On the Excitation of Anomalous EM Transients Along the Surface of a Thin Highly Contrasting Sheet With Dielectric and Conductive Properties

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On the Excitation of Anomalous EM Transients Along the Surface of a Thin Highly-Contrasting Sheet With Dielectric and Conductive Properties

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***Abstract*—The electric line source excited, pulsed electromagnetic (EM) field response on the surface of a highly-contrasting thin sheet with dielectric and conductive properties is studied analytically in the time domain (TD) with the aid of the Cagniard-DeHoop (CdH) technique. Closed-form TD expressions reveal anomalous highly-oscillatory EM transients propagated over the surface of the layer. Illustrative numerical examples demonstrate the EM surface phenomenon.**

***Index Terms*—time-domain analysis, thin-sheet cross-layer conditions, pulsed EM fields, electromagnetic scattering, surface waves.**

I. Introduction

A GREAT success in the EM field long-range wireless transfer achieved in the beginning of the 20th century has triggered the theoretical research into the EM wave propagation mechanisms [1]. With the concept of elastic surface waves in mind [2], it was hoped to explain the long-distance EM transmission by proving the existence of an EM surface wave. These efforts resulted in useful mathematical tools for solving a class of EM boundary value problems [3], but also led to long-standing controversies (see e.g. [4], [5]) and terminology confusion [6]. While such disputes are still not fully settled in the frequency domain [7], the situation is truly transparent in the TD, where all wave phenomena actually manifest themselves. Indeed, under the causality-preserving CdH representation [8], any singularity in the complex slowness plane can be directly associated with a physical phenomenon occurring in the resulting wave motion [9]. Hence, the presence of a pole singularity in the pertaining slowness complex plane implies the existence of a true (causal) surface wave (e.g. Rayleigh's wave at the traction-free boundary of a solid or Scholte's wave along a fluid-solid interface [10]). Consequently, the CdH approach is pursued in the present letter, where the electric-line-source excited pulsed EM field response on the surface of a highly-contrasting, dielectric thin sheet is studied analytically. The resulting TD closed-form expressions clearly reveal that under certain circumstances strongly oscillatory anomalous EM transients can occur.

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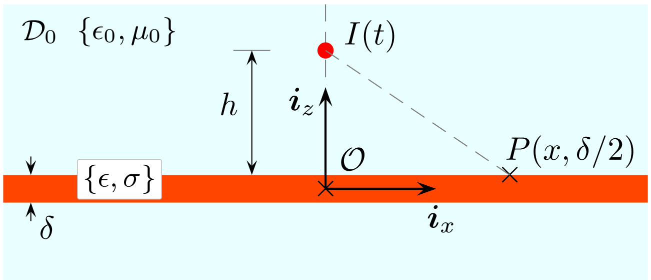

Fig. 1. An impulsive electric-line source in the presence of a highly-contrasting thin layer.

II. Problem Definition

The problem configuration under consideration is shown in Fig. 1. Here, the position is specified by coordinates $\{x, y, z\}$ with respect to an orthogonal, Cartesian reference frame with the origin $\mathcal{O}$ and the standard base formed by unit vectors $\{\boldsymbol{i}_x, \boldsymbol{i}_y, \boldsymbol{i}_z\}$. The time coordinate is denoted by $t \in \mathbb{R}$. The partial differentiation operator is denoted by ∂ that is supplied with the pertaining subscript. The time-convolution operator is denoted by $*_t$. Finally, $\mathrm{H}(t)$ is the Heaviside unit-step function and $\delta(t)$ denotes the Dirac-delta distribution.

The problem configuration consists of a layer of thickness $\delta > 0$ that is relatively small with respect to the spatial support of the excitation pulse, that is, (EM wave speed)×(incident wave pulse time width). The EM properties of the layer are described by the (real-valued, scalar and positive) electric permittivity, ϵ, and electric conductivity, σ. The layer is located in the loss-free background medium occupying $\mathcal{D}_0$. Its EM properties are described by electric permittivity ϵ_0 and magnetic permeability μ_0. The corresponding EM wave speed is $c_0 = (\mu_0\epsilon_0)^{-1/2} > 0$ and the wave admittance is denoted by $Y_0 = (\epsilon_0/\mu_0)^{1/2} > 0$. It is assumed that the layer's constitutive parameters show a high contrast with respect to the ones of the embedding.

The electric-line source, defined by its causal electric-current pulse $I(t)$ (in A), excites y-independent, TE-polarized EM field components $\{E_y, H_x, H_z\}(x, z, t)$ that are in $\mathcal{D}_0$ governed by [11, Sec. 18.2]

$$-\partial_z H_x + \partial_x H_z + \epsilon_0 \partial_t E_y = -I(t)\delta(x)\delta(z-h) \quad (1)$$

$$\partial_x E_y + \mu_0 \partial_t H_z = 0 \quad (2)$$

$$-\partial_z E_y + \mu_0 \partial_t H_x = 0 \quad (3)$$

Across the sheet, the EM field equations are supplemented with the saltus-type TD conditions (cf. [12, Eqs. (3) and (4)])

$$E_y^+ - E_y^- = o(\delta) \tag{4}$$

$$H_x^+ - H_x^- = (G^{\mathrm{E}} + C^{\mathrm{E}}\partial_t)E_y(x,0,t) + o(\delta) \tag{5}$$

as $\delta \downarrow 0$ for all $x \in \mathbb{R}$ and $t > 0$, where superscripts $^+$ and $^-$ denote the field values approaching the upper and lower surface of the layer. Furthermore, the coefficients $\{C^{\mathrm{E}}, G^{\mathrm{E}}\}$ follow from [13, (2) and (3)]

$$G^{\mathrm{E}} = \int_{\zeta=-\delta/2}^{\delta/2} \sigma(\zeta)\mathrm{d}\zeta \text{ and } C^{\mathrm{E}} = \int_{\zeta=-\delta/2}^{\delta/2} \epsilon(\zeta)\mathrm{d}\zeta \tag{6}$$

which can be viewed as local Kirchhoff lumped electric-circuit elements characterizing the layer. They can be further used to define the *layer conductance ratio*, $\eta_{\mathrm{L}} = G^{\mathrm{E}}/Y_0$ and the *layer admittance time constant* $\tau_{\mathrm{L}} = C^{\mathrm{E}}/G^{\mathrm{E}}$ [13, (39) and (40)].

III. Slowness-Domain Expressions

The pulsed EM response of a highly-contrasting thin layer will be found with the aid of the classic CdH technique [8]. To that end, we employ the space-time shift invariance of the problem configuration to combine an unilateral Laplace transformation with the wave slowness representation in the x-direction. To show the notation, the corresponding expressions are given for the s-domain counterpart of E_y-field, that is

$$\hat{E}_y(x,z,s) = \int_{t=0}^{\infty} \exp(-st)E_y(x,z,t)\mathrm{d}t \tag{7}$$

for $\{s \in \mathbb{R}; s > 0\}$, thus relying on Lerch's uniqueness theorem [14, Appendix], and

$$\hat{E}_y(x,z,s) = \frac{s}{2\pi\mathrm{i}} \int_{p=-\mathrm{i}\infty}^{\mathrm{i}\infty} \exp(-spx)\tilde{E}_y(p,z,s)\mathrm{d}p \tag{8}$$

where p is the wave slowness parameter along the x-direction. The EM field equations (1)–(3) with the cross-layer conditions (4) and (5) are next solved using Eqs. (7) and (8). Accordingly, the s-domain solution of Eqs. (1)–(3) as observed at $P(x, \delta/2)$ on the layer's surface has the following form

$$\begin{aligned}\hat{E}_y(x,0,s) = -\frac{s\mu_0\hat{I}(s)}{2\pi\mathrm{i}} \int_{p=-\mathrm{i}\infty}^{\mathrm{i}\infty} \exp\{-s[px + \gamma_0(p)h]\} \\ \times \frac{\Psi_\perp(p)}{s + \tau_{\mathrm{L}}^{-1} + \Psi_\perp(p)} \frac{\mathrm{d}p}{2\gamma_0(p)}\end{aligned} \tag{9}$$

for $x \in \mathbb{R}$ and $\{s \in \mathbb{R}; s > 0\}$, where $\Psi_\perp(p) = 2\gamma_0(p)/\mu_0 C^{\mathrm{E}}$ and

$$\gamma_0(p) = (1/c_0^2 - p^2)^{1/2} \text{ with } \mathrm{Re}(\gamma_0) \geq 0 \tag{10}$$

is the slowness parameter in the z-direction. In accordance with the analysis given by de Hoop and Jiang [15], it is seen that the integrand in Eq. (9) has no poles in the complex p-plane for $\{s \in \mathbb{R}; s > 0\}$, $\mathrm{Re}(\Psi_\perp) \geq 0$ and $G^{\mathrm{E}}/C^{\mathrm{E}} \geq 0$, *which implies the absence of true (causal) surface waves*. As indicated in [15], however, the excitation of a strongly oscillatory TD EM effect is still feasible. Its detailed space-time description is the main subject of the letter.

Finally note that a similar analysis can be readily carried out for the TM-polarized EM fields excited by an impulsive magnetic-line source $\hat{K}_y(x,z,s) = \hat{V}(s)\delta(x)\delta(z-h)$. To this end, we use the following expression for the s-domain magnetic-field strength observed just above the surface of a dielectric/conductive thin layer

$$\begin{aligned}\hat{H}_y(x,0^+,s) = 2\hat{H}_y^{\mathrm{i}}(x,0,s) \\ + \frac{s\epsilon_0\hat{V}(s)}{2\pi\mathrm{i}} \int_{p=-\mathrm{i}\infty}^{\mathrm{i}\infty} \exp\{-s[px + \gamma_0(p)h]\} \\ \times \frac{\Psi_\parallel(p)}{s + \tau_{\mathrm{L}}^{-1} + \Psi_\parallel(p)} \frac{\mathrm{d}p}{2\gamma_0(p)}\end{aligned} \tag{11}$$

where $\hat{H}_y^{\mathrm{i}}(x,z,s)$ denotes the incident (cylindrical) wave and $\Psi_\parallel(p) = 2\epsilon_0/\gamma_0(p)C^{\mathrm{E}}$. The integrand in Eq. (11) has no poles in the entire complex p-plane, which, again, attests the *absence of true surface waves*. Moreover, owing to the behavior of $\Psi_\parallel(p)$ along the pertaining CdH path, no significant surface transients can occur in this case (see [16], for details).

A thorough discussion on the real-FD modal properties of a dielectric slab can be found in [17, Sec. 11.5], for instance. In the solution of a TD wave field problem, however, the nature of a source must be properly accounted for (see also Sec. VI).

IV. Time-Domain Solution

The space-time analytical expressions will be provided for the line source located close to the surface, $h \downarrow 0$, for which the strongest surface phenomena can be expected [15], [16], [18]. To that end, we shall transform the slowness integral representation (9) to the TD. In the limit $h \downarrow 0$, the original integration contour along the imaginary p-axis is, under the application of Cauchy's theorem and Jordan lemma [11, p. 1054], deformed into the CdH path that is defined via $p(\tau) = \tau/x$ for $\{|x|/c_0 \leq \tau < \infty\}$, thus representing a loop encircling the branch cuts along $\{1/c_0 < |\mathrm{Re}(p)| < \infty, \mathrm{Im}(p) = 0\}$. Consequently, upon combining the integrations just above and just below the branch cuts, while introducing τ as the new variable of integration, we arrive at integral expressions that can be uniquely transformed back to the TD using the Schouten-Van der Pol theorem [11, p. 1056]. For more details regarding the relevant CdH transformation procedure we refer the reader to [8], [15], [16]. Pursuing the CdH approach, the TD original of Eq. (9) is found in the following form

$$\begin{aligned}\lim_{h\downarrow 0} E_y(x,0,t) = -\partial_t I(t) *_t (\epsilon_0/C^{\mathrm{E}})(Y_0\pi)^{-1} \\ \times \int_{u=1}^{\frac{c_0 t}{|x|}} \sin\left[(2\epsilon_0/C^{\mathrm{E}})|x|\left(u^2-1\right)^{1/2}(c_0 t/|x| - u)\right] \\ \times \exp\left[-\eta_{\mathrm{L}}(\epsilon_0/C^{\mathrm{E}})|x|\left(c_0 t/|x| - u\right)\right]\mathrm{d}u\end{aligned} \tag{12}$$

for all $x \in \mathbb{R}$ and $t \geq |x|/c_0$, thus expressing the field at $z = 0$ by virtue of its continuity across the layer (see Eq. (4)). Interpreting (12) as a function of the normalized time $c_0 t/|x|$ (with respect to the pulse travel time $|x|/c_0$), it is seen that its oscillations get faster as both time and $\epsilon_0|x|/C^{\mathrm{E}}$ increase. Furthermore, the TD response is exponentially attenuated with the decay constant proportional to the factor $\eta_{\mathrm{L}}\epsilon_0|x|/C^{\mathrm{E}}$. To gain further insights into the TD phenomenon, the integration with respect to u will be, in a heuristic manner, carried out analytically. To that end, the argument of the sine function is replaced with a parabola and the thus obtained integral is then evaluated with the help of formula [19, Eq. (7.4.39)]. In this way, we arrive at the following approximate formula

$$\begin{aligned}&\lim_{h\downarrow 0} E_y(x,0,t) \simeq -\partial_t I(t) *_t \frac{\epsilon_0}{C^{\mathrm{E}}}\frac{1}{Y_0\pi}\left(\frac{2\pi}{\beta(t)}\right)^{1/2}\\ &\left\{\mathrm{C}\left[\left(\frac{\beta(t)}{2\pi}\right)^{1/2}\left(\frac{c_0t}{|x|}-1\right)\right]\sin\left[\frac{\beta(t)}{4}\left(\frac{c_0t}{|x|}-1\right)^2\right]\right.\\ &\left.-\,\mathrm{S}\left[\left(\frac{\beta(t)}{2\pi}\right)^{1/2}\left(\frac{c_0t}{|x|}-1\right)\right]\cos\left[\frac{\beta(t)}{4}\left(\frac{c_0t}{|x|}-1\right)^2\right]\right\}\\ &\times\exp\left(-\frac{\eta_{\mathrm{L}}}{2}\frac{\epsilon_0}{C^{\mathrm{E}}}|x|\frac{c_0t}{|x|}\right)\mathrm{H}(c_0t-|x|)\end{aligned} \tag{13}$$

where $\mathrm{C}(x)$ and $\mathrm{S}(x)$ denote Fresnel's integrals [19, Eqs. (7.3.1) and (7.3.2)].

$$\beta(t) = \frac{2\epsilon_0}{C^{\mathrm{E}}}|x|\left[\frac{(c_0t/|x|+1)^2+1}{(c_0t/|x|-1)^2+1}\right]^{1/2} \tag{14}$$

Since the determination of the range of validity of the closed-form formula (13) is beyond the scope of this work, we shall further limit ourselves to its validation via a numerical example. To our best knowledge, the closed-form TD analytical expression (12) and its approximation (13) are new to the literature. The validity of the approximate expression will be next demonstrated on a numerical example.

V. Illustrative Numerical Example

For the sake of simplicity, we shall analyze the surface effect on a homogeneous thin slab for which the Kirchhoff circuit coefficients (see Eq. (6)) can be expressed as $G^{\mathrm{E}} = \delta\sigma$ and $C^{\mathrm{E}} = \delta\epsilon_{\mathrm{r}}\epsilon_0$, where ϵ_{r} is the relative permittivity. For demonstrating the aimed at highly-contrasting, thin-sheet behavior, we take the layer conductance ratio $\eta_{\mathrm{L}} = G^{\mathrm{E}}/Y_0$ to be significantly smaller than 1 and ϵ_{r} to be significantly larger than 1 – this combination is illustrative for a thin sheet of conductive silicon the type of which is standardly employed in complementary metaloxide semiconductor (CMOS) technology. The field response is excited by the impulsive line source with the rectangular pulse shape

$$I(t) = I_{\mathrm{m}}[\mathrm{H}(t) - \mathrm{H}(t-t_{\mathrm{w}})] \tag{15}$$

where we take the amplitude $I_{\mathrm{m}} = 1.0\mathrm{mA}$ and the pulse time width t_{w} such that the pulse's spatial extent, $d_{\mathrm{w}} = c_0t_{\mathrm{w}}$, to be considerably smaller than δ. The following parameters are then selected for the discussed numerical experiment:

- $d_{\mathrm{w}}/\delta = 3/4\epsilon_{\mathrm{r}}$;
- the field response is calculated at the horizontal offset $|x| = \epsilon_{\mathrm{r}}\delta$, corresponding to $d_{\mathrm{w}}/|x| = 3/4$;
- $\eta_{\mathrm{L}} = 1/5$, corresponding to $\sigma = Y_0/5\delta$;
- $\tau_{\mathrm{L}} = C^{\mathrm{E}}/G^{\mathrm{E}} = 20/3t_{\mathrm{w}}$, corresponding to $C^{\mathrm{E}}/Y_0t_{\mathrm{w}} = 4/3$ and entailing $\epsilon_0|x|/C^{\mathrm{E}} = 1$.

The pulsed electric field response, as calculated (exactly) by using (12), is shown in Fig. 2a. As can be seen, the computed oscillatory response is well estimated by the closed-form (approximate) TD formula (13). To show the effect of the layer, we have also plotted the corresponding response that

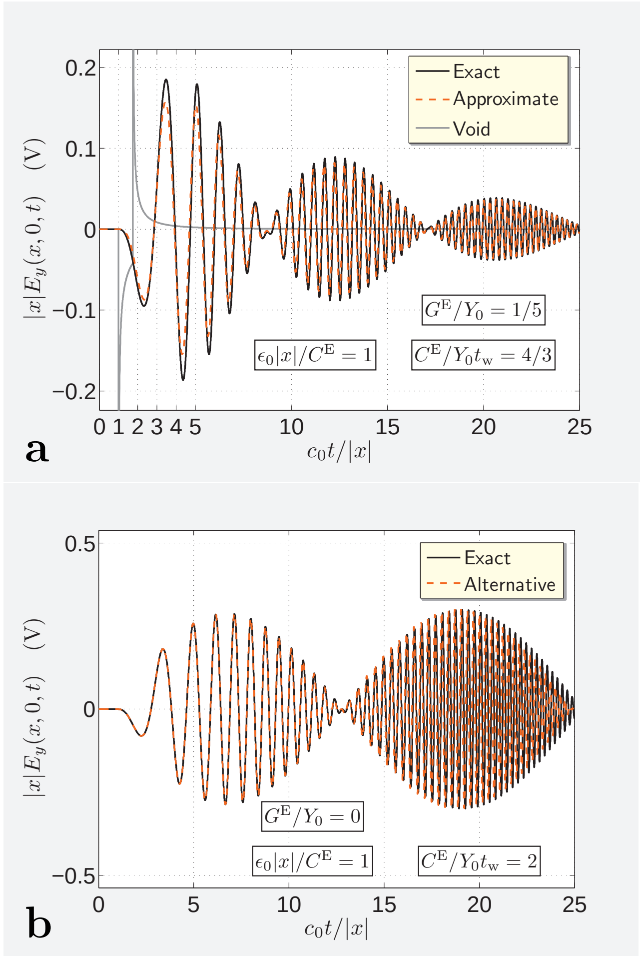

Fig. 2. The scaled electric-field pulsed responses observed on the surfaces of highly-contrasting thin layers. (a) The exact solution (12) and its approximation (13) for $G^{\mathrm{E}}/Y_0 = 1/5$ and $C^{\mathrm{E}}/Y_0t_{\mathrm{w}} = 4/3$; (b) The exact solution (12) and its alternative composed of head waves for $G^{\mathrm{E}}/Y_0 = 0$ and $C^{\mathrm{E}}/Y_0t_{\mathrm{w}} = 2$.

would be excited in the absence of the layer (void), that is (cf. [15, Eq. (35)])

$$\lim_{\epsilon\downarrow\epsilon_0,\sigma\downarrow 0} E_y(x,0,t) = -\frac{I_{\mathrm{m}}}{|x|Y_0}\left\{\frac{\mathrm{H}(c_0t/|x|-1)}{(c_0^2t^2/x^2-1)^{1/2}} - \frac{\mathrm{H}[c_0(t-t_{\mathrm{w}})/|x|-1]}{[c_0^2(t-t_{\mathrm{w}})^2/x^2-1]^{1/2}}\right\} \tag{16}$$

with its typical (line-source) inverse-square root behavior at $c_0t/|x| = 1$ (i.e. at the pulse travel time) and at $c_0t/|x| = 1 + c_0t_{\mathrm{w}}/|x| = 7/4$.

In the final example, we shall validate the conclusions drawn in the Appendix by calculating the response just above the surface of a loss-free, high-dielectric thin layer. In order to demonstrate the effect of the excitation pulse-time width on the transient response, we now take a (relatively) shorter pulse with $c_0t_{\mathrm{w}}/\delta = \epsilon_{\mathrm{r}}/2$, which is still supposed to be relatively high. Since we keep $|x| = \epsilon_{\mathrm{r}}\delta$, we have $c_0t_{\mathrm{w}}/|x| = 1/2$ and the relative layer's admittance increases to $C^{\mathrm{E}}/Y_0t_{\mathrm{w}} = 2$. Figure 2b shows that the exact solution (12) can be alternatively expressed as a sum of TD head-wave constituents propagating in the layer (see Appendix).

VI. Conclusions

The pulsed EM field response of a thin, highly-contrasting layer with dielectric and conductive properties excited by an electric-line source has been analyzed analytically via the CdH technique. It has been demonstrated that the layer can support anomalous, highly-oscillatory EM transients propagating over its surface. Their TD analytical description, including its closed-form approximation is provided.

Duality predicts that such TD EM surface effects can also be excited by a magnetic-line source located just above a thin, high-permeability layer. Nonetheless, it was shown that no significant surface EM transients can be excited by a (TM-polarized) magnetic-line source above the surface of a high-dielectric thin film. The described TD surface phenomenon bears similarities with the one exhibited by the TM-polarized, TD EM reflected field observed just above the surface a thin plasmonic sheet [16], [18]. Consequently, the TD EM wave phenomenon may find its applications in designing sensing structures employing the high sensitivity of the EM response to parameters of the thin-layer's surface [20].

The present work concentrated on transients triggered by a single-pulse excitation. An intriguing question is the manner in which the observed phenomena evolve towards a steady-state behavior entailed by a periodic excitation, with the response to a train of pulses as a technologically extremely relevant intermediate step. Such a study is also expected to yield enlightening correspondences with standard results obtained via FD arguments, e.g. steady-state surface waves. This evidently broad exploration is a topic of future research.

Appendix
Alternative solution

In order to further explain the physics of EM surface transients, we shall discuss the solution pertaining to a dielectric layer of a finite thickness $\delta > 0$. Hence, upon replacing Eqs. (4) and (5) with the continuity-type boundary conditions applying at $\{x \in \mathbb{R}, z = \pm\delta/2\}$ for all $t > 0$, the transform-domain electric-field strength just above the surface can be expressed in the geometric-series form

$$\begin{aligned}\lim_{z\downarrow\delta/2} \tilde{E}_y(p,z,s) = &-\big[\mu_0/2\gamma_0(p)\big]\hat{I}(s)\big[1+\tilde{R}(p)\big] \\ &+ \big[\mu_0/2\gamma_0(p)\big]\hat{I}(s)\tilde{R}(p)\big[1-\tilde{R}^2(p)\big] \\ &\times \sum_{N=0}^{\infty} \tilde{R}^{2N}(p)\exp[-s\gamma_1(p)Z_N] \qquad (17)\end{aligned}$$

as $h \downarrow \delta/2$, where $Z_N = 2(N+1)\delta > 0$ is the vertical propagation path and

$$\tilde{R}(p) = [\gamma_0(p) - \gamma_1(p)]/[\gamma_0(p) + \gamma_1(p)] \qquad (18)$$

has the meaning of the (transform-domain) reflection coefficient with $\gamma_1(p) = (1/c_1^2 - p^2)^{1/2}$ denoting the vertical slowness parameter in the dielectric layer (cf. Eq. (10)) with $c_1 = (\epsilon\mu_0)^{-1/2} > 0$. The terms included in the sum of Eq. (17) can be understood as generalized-ray constituents propagating in the layer. They can be readily transformed to the TD via the CdH inversion procedure [21, Appendix A]. Due to the reflections against the surrounding free-space in which they do not propagate, the total wave motion, in general, consists of the head-wave (also referred to as lateral-wave [22, p. 97]) and body-wave TD contributions whose arrival times are $T_{\rm H} = |x|/c_0 + Z_N(1/c_1^2 - 1/c_0^2)^{1/2}$ and $T_{\rm B} = (x^2 + Z_N^2)^{1/2}/c_1$, respectively. The N-th head-wave constituent occurs only in the region where $|x|/(x^2 + Z_N^2)^{1/2} > c_1/c_0$.

Now, if the layer under consideration is assumed to be thin (i.e. $\delta \downarrow 0$) and highly dielectric (i.e. $c_1 \ll c_0$), it follows that the oscillatory surface response is dominantly composed of head-wave constituents propagated via reflections inside the layer. Mathematically, the head-wave contributions arise from the integration along the so-called head-wave CdH path encircling $\{c_0^{-1} < |{\rm Re}(p)| < |x|/(x^2 + Z_N^2)^{1/2}c_1^{-1}, {\rm Im}(p) = 0\}$ along the branch cut in the complex p-plane. In Fig. 2b it is demonstrated that the sum of the TD head-wave constituents is in the limit equivalent to the closed-form analytical solution (12) pertaining to the saltus-type conditions (4) and (5).

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