should be noted that this is the first study of the scattering of precursors from targets embedded in dispersive media.

1 Computational Modeling Using Finite Difference Time Domain Technique (FDTD)

Figure 1(a) shows a setup for which the transmitter (T) and receiver (R) are located at the same elevation above the air-water interface, similar to the Ground Penetrating Radar (GPR) geometry studied in [2]. The transmitter is a stationary source, located at a distance $\Delta z + D$ above the object in the free space. The receiver moves...
moves parallel to the interface at the same $z$-coordinate as the transmitter. The scattering object has a square shape with sides equal to $d$ and is located at distance $D$ from the interface. To simulate the dispersive behavior of water we have used the Rocard-Powles-Debye model in our analysis. The complex index of refraction of the medium is given by

$$n(\omega) = \left[\epsilon_\infty + \frac{(\epsilon_s - \epsilon_\infty)}{(1 - i\omega\tau)(1 - i\omega\tau_f)}\right]^{1/2},$$

(1)

where $\tau$ is the relaxation time with an associated friction time $\tau_f$. The quantity $\epsilon_\infty$ is the high frequency limit of the dielectric permittivity and $\epsilon_s$ is the static permittivity which denotes the low frequency limit. The index of refraction is described by Eq.(1) with parameters $\epsilon_\infty = 2.1$, $\epsilon_s = 76.2$, $\tau = 8.44 \times 10^{-12} s$, $\tau_f = 4.62 \times 10^{-14} s$ models triply-distilled water at $25^\circ C$ [1].

According to [1], the pulse which provides near-optimal penetration is comprised of a pair of Brillouin precursor pulses with the second one delayed in time and $\pi$ phase shifted with respect to the first. The closed form of the double Brillouin pulse ($f_{DB}(t)$) which consists of two “single Brillouin” pulses ($f_{SB}(t)$) is given by

$$f_{DB}(t) = f_{SB}(t) - f_{SB}(t - T),$$

(2)

where, $f_{SB}(t)$ is the temporal distribution of the Brillouin precursor in Rocard-Powles-Debye medium. The value $T = 1/f_c$ describes the fixed time delay between the leading and trailing-edge single Brillouin pulses. Figure 1(b) shows the temporal distribution of the double Brillouin pulse.

In the FDTD computational domain the excitation is a point source, which radiates omni-directionally and has transverse electric ($E_y, H_x, H_z \neq 0$) polarization. It is in the middle of the computational domain along the $x$-axis, $2\lambda_0$ before the interface.
along the $z$-axis ($\lambda_0 = c/f_c$ is the free space wavelength where $f_c = 1$ GHz). We have used the space and time discretization parameters, $\delta_x = \delta_z = \lambda_0/40$, $\delta_t = s\delta_x/c$ where, $s = 0.7$ is the Courant stability number. Both free space and the dispersive medium are semi-infinite. Hence, a perfectly matched layer (PML) is used to implement the unbounded media along $x$- and $z$-directions. The length of the PML is 10 cells along both $x$- and $z$-directions. The length of the free space computational domain along the $z$-axis is $4\lambda_0$ and the length of the dispersive medium along the $z$-axis is $5\lambda_0$. The simulated cases for the side $d$ of the square scatterer are: $5\lambda_c$ to $10\lambda_c$ where, $\lambda_c = \lambda_0/n_r(\omega_c)$ is the wavelength inside water at 1 GHz ($n_r(\omega_c)$ is the real part of the index of refraction in Eq. (1) at carrier frequency $\omega_c$).

2 Scattering of the Double Brillouin Pulse from an Object Inside Water

Next, the double Brillouin pulse is compared to a modulated Gaussian excitation which has the same energy as the double Brillouin pulse. The closed form of the modulated Gaussian pulse (Fig. 1(c)) is given as

$$E^G_y(t) = A_g \exp\left[-\left(\frac{t-t_0}{T_g}\right)^2\right]\sin(\omega_c t),$$

where, $A_g$ is the maximum amplitude of the pulse, $t_0 = 3T_g$ is the point in time where the maximum of the pulse appears. The maximum amplitude of the pulse ($A_g$) is set at 0.5 and $T_g$ is set to match the energy of the modulated Gaussian pulse with the double Brillouin pulse. Here, the value of $T_g$ is 4.5 ns. The amplitude of the modulated Gaussian pulse is chosen in a way that the temporal support of the pulse is larger than the temporal support of the double Brillouin pulse. Hence, the energy of the pulse is not concentrated in the time domain where the Brillouin precursor exists.

In order to compare the two pulses (Gaussian and double Brillouin) we have calculated the back-scattered energy at the receiver according to

$$E = \sum_{n=1}^{N} |E^{scattered}_{y}(n\delta t)|^2,$$

where, $E^{scattered}_{y}$ is the sampled scattered field and $N$ is the number of time steps in the FDTD simulations. Figures 2(a) and (b) show the energy of the scattered field from the perfect electric conductor inside water when the excitation is the double Brillouin pulse for $d = 5\lambda_c$ and $10\lambda_c$, respectively. Figures 2(c) and (d) show the same results for the modulated Gaussian pulse. The horizontal axis is the displacement (of the receiver) along the $x$-direction.
3 Discussion and Conclusion

The feature which is common in Figs. 2(a) to (d) is the bell shape of all the curves. The maximum appears at the sampling point which is closest to the object and the energy decreases as the sampling point moves away from the object. As expected, comparing the figures shows that the scattered field energy is higher for objects with bigger sizes. The figures also show that the scattered energy for double Brillouin pulse is larger than the reference Gaussian pulses under identical conditions in terms of the location and size of the object. In other words, the double Brillouin pulse has a better performance than the corresponding Gaussian pulse. We have also compared the double Brillouin pulse with modulated rectangular and sinusoidal pulses in terms of the energy of the scattered field. The simulation results show that the double Brillouin pulse also has superior performance with respect to these pulses in terms of the energy of the scattered field. These results will be discussed in the presentation.

References
