SUBSURFACE APPLICATIONS OF PERIODIC ELECTROMAGNETIC VIDEO PULSE SIGNALS

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Introduction

Considerable current interest is evident[1,2] in the use of transient electromagnetic methods for subsurface remote sensing. A transient method is discussed which uses a periodic video-type pulse containing a wide frequency range. A video pulse is used as an interrogating signal both for "target" identification and detection for relatively short depth (< 20 meters) applications in soil and soft rock media. If the medium is favorable, e.g., hard rock, greater depth applications appear to be feasible. The same procedures would be applicable for deep geological exploration but would require a substantial reduction in frequency and increase in target size. It should be noted that video pulse generators with 35 kv peak voltage and nanoseconds base widths are now within the state-of-the-art, thus significant power over broad spectral ranges is possible.

In the design of a video pulse sounding system, 5 main problem areas can be identified; 1) selection of the pulse shape or spectral content of the video pulse, 2) design of a radiating structure which effectively couples such a pulse into the medium, 3) isolation of the radiating and receiving mechanisms, 4) realistically accounting for the dispersion and attentuation of the medium and the air-medium interface, and 5) interpretation or processing of the received signal waveform. Each of these problem areas will be discussed and illustrated with experimental and/or theoretical results.

The Video Pulse

Selection of the proper video pulse signal is dictated by 3 considerations, the maximum desired depth of penetration, the attenuation of the medium and the required resolution and size of the target. For a lossy medium, penetration and resolution are clearly at cross purposes and a compromise is necessary. The exact nature of the compromise is dictated by the application, but the spectrum of the video pulse should not contain any frequencies higher than the predicted cut-off, i.e., that frequency which is attenuated to the threshold level of the receiver. As a practical matter, it may be necessary to select 1 or 2 video pulses reasonably suited for a variety of applications. For example, the experimental data presented here were obtained using 2 video pulse signals - a 1,000 volt peak picoseconds base width with a spectrum essentially flat to the GHz range and a 50 volt peak nanoseconds base with significant spectrum to roughly 60 MHz. With current technology, the video pulse can be taylored to an individual application. It is stressed however that for a diagnostic capability, all frequencies which can realistically be observed must be included in the pulse spectrum. Geological exploration would involve larger targets at greater depths but pulses with lower frequency content would be used.

The Antenna

Required is a structure which when oriented on or above a given medium effectively couples energy into the medium over a broad range of frequencies. The broadband requirement precludes achieving significant gain. For the video pulse sounding system, a dipole antenna is used with each dipole arm made up of two linear conductors in a V arrangement. The angle of the V is adjusted to control, in situ, the characteristic impedance of the dipole at the feed point. In the time domain the objective is to minimize sequentually and individually each reflection along the feed system and antenna. This is most simply done experimentally using a fast rise time pulse with a very long period and viewing the feed system and antenna as a transmission line with changing characteristic impedance along its length. Assuming a well selected feed system, the major sources of reflection are the antenna feed point and the ends of the dipole arms. Feed point reflections are minimized by adjusting the angle of the V arms. End reflections are controlled by 3 different mechanisms. In soil media, adjustable depth grounding rods at the end of each dipole arm element effectively controls the reflection. Often, if the soil has a vegetative cover, the attenuation of the vegetation is sufficient for control. On rock media, the large dipole (28 feed) has 8 foot long solid metal sheets at the end of each arm. For the small dipole, a thin layer of absorber material (Hairflex) is inserted between the antenna and the medium. When the local geometry permits, the most effective method of end reflection control is simply to extend the arms such that end reflections are beyond the "time window," i.e., would return to the feed point at times later than those from the target. Successful end reflection control using these mechanisms have been documented with experimental measurements[3,4].

Isolation

With video pulse systems, the receiver is usually a sampling oscilloscope. In a direct or monostatic mode where a single antenna is used for both transmission and reception the antenna can be switched between generator and sampler or alternatively a limiter to protect the sampler is provided and the entire time history is viewed. This direct mode of operation has the advantage of using same polarization transmission and reception. A major disadvantage is that a strong reflection from the air-medium interface can be anticipated. In addition, the ringing associated with horizontally stratified media would always be present which may or may not be desirable depending upon the application. The video pulse sounder can be operated in the direct mode (with limiter) but measurements indicate a need for faster diodes in the limiter for high power operation. Isolation via bistatic mode operation with two antennas (one for transmission one for reception) arrayed side by side with some horizontal separation is also possible. With dipole antennas on rock and soil media it was found that a surface wave component bound to the lower impedance medium resulted in a strong direct coupling which would be difficult to control.

The video pulse sounder is operated principally in an orthogonal mode using again two dipoles on the medium surface but oriented orthogonally with the feed points in very close proximity. In this case the direct coupling is a substantially reduced replica of the pulse delivered to the input feed point and therefore has a very brief time duration therefore permitting a clean time window. Orthogonal mode operation has the disadvantage (assuming only partial depolarization) of using the depolarized component of the scattered field. Note however that in this mode the sounder does not respond to targets which are symmetric to a vertical axis through the feed points. Thus the air-medium interface and other horizontal stratifications are not seen.

Attenuation, Dispersion, Interface

To properly process video pulse soundings it is desirable to remove from the received transient signal spectrum the effects of the antennas in situ, the feed system, and the medium. The effects of the feed system can be accurately measured. While certain locations and media offer geometries whereby the antenna in situ and medium effects can be measured, a theoretical capability is highly desirable.

An analysis and computer programs have been developed employing piecewise-sinusoidal expansion functions and Galerkin's method to formulate a solution for an arbitrary thin-wire antenna configuration in an infinite, homogeneous, isotropic, conducting medium[5]. The solution determines the current distribution, impedance, radiation efficiency, gain and both near zone fields and far-field patterns. As a first order approximation to account for the half-space, 3 possible modifications have been added. Note that the goal is a simple modification of an existing state-of-the-art computer program for an infinite medium which yields reasonable results in the vicinity of broadside for the same antenna on a half-space. One modification is an image-type using a plane wave reflection coefficient most appropriate if the antenna were immersed in the half-space. A second modification takes the wavenumber for the current flowing on the dipole to be the geometric mean of the wavenumbers for air and the half-space. A third modification combines the first 2. An example of the results is shown in Fig. 1, where the result of each modification is shown and compared to the result for an infinite medium. The antenna is a 6 foot V dipole with an included V angle of 30°. The frequency and half-space parameters are shown in the figure. Similar results for this antenna and half-space spanning 100 KHz to 100 MHz are given in reference 4. At 100 KHz (Fig. 1), none of the modifications alter the θ-dependence of the fields. At higher frequencies[4], the θ-dependence does change. In the broadside region ($\theta = 0^{\circ}$) and at low frequencies, both the image and current modifications alone are roughly compatible with results given by Wait[6] for an infinitesimal dipole under the quasi-static approximation. At this point, no claim is made as to the appropriateness of these modifications but the versatility of the available programs dictate an attempt at simple corrections. That only simple corrections may be needed near broadside is illustrated in Fig. 2 where a comparison of measured and calculated pulses transmitted through 20 feet of limestone is shown. The calculated pulse was obtained without any modification of the infinite medium program. The agreement between calculated and measured pulse shape is excellent. The magnitude error is partially accounted for by the fact that in the measurements, the thin absorber layer described previously was used on both the transmitting and receiving dipoles. The absorber was not taken into account in the calculations.

Attenuation and dispersion may also be calculated using the program. In Fig. 3, calculated received pulses are shown for transmission between 2 identical dipoles (Fig. 1) over 2 different path lengths. The antennas are broadside to each other, the transmitted signal is a 45 volt peak 50 nanosecond base width pulse, and the electrical properties of the medium have the assumed linear frequency dependence given in Fig. 3. A linear frequency dependence may not be realistic, but because the calculated pulses are obtained via transforms of frequency domain calculations, any frequency dependence can be used.

Processing

The processing scheme presently being utilized is to obtain from the measured orthogonal mode signal the band-limited impulse response of the target. In this approach, a given signal in the "time window" is isolated in time by gating and then transformed to the frequency domain. This spectrum is then normalized by the spectra of the interrogating pulse, the feed system, the antennas and the medium. The resultant spectrum is then inverse transformed to the time domain. In Fig. 4, the band-limited impulse response of a large cylindrical void (road tunnel) in limestone at a depth of 20 feet is shown. The specular-type impulse response in Fig. 4 is reasonable considering the size ($\approx$ 25 foot diameter) of the tunnel.

Conclusions

In applications where either the medium or required penetration depth make the use of video pulse signals feasible the electromagnetic video pulse sounder offers a new capability. Such applications as plastic and metal pipe detection in soil, overburden profiling, hazard detection in hard rock tunneling, route selections for subsurface installations, volumetric mapping of abandoned and hazardous drift coal mines, backfill analysis of pipe installations in permafrost, etc., would appear to be within the capabilities of the present system. Again, deep probing would require much different pulses and larger targets. The present system has also been used to experimentally record the responses of geological features such as joints, faults and a lithologic contrast in a dolomite medium.

References

1. Wait, J.R., "On the Theory of Electromagnetic Sounding Over a Stratified Earth," Canadian Journal of Physics, Vol. 50, No. 11, 1972.

2. Vanyan, L.L., Electromagnetic Depth Soundings, Translated from the Russian by G.V. Keller, Consultant Bureau, 1967.

3. L. Peters, Jr., and D.L. Moffatt, "Electromagnetic Pulse Sounding for Geological Surveying with Application in Rock Mechanics and Rapid Excavation Program," Report 3190-2, September 1972, ElectroScience Laboratory, Department of Electrical Engineering, The Ohio State University; prepared under Contract No. H0210042 for Bureau of Mines, Department of Interior (ARPA), Denver, Colorado.

4. Moffatt, D.L., R.J. Puskar, and L. Peters, Jr., "Electromagnetic Pulse Sounding for Geological Surveying with Application in Rock Mechanics and the Rapid Excavation Program," Report 3408-2 (in preparation), ElectroScience Laboratory, Department of Electrical Engineering, The Ohio State University; prepared under Contract No. H0230009 for Bureau of Mines, Department of Interior (ARPA), Denver, Colorado.

5. Richmond, J.H., "Radiation and Scattering by Thin-Wire Structures in the Complex Frequency Domain," Report 2902-10, July 1973, ElectroScience Laboratory, Department of Electrical Engineering, The Ohio State University; prepared under Grant No. NGL 36-008-138 for National Aeronautics and Space Administration, Washington, D.C.

6. Wait, J.R., "Theory of Wave Propagation Along a Thin Wire Parallel to an Interface," Radio Science, Vol. 7, No. 6, June 1972.

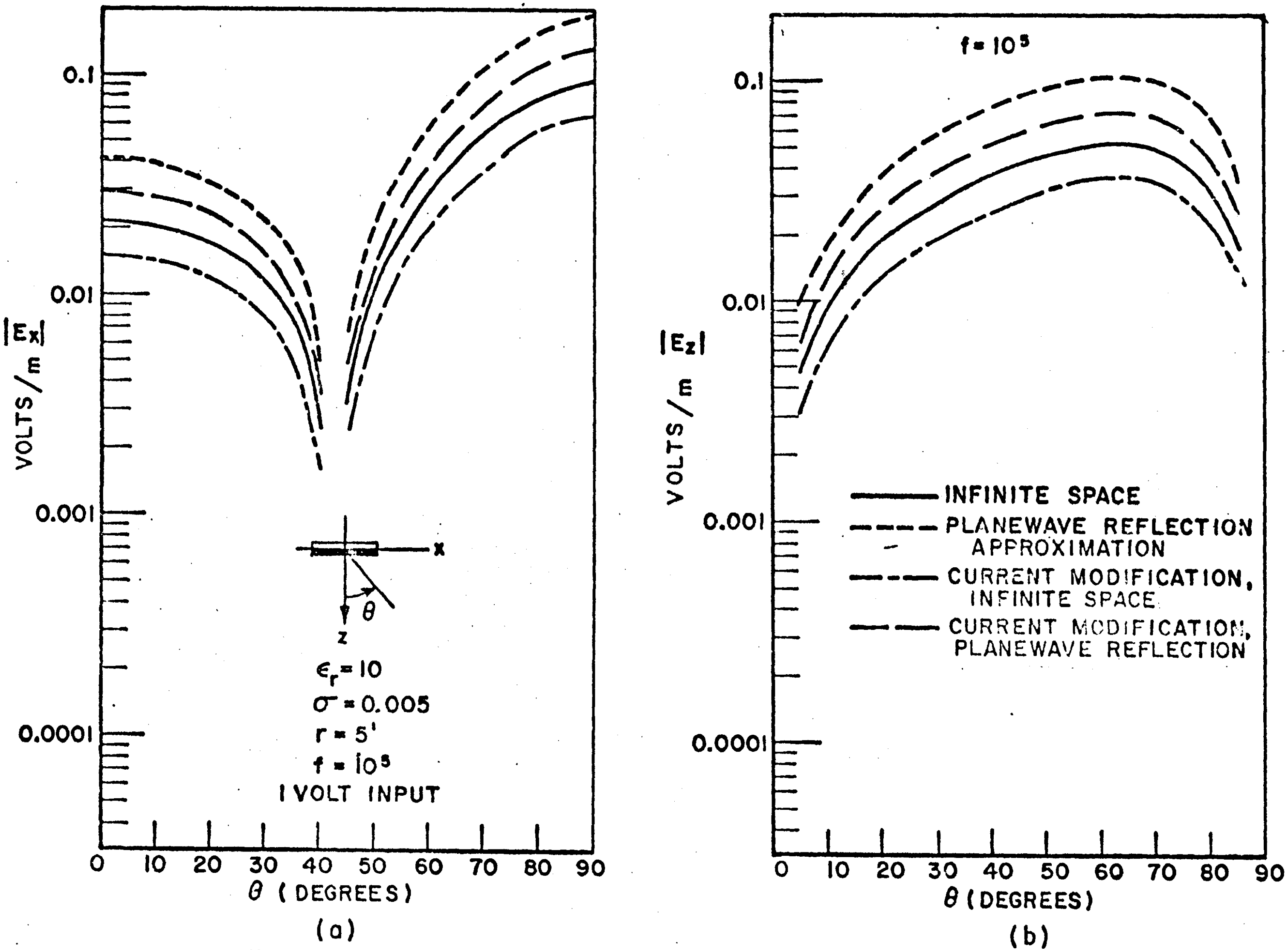

Fig. 1. Subsurface fields of 6 foot dipole, 100 KHz.
(a) x-component (b) z-component.

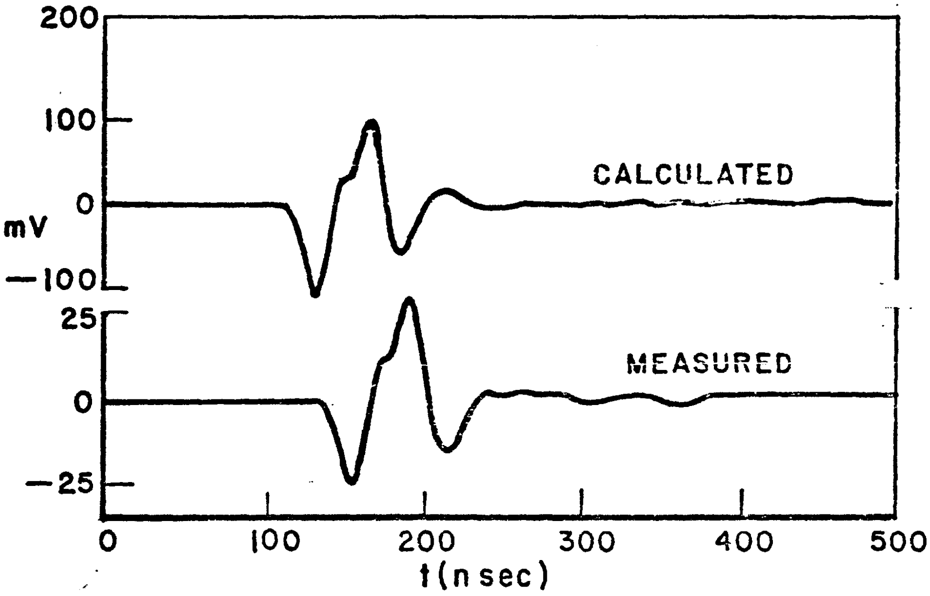

Fig. 2 Comparison of measured and calculated pulse transmission waveforms

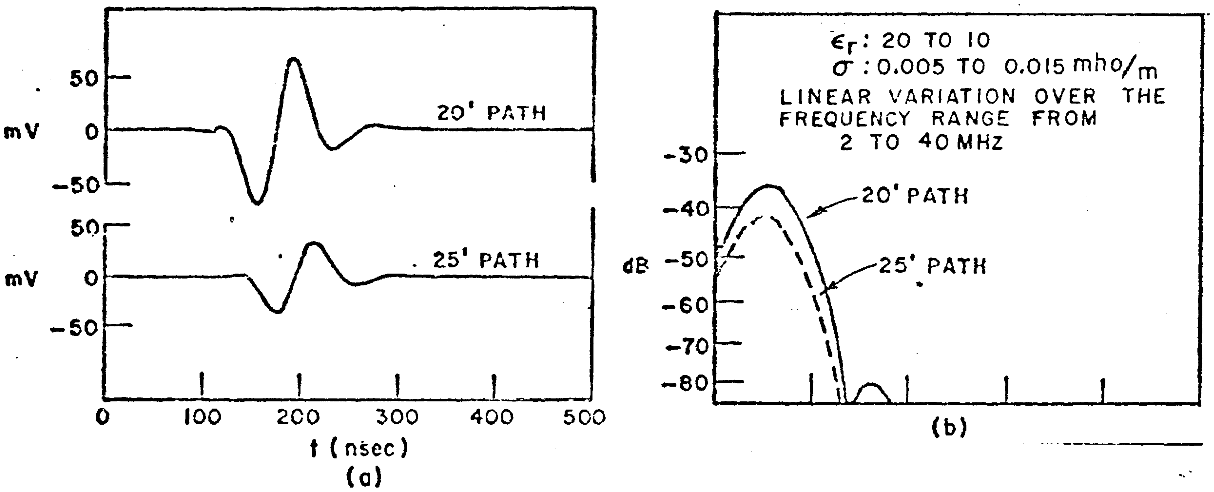

Fig. 3 Effect of dispersion on pulse propagation.
(a) time domain waveform
(b) amplitude spectra

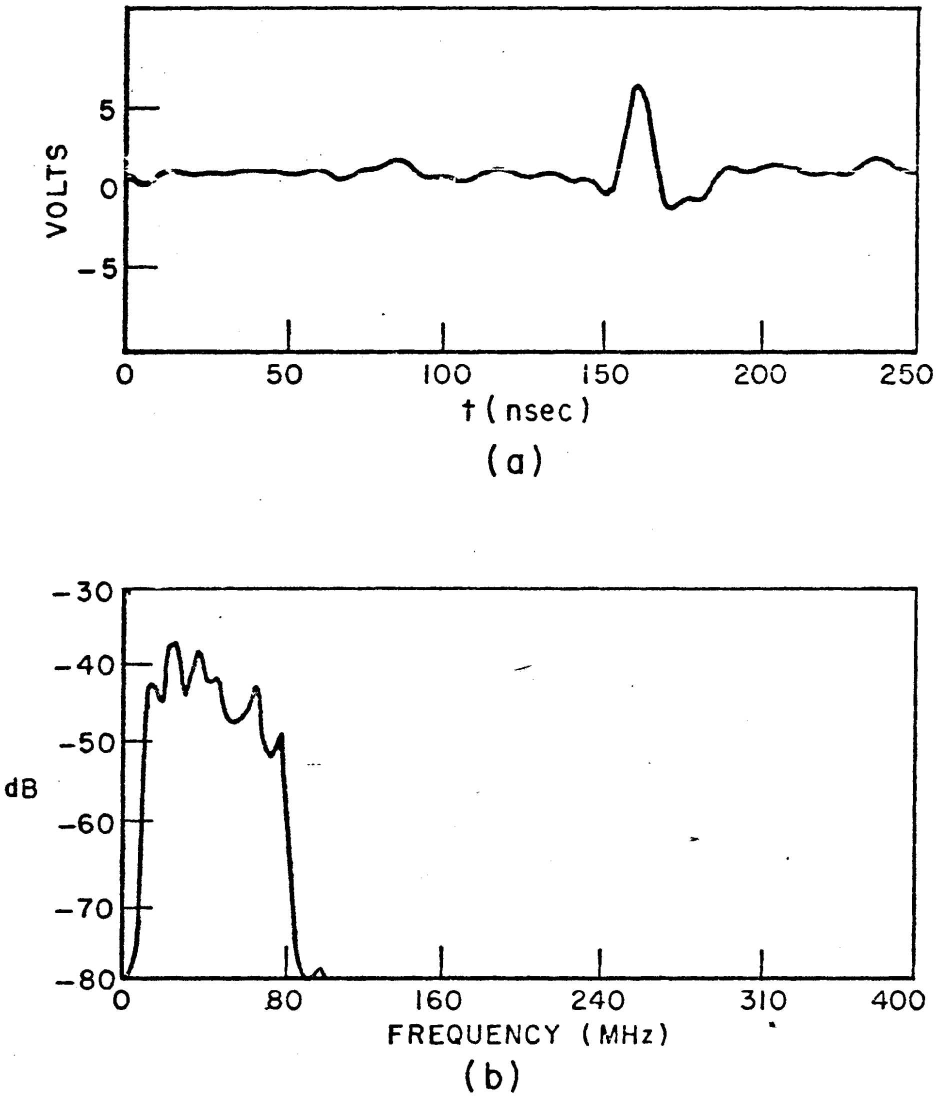

Fig. 4 Processed measurements over the tunnel.
(a) time domain waveform
(b) amplitude spectra.