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GPRMODEL: One-Dimensional Full Waveform Forward Modeling of Ground Penetrating Radar Data

by

Michael H. Powers[1], Steven K. Duke[2], Arlie C. Huffman III[1] and Gary R. Olhoeft[1]

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The U.S. Geological Survey preliminary computer program for modeling ground penetrating radar data is written in C for compilation with Intel 386/486 C Code Builder Kit, version 1.1a, to run under MS-DOS 3.0 or later on 80386/80387 or 80486 computers with 1 Mbyte or greater memory available to the program. Source code is included.

[1] U.S. Geological Survey, Box 25046, MS 964, Denver, CO 80225
[2] Currently with Woodward-Clyde Consultants, 2020 E. First St., Suite 900, Santa Ana, CA, 92705.

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System Requirements

Hardware: This program will run on most standard IBM-compatible personal computers with an 80386/80387 or 80486 central processing unit. It requires a screen with VGA or better graphics capability, at least 1 Mbyte of memory available to the executable program, and storage capacity (hard disk, floppy disk, etc.) of at least 1 Mbyte to hold the required software.

Software: The minimum software to run this program includes MS-DOS 3.0 or higher operating system, the executable file, and at least one transmission wavelet file. The transmission wavelet file must have an extension of .TRN and is described in detail in this report. Other files associated with radar field data can be used by the program, and are all described in this paper. To change the source code and re-compile the program requires the source code, a program editor, a 32-bit C compiler, Olhoeft's (1990) graphics library and include file, Pinson's (1991) window library and include file, standard C include files, and a C linker, librarian and binder. The program is only known to properly compile and link with the Intel 386/486 C Code Builder Kit, version 1.1a. Other compiler kits may or may not work.

Introduction

This program is designed to help the user obtain detailed information on the subsurface dielectric properties of a layered media from ground penetrating radar (GPR) data. Field radar data acquired with a calibrated antenna can be compared to model synthetic data. The user must have a data file containing the antenna output wavelet in air. He then describes an earth model of up to ten layers, defining the real and imaginary relative dielectric permittivity, the conductivity and thickness for each layer. The program assumes zero source-receiver offset, normal incidence, and no dispersion or scattering effects as it convolves the original wavelet with the appropriate transmission and reflection operators. The modeled response is displayed on the screen and, optionally, compared visually to a calibrated field scan.

Most radar antennas couple with the surface earth material and change their output response with changing surface dielectric properties. Field experience suggests that this effect is often expressed as a stretching or squeezing of the antenna output wavelet in time. Therefore, the user can optionally stretch or squeeze the starting transmission air wavelet such that the resulting modeled scan best matches the frequency content of his field scan.

The program enables the user to interactively change the earth model parameters and watch the response become more or less similar to the field data.

The user gains an understanding of how GPR data is affected by different material parameters and, once the best graphical fit is obtained, has a possible description of the shallow, subsurface electrical properties at the field site.

Successful use of this program to describe the electrical properties of a field site is equivalent to the technique of Time Domain Reflectometry (TDR) (Cole, 1977; Topp and others, 1980). Using TDR in the lab, one can measure the dielectric properties of a sample over a wide range of frequencies, but the lab sample may not adequately represent the in-situ material. Field TDR instruments are available, but are limited in depth to the distance the probe can be driven into the ground, and in frequency to the range of the instrument (Dalton and others, 1984; Topp and others, 1982a,b). Using GPR data and this program, the in-situ dielectric properties can be measured to the depth of the signal penetration without any invasive procedures. In general, depth of penetration of GPR data is greater for more resistive media. Olhoeft (1984) gives a short and useful discussion of the factors limiting radar penetration depth. The frequency range is limited to the return of the antenna output, similar to the range of the field TDR instruments.

The document describing the objective and theory of this program in more detail is Duke (1990). The forward modeling subroutines at the heart of this program were written by Duke and are described in detail in the above reference.

Basic Theory

The governing electromagnetic wave equation used by this program is

$$\frac{d^2E(z)}{dz^2} = -k^2E(z),$$

where **E** is the electric field vector, z is distance along the direction of propagation, and k is the wavenumber (or magnitude of the wave vector in the direction of propagation). Without any further physical understanding of this equation, a mathematical solution can be written as

$$E(z)=E_oe^{\pm ikz},$$

and, if a harmonic time-dependence is assumed, then

$$E(z,t)=Re[e^{i\omega t}E_oe^{\pm ikz}],$$

where ω is the angular frequency and t is time.

For electromagnetic propagation through a conductive media, the wavenumber is generalized to be

$$k^2 = \omega^2 \mu \epsilon - i\omega\mu\sigma.$$

In this program the imaginary parts of both the conductivity σ and the magnetic permeability μ are zero. It is further assumed that μ is everywhere equal to μ_o, the magnetic permeability of free space ($4\pi\ 10^{-7}$ H/m). The dielectric permittivity may have non-zero real and imaginary parts ($\epsilon = \epsilon' - i\epsilon''$). Other assumptions are (1) vertical, single-dimension propagation in the z-direction only, and (2) a lossy, source free medium characterized by horizontal layers with constant values of κ', κ'' and σ. The values κ' and κ'' are the real and imaginary parts of the relative dielectric permittivity, and are defined as

$$\kappa' = \epsilon'/\epsilon_o \text{ and } \kappa'' = \epsilon''/\epsilon_o$$

where ϵ_o is the permittivity of free space (8.854×10^{-12} Farads/meter).

Some confusion is created by different conventions in the literature regarding the wavenumber definition. In Duke (1990) and in some texts such as Ulaby, et al. (1981), the governing equation is written as

$$\frac{d^2E(z)}{dz^2} = -\omega^2 \mu \epsilon^* E(z),$$

where $k^2 = \omega^2 \mu \epsilon^*$. For this case ϵ^*, called the apparent complex dielectric permittivity, must be defined as

$$\epsilon^* = (\epsilon' - i\epsilon'') - i(\sigma'/\omega + i\sigma''/\omega).$$

In other publications, such as Olhoeft (1985), the same equation is represented as

$$\frac{d^2E(z)}{dz^2} = i\mu\omega\sigma_T E(z),$$

where $k^2 = -i\mu\omega\sigma_T$. Here, σ_T, known as the complex total electrical conductivity must be defined as

$$\sigma_T = (\sigma' + i\sigma'') + i\omega(\epsilon' - i\epsilon'').$$

The relationship that must hold to make both equations equally valid is $\sigma_T = i\omega\epsilon^*$.

When the real and imaginary parts of the two definitions are combined, the equations are

$$\sigma_T = (\sigma' + \omega\epsilon'') + i(\sigma'' + \omega\epsilon') \text{ and } \epsilon^* = (\epsilon' + \sigma''/\omega) - i(\epsilon'' + \sigma'/\omega).$$

The loss tangent, $\tan\delta$, is defined as the ratio of the real over the imaginary parts of σ_T, or as the ratio of the imaginary over the real parts of ϵ^*. Both lead to the same definition. When the imaginary part of the conductivity is zero ($\sigma''=0$), the loss tangent is

$$\tan\delta = [\frac{(\sigma+\omega\epsilon'')}{\omega\epsilon'}] \quad \text{or} \quad \tan\delta = \{\frac{[\kappa'' + \sigma/(\epsilon_0\omega)]}{\kappa'}\}.$$

Another form of the governing electromagnetic wave equation is

$$\frac{d^2E(z)}{dz^2} = \gamma^2 E(z),$$

where γ is defined as the propagation vector and is equal to ik. The propagation vector is a complex value. Its real part is defined as the attenuation vector, and its imaginary part is defined as the phase vector (IEEE Standard 211, 1990). (Note that the above definitions are consistent with the common mathematical convention that has the phase as the real part of the wavenumber k, and the attenuation as the imaginary part of k.) Some authors, including Duke (1990), Ulaby et al. (1981), and Ulriksen (1982) set $\gamma=(\alpha+i\beta)$ directly. Others set $k=(\beta-i\alpha)$ (King and Harrison, 1969). Both of these lead to α as the attenuation constant and β as the phase constant (magnitudes of the attenuation and phase vectors in the direction of propagation). Another common convention is to set $k=(\alpha-i\beta)$ (Lorrain and Corson, 1971; Ward and Hohmann, 1988), which simply reverses the roles of α and β. (In the GPRMODEL code, the attenuation and phase constants are defined as `k.i` and `k.r`, respectively, in subroutine `cprop()`.) The IEEE convention will be followed here, such that α is the attenuation constant and β the phase constant, as defined by $\gamma=(\alpha+i\beta)$ or $k=(\beta-i\alpha)$. The expressions for the two terms are as follows:

$$\beta = \omega\{\tfrac{1}{2}\mu\epsilon'[(1+\tan^2\delta)^{\frac{1}{2}}+1]\}^{\frac{1}{2}},$$

$$\alpha = \omega\{\tfrac{1}{2}\mu\epsilon'[(1+\tan^2\delta)^{\frac{1}{2}} - 1]\}^{\frac{1}{2}}.$$

Going back to the wave equation solution as

$$E(z,t) = Re[e^{i\omega t}E_o e^{\pm ikz}],$$

and substituting (β-iα) for k, one arrives at the propagation equation used for forward modeling;

$$E(z,t) = E_o e^{-\alpha z}\cos(\omega t \pm \beta z).$$

The model parameters input by the user are the real and imaginary parts of the relative dielectric permittivity, κ' and κ'', respectively; and the real conductivity and depth. Using these, the program calculates the loss tangent, and then α and β for each layer. Continuing, the above equation can be used to calculate the effects of propagation through the model.

In the program, transmission and reflection at layer boundaries and propagation through layers are achieved in the frequency domain. For each frequency in the starting wavelet (contained in the .TRN file described in detail below), the frequency dependent parameters α and β are found for each layer. The program starts by computing the transmission coefficient between air and the first layer, and traces down and back through the layers by computing appropriate transmission and reflection coefficients. They are calculated as

$$T = \frac{(2k_1)}{(k_1+k_2)} \qquad \text{and} \qquad R = \frac{(k_1-k_2)}{(k_1+k_2)},$$

where k_1 and k_2 are the complex wavenumbers of the two media ($k=\beta-i\alpha$). (See Balanis, 1989, for a comprehensive discussion of this material). After all the reflections have been calculated for every frequency, they are transformed back to the time domain, delayed to the appropriate two-way travel time, and summed to form the modeled trace.

The output graphic is a wiggle trace of amplitude versus time, and represents the zero-offset trace recorded at the surface above the model. In this program, the conversion from depth to time is made with a frequency independent velocity for each layer of $V=(c/\sqrt{\kappa'})$, where c is the speed of light in free space (0.2998 m/ns).

Input Files and Parameters

The user starts the program, loads information, and uses the screen graphics to learn by changing the earth model. In general, the information is loaded via one of three different paths.

The first and simplest is the specification of a transmission data filename and no other input files. In this case, no field data are ever displayed. The user creates earth models and observes the zero-offset, normal-incidence, two-way travel time response given the wavelet in his transmission file as the input. A sample run of this type is described below in detail.

The second method assumes the user wishes to compare the model response with raw field data. The required files are (1) a calibrated transmission air wavelet, (2) a raw field radar scan, (3) a range-gain file containing records associated with the raw field radar scan, and (4) a time-calibration file containing records associated with the raw field radar scan. A subroutine analyzes the time-calibration record(s) to determine the sample rate of the field data. Another subroutine analyzes the range-gain record(s) to determine the time-varying gain function applied to the raw field scan, and to remove it. A final subroutine allows the user to zero-out early parts of the field scan that may contain the unmodeled direct wave between two antennas in air. The resulting calibrated radar scan, after the raw field scan has the instrument gain removed, its sample rate determined and the direct wave zeroed, is stored with a filename extension of .CAL and used for comparison with the model synthetic data. A sample run of this procedure is also described in detail below.

The third form of input is to specify a previously saved model. When a model is saved a file is created with a .MOD extension. It contains ASCII data describing the current earth model parameters, the graphic display parameters, and the names of the transmission file and the calibrated field scan file if one was specified. The files are read, and the program displays the data.

The program uses standard extensions to identify file types. The following file formats are described below:

Filename extension	Contents of file	Format of data
.TRN	transmission wavelet file	513 doubles
.RAW	raw field radar scan	512 unsigned chars
.TC	time-calibration records	512 unsigned chars
.RG	range-gain records	512 unsigned chars
.CAL	calibrated field scan	513 doubles
.MOD	saved model file	ASCII data

Transmission wavelet file (.TRN) - The data in this file should describe the antenna response in air. A separate file is required for each unique antenna response. The program expects the data to be stored in binary as 513 double-precision floating-point values. The last one must be the sample rate in nanoseconds per point. The C code to read the file uses the following commands (where N=512):

```
char filename;
FILE f_tran;
double dtdata_in[N+2],trn_sample_rate;
...
f_tran=fopen(filename,"rb");  /* read binary */
fread(&dtdata_in[1],sizeof(double),N+1,f_tran);
...
trn_sample_rate=dtdata_in[N+1];
```

Raw field scan (.RAW) - A single radar scan of 512 character bytes (8-bit bytes) stored in binary format. This data typically has been through the instrument range-gain, and the only way of knowing its sample rate is to examine a time-calibration dataset recorded with the same instrument settings. The C code to read this file is as follows:

```
unsigned char ch_raw_data[N+1];
char filename;
double raw_data[N+1];
FILE *f_raw;
...
f_raw=fopen(filename,"rb");
fread(ch_raw_data,1,N,f_raw);
...
for(i=0;i<N;i++) raw_data[i+1]=(double)ch_raw_data[i];
```

Time-calibration records (.TC) - This file should contain one or more 512 character byte records in binary format just as the .RAW file described above. The data should represent an oscillating signal where the period of each cycle is 10 nanoseconds. At least one clean cycle is necessary, and several are preferable.

Range-gain records (.RG) - This file should also contain one or more 512 single character byte records just as the .RAW and .TC files. Each record should be an oscillating signal of constant frequency with amplitudes that increase with time according to the instrument range-gain present when the .RAW data was acquired.

Calibrated field scan (.CAL) - In the second of the three program input methods described above, this file is output. It is written in binary as 513 double-precision values where the last one is the field scan sample rate in ns/point. Its format is exactly the same as the .TRN transmission wavelet file. The data represents a single field scan with range-gain removed, initial direct-wave data that may have been optionally zeroed, and the sample rate attached. If a program run comparing modeled data with field data is saved, the name of this .CAL file is stored in the .MOD file (see below). A subsequent program run that starts by naming a .MOD file will read the .CAL file and use it for comparison with the modeled data.

Saved model file (.MOD) - When a user elects to save the information in a particular program run, a .MOD file is created. It is an ASCII file containing the current plot parameters, the number of layers in the current model and the layer parameters that make up the model, and the names of the transmission file and the calibrated field file. An example with a simple two layer model is as follows:

Plot title ==> 900 MHz Pulse Test
# of layers ==> 2
Δt ==> 0.036765
time offset ==> 2.400000
first ==> 0.000000
last ==> 18.786765
transmission file ==> 900.TRN
field file ==> E900.CAL
coupling ratio ==> 1.000000
Layer ==> 1
er ==> 1.000000
ei ==> 0.000000
conductivity ==> 0.000000
thickness ==> 1.000000
Layer ==> 2
er ==> 100.000000
ei ==> 0.000000
conductivity ==> 0.000000

Output Files and Graphics

Three different file types can be created by the program. The first two, a calibrated field scan and an ASCII model parameter file, can also be used for input. They were discussed in the preceding section on input files. The only other possible output file is an HP-GL (Hewlett-Packard Graphics Language) plot file. It is created by selecting the ***Alt-P*** option in the program, filling in the output filename (which the program gives an automatic extension of .PLT), and then creating a plot on the screen which is also written to the file. The plot file can be displayed using any device or software capable of interpreting HP-GL commands.

Primarily, the program involves the use of screen graphics as output. The user selects a starting wavelet (.TRN file) and, optionally, a field scan, and changes earth model parameters to see the response as a modeled scan on the screen (optionally compared to the field scan).

The Calibrated Transmission Wavelet

To simulate real radar data in the computer with a forward modeling program, the starting wavelet must be as close as possible to the starting wavelet entering the earth in the field. This wavelet can be considered as the convolution of a spike with the system electronics and the particular antenna radar characteristics.

For most ground penetrating radar antennas, the antenna output also varies as the dielectric permittivity of the media surrounding the antenna varies. This means the output wavelet of an antenna on dry sand will be different from the output wavelet of the same antenna on wet sand, and different again from the wavelet in air.

Thus, the antenna output will change with changes in (1) the system electronics (including changes in the range-gain function), (2) the configuration and geometry of the antenna itself, and (3) the material near the antenna. Ideally, one needs a new wavelet each time any of the above changes occur.

Duke (1990) measured the output response in air of four antennas. For three of these, he calibrated the wavelets by removing the system range-gain and the geometric spreading loss factor and by determining their sample rates such that they could be matched to field data. When the same system and same antennas are used to acquire field data and the range-gain is removed from the data, the only unaccounted difference between the model starting wavelet and the field starting wavelet is from the surface material-antenna coupling effects. These effects are assumed to be manifested as a simple stretching or squeezing in time of the wavelet measured in air, and the user is optionally allowed to perform this operation.

Stretching and squeezing the transmission wavelet is performed by user changes in the coupling ratio. From the main parameter screen, the user can change the coupling ratio by pressing ***Alt-R***. A small window appears on the screen showing the current value of the ratio, which can be edited. Following the entry of either a default to the value shown or of a new coupling ratio, a graphics screen appears. Both the original transmission wavelet (in white) and the current one (in yellow) which has been modified by the current coupling ratio, are shown in time and as power spectra in frequency. The dominant frequency is labeled for both cases (original and current).

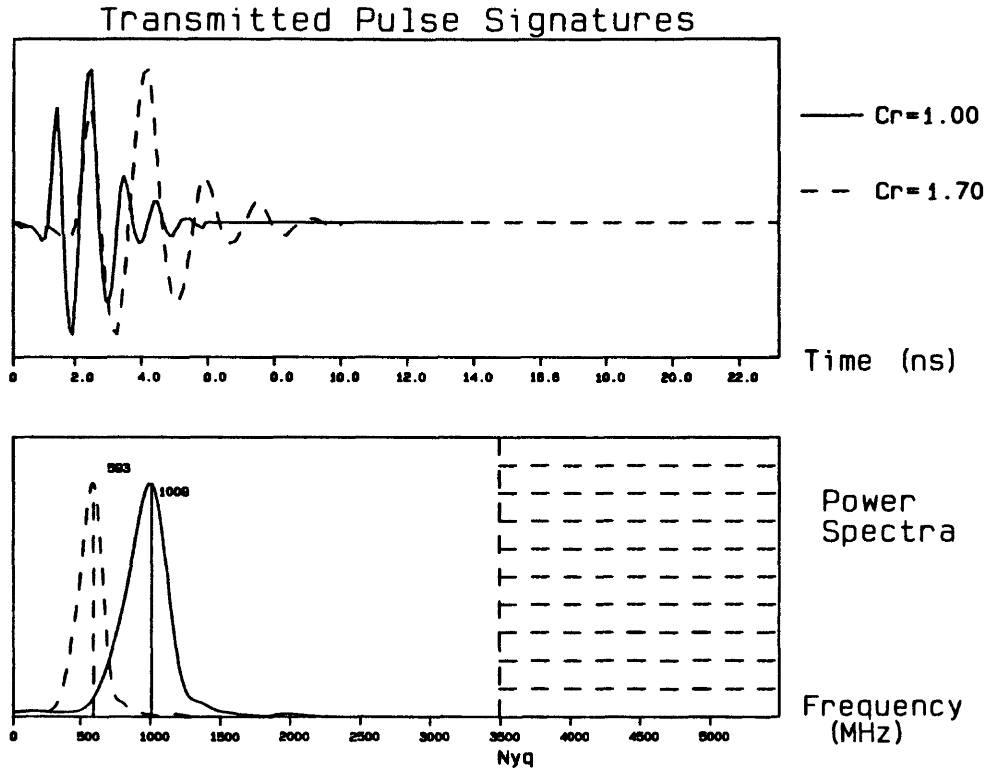

Figure 1. This plot is displayed on the screen when Alt-R is used to change the coupling ratio (Cr). A coupling ratio greater than one stretches the transmission wavelet prior to modeling and decreases the frequency content. This is used to simulate the effects of different ground materials coupling with the antenna and changing its dominant output frequencies.

As described in a later section on program sample rates, the transmission wavelet must be resampled to the display sample rate (Δt) prior to modeling. As the coupling ratio is lowered below 1.0, the transmission wavelet frequency content goes up. It is possible to create combinations of Δt and coupling ratio such that some of the frequencies in the transmission wavelet will be above the highest frequency allowed by the display sample rate (Δt Nyquist frequency equal to $1/2\Delta t$). If this occurs, a Hanning ramp filter zeroes the frequencies above the display Nyquist frequency. In cases where the display Nyquist frequency is below the highest Nyquist frequency of the two transmission wavelets (the original and the current one altered by the coupling ratio) the screen shows the display Nyquist frequency as a limiting high frequency on the power spectra plot (a magenta line).

To avoid altering the shape of the transmission wavelet, the user must keep this limiting frequency above the non-zero frequencies in the current wavelet (the yellow plot). This can be done by decreasing the display sample rate (raising its Nyquist frequency) or increasing the coupling ratio (lowering the frequency content of the current transmission wavelet). An example of the transmitted pulse display is shown in figure 1.

The transmission wavelet can also be stretched or squeezed by changing the coupling ratio interactively on the modeled data graphics screen (***Vary ON***).

To summarize, the data in the .TRN file should represent the wavelet in the field that enters the ground surface. As an approximation of this wavelet, our files 300.TRN, 500.TRN and 900.TRN represent the far-field output in air of the USGS-owned GSSI 300 MHz (Models 3205-T and 3205-T/R, Serial #026), 500 MHz (Model 3102, Serial #016) and 900 MHz (Model 101-A, Serial #88) antennas when used with the USGS-owned GSSI SIR System Model 700 control module. They have been corrected for the range-gain applied when they were recorded, and for an equivalent geometric spreading loss at zero distance. They contain sample rates such that they can be resampled to match different field sample rates. To approximate particular field coupling effects, they are stretched or squeezed as seems appropriate for particular field data.

The Calibrated Field Scan File

Currently, the USGS system for acquiring surface radar data is a GSSI SIR-7 control module with a DT-6000 digital tape recorder. Because the analog to digital conversion (A/D) is done with fixed eight-bit resolution, it is necessary to gain the late arrivals prior to digitization. In the computer, the eight-bit values which vary from 0 to 255 can be converted to double-precision floating point values. The gain can then be removed with the assurance that even slight signal variations can be recovered.

The gain applied in the field prior to the A/D must be recorded if it is to be removed later in the computer. The SIR-7 allows the user to record on tape a system-generated oscillating signal that has been fed through the Time Gain Amplifier. It applies the current settings of range-gain. This data is transferred to disk and stored with a .RG extension. Its format is described above in the section on input files. One range-gain file can contain one or many records of 512 values each.

On the SIR-7, the field operator can change the total record time by setting a range switch and a pot adjustment. To accurately determine the sample interval in nanoseconds between the 512 digital values recorded on tape for each scan, time-calibration records are also recorded to tape. Each of these is a 100 MHz signal digitized into 512 samples representing the same total record time as the field scans. A file of one or more of these records is transferred to disk and stored with a .TC filename extension. The format for this file is the same as the .RG file and also explained above in the section on input files.

A raw field scan consists of 512 values that each vary between 0 and 255. Alone, it represents data of unknown total time and has applied to it an unknown, time-variable gain. A calibrated field scan consists of 513 values that can vary from something like $10^{\pm 37}$ in absolute range. The last value is the sample interval time in nanoseconds. Alone, the calibrated field scan represents data of known total time and relative true amplitudes with respect to time.

Two subroutines convert a raw field scan to a calibrated field scan. The first requires a .TC file with one or more time-calibration records. The second requires a .RG file with one or more range-gain records. All of the records, the raw data, the .TC and the .RG, must correspond to the same field settings on the instrument.

The time-calibration subroutine reads in all of the 512 sample records in the .TC file and averages them if there are more than one. It then identifies complete cycles of the 100 MHz signal and finds the number of samples in each cycle. It returns an average and a standard deviation for nanoseconds per sample. The average is assumed to be the sample rate of the field data (variable `f_sample` in the code).

The range-gain subroutine (`display_gain()` which calls `remove_gain()` and `eliminate_field()`) reads in all of the 512 sample records in the .RG file. They are not averaged. For each one, minimum and maximum value envelope points are stored. The envelope functions are sampled more finely with each new record. After all the records have been read, a linear interpolation and extrapolation is performed on the minimum and maximum envelope functions to make them complete (512 samples in each). They are also forced to be monotonically increasing as this is a feature of the Time Gain Amplifier. A new field scan is built from the raw field scan by removing the gain approximated by the minimum and maximum envelope functions.

At the start of the record, our field data always contains a direct arrival that is undesirable because it is a system manifestation that says nothing of the subsurface, and it biases the amplitude scale (as the direct wave is typically far greater in amplitude than anything that follows). The user is presented with an interactive screen showing the new field scan, and can zero as much of the start of the scan as is desirable. Because the model response record starts with the first subsurface reflection, the goal is to zero the field scan to this point, masking out the direct arrivals. Often the end of the direct wave interferes with the first subsurface reflection. If some of the first reflection is zeroed, or included but with direct wave interference present, then an imperfect match of model versus field data should be expected at the first reflection.

The new field data consists of double precision floating-point values. At the end of the `display_gain()` subroutine, after calling `remove_gain()` and `eliminate_field()`, the field sample rate f_sample is attached as a 513th sample of the new ungained data. The new samples are then output as a calibrated field scan to a file with a .CAL extension.

If field data is acquired with a different system, perhaps one that has an instantaneous floating point representation prior to digitization such that no field gain is applied, and if the sample rate is known, then the user can create a .CAL file directly. Just store the data in the format described in the section on input files. In this case, no .TC or .RG files would exist, and the user would say *No* to the question on importing raw field data. ***Alt-F*** should be used to import the .CAL once a model is described.

Program Sample Rates

In the code, there are three general sample rate values: t_sample, the sample rate of the transmission file data; f_sample, the sample rate of the field data; and sample, the display sample rate shown on the screen as Δt and allowed to be set by the user.

When the user is only modeling and has no field data, Δt is by default set to t_sample when the .TRN file is read. If ***Alt-T*** is used to bring in a new .TRN wavelet, Δt retains its first value and is not reset to the new t_sample. Also, the user is always allowed to change Δt. In every case, the .TRN data is resampled to match the current display rate (Δt) before the modeling begins.

The user can change the frequency content of the transmission wavelet by changing the coupling ratio (cr). Pressing ***Alt-R***, or changing the variable cr on the interactive graphics screen, changes the coupling ratio by calling the resample() algorithm. For values of cr greater than one, the frequencies in the transmission wavelet are decreased, and the wavelet is stretched in time. For values of cr less than one, the frequencies in the transmission wavelet are increased, and the wavelet is squeezed in time. The ***Alt-R*** graphics screen shows the .TRN wavelet displayed in white with its original sample rate (t_sample) and original frequency content. It is displayed in yellow to show its current sample rate (t_sample*cr) and associated current frequency content.

The user must keep in mind that every Δt has an associated Nyquist frequency (equal to $1/(2\Delta t)$). Any signal frequencies higher than the current Δt Nyquist frequency would be aliased if not filtered out. The resample algorithm has an anti-alias filter. If Δt is too large for the current .TRN, the anti-alias filter will remove some of the .TRN signal frequencies. This will result in a distorted shape to the transmission wavelet and the resulting model synthetic response. There is no warning or check against setting a combination of Δt and cr such that the transmission wavelet is altered. But, by pressing *Alt-R*, the user can see if the anti-alias filter is effecting the wavelet. If the Δt Nyquist frequency is lower than the Nyquist frequency associated with t_sample and t_sample*cr, it will show up as a magenta line on the *Alt-R* graph. To keep from distorting the wavelet, the user must keep the magenta line above any non-zero values in the current, yellow wavelet frequencies. This can be done by increasing cr, or decreasing Δt.

Besides its primary purpose of matching the frequency content of the modeled data to that of field data, the coupling ratio can be used in modeling only. For example, imagine one wants to model an 80 MHz antenna over 10 meters of fresh water, but has a lowest frequency calibrated transmission wavelet of 300 MHz. The first arrival from the water bottom will be at about 600 nanoseconds. A display sample rate of 2 nanoseconds will show 1024 nanoseconds of data, which may be required to show the full desired response. Unfortunately, the Nyquist frequency of a 2 ns sample rate is 250 MHz, which will alter the 300 MHz wavelet. If the coupling ratio is set to 4, the user can approximate a lower frequency antenna, while using the undistorted wavelet shape of the 300 MHz antenna.

When *Alt-T* is used to bring in a new transmission wavelet, the display sample rate is not changed, but the coupling ratio is reset to 1.0 and the transmission wavelet is resampled to match the existing display sample rate.

When the user brings in field data to compare with a model response, the display sample rate (Δt, or sample in the code) is set equal to the field sample rate (f_sample), and the transmission wavelet is resampled to match prior to modeling. The field sample rate of a raw field scan is calculated by using the time-calibration records as described in the section on the calibrated field scan file. When the time-calibration subroutine finds f_sample, it sets sample equal to f_sample. For a particular raw field scan, this process only needs to be done once, as the field scan is then corrected for range-gain and stored with its f_sample as a calibrated field scan (.CAL file). Whenever a calibrated field scan is brought into the program, either by importing a .MOD file or using *Alt-F* to read a .CAL file directly, then sample is set equal to the new f_sample.

Whenever sample (Δt) is changed by the user, the transmission wavelet is resampled to match the new display sample rate before modeling. If Δt is changed by the user during a comparison run, and no longer is equal to either f_sample or t_sample, then both the transmission wavelet and the field data are resampled before modeling and display, respectively. Note that a new, smaller Δt loses late time data, as the maximum available display is always from 0 ns to (512*Δt) ns.

In most cases, the display sample rate will not need to be changed. If it is changed to see longer in time or more finely sample a wavelet, the user must keep in mind the Nyquist frequencies of the transmission wavelet (after alteration by the coupling ratio) and the field scan. This can be boiled down to a simple advisement: be careful about large changes in Δt, small changes are okay.

Sample Run #1: Modeling Only

For this run, the minimum hardware requirements are an 80386/80387 machine with a color screen and VGA graphics. Also required is a copy of the executable program GPRMODEL.EXE, and one or more transmission wavelet files such as 300.TRN, 500.TRN and 900.TRN. Imagine the task at hand is to simulate the case where a radar pulse goes through two meters of air, hits an aluminum sheet and is reflected back to the receiver.

The program is started by typing ***gprmodel*** followed by a screen code number. Type ***gprmodel*** and return to find the correct code number. After starting the program with the appropriate screen code number, continue through the introductory screens until asked to make a choice between *Input or Create*. Because a previously saved file with extension .MOD does not exist at this point, choose to *Create* a model. To use the 300 MHz antenna, type ***300*** for the transmission file. The number of layers is ***2***, a title might be ***Pulse Test***, and because no field data exists to match this model, answer ***No*** to the question on importing raw field data.

Now on the screen should be a display of the model parameters. Input the following values:

Layer 1 -	$\kappa'=1.0$,	$\kappa''=0.0$,	$\sigma=0.0$,	thickness=2.0;
Layer 2 -	$\kappa'=100.0$,	$\kappa''=100.0$,	$\sigma=10000.0$.	

Default through the sample rate (Δt), first, last and offset, which are display parameters. One more carriage return should lead to a graphical display of the data.

At this point, all that can be done with this display is to look at it. Note the total record time is 512 times Δt. The current display sample rate, Δt, has been picked up from the .TRN file, and is the sample rate of the transmission wavelet as stored. (See the above section on sample rates.) Note a simple graphical representation of the model is drawn on the right side of the screen using the blue lines as layer boundaries. The parameters of each layer are shown. Also displayed at the bottom are the current values of offset and coupling ratio. Optionally, all of these displayed parameters can be varied interactively.

Pressing any key will return to the parameter screen. Back at the parameter screen, press ***Alt-V*** and study the information window. Now by pressing two ***Returns***, the program returns to the graphics screen in interactive mode. The first parameter of the first layer should be highlighted in red. This parameter can be increased by using the Home, Up Arrow, and Page Up keys. It can be decreased with the End, Down Arrow and Page Down keys. The Right Arrow and Left Arrow keys move the highlight to a neighboring parameter. At any time, Enter or Carriage Return will calculate and display the new synthetic trace. By changing the parameters of the layer one material, one can immediately watch the corresponding response change. Increasing the coupling ratio stretches the wavelet, and decreasing the ratio squeezes it. Note that changing offset does nothing. Offset moves the field data in nanoseconds, and has no effect when field data are not present. Press ***Esc*** to return to the parameter screen.

A new transmission wavelet can be used by pressing ***Alt-T***. Note that the display sample rate does not change. ***Alt-R*** will show the power spectrum of the current transmission wavelet in case there is some concern that it is being altered by a display sample rate that is too coarse.

Alt-S allows the current model parameters to be saved without exiting the program. If a calibrated field scan existed that was acquired by bouncing one of the available .TRN wavelets off of a perfect reflector in air, ***Alt-F*** could be used to bring it into the program for comparison. ***Alt-P*** allows the user to name an output plot file. After doing so, the next graphics screen that is created, either the modeled data or the wavelet shown by ***Alt-R***, will be drawn on the screen and simultaneously written to the named file as a set of HP-GL commands. ***Alt-O*** allows the activation of some optional calculations. Multiples are only calculated in the case of three or more layers. The power difference is only calculated when a field scan is available for comparison to the modeled data.

The parameters first, last and Δt effect the display only. They can be used to zoom in on a window of the data. The above section on sample rates gives information on the effects of changing Δt. The program is exited by pressing ***F10***, and answering the questions.

Sample Run #2: Comparison of Field and Modeled Data

The requirements for this run are 1) all of the hardware and software described above for modeling only, and 2) either a calibrated field scan file or a set of three files representing a) a raw field data scan, b) time-calibration records, and c) range-gain records. See the section on the calibrated field scan file for more information on these files.

A sample dataset of 900 MHz data from the Great Sand Dunes National Monument in the San Luis Valley of Colorado is provided with the code. The files are named 900.RAW, 900.TC, 900.RG, 900.CAL and 900.MOD. The .CAL and .MOD files are really the output of a previous run, and are not necessary to get started. On the other hand, once they are created they contain the essence of the program's output, and can be used to shortcut the input process straight to a solution.

Start the program as before by typing *gprmodel* <code #>. If 900.TRN, 900.CAL and 900.MOD are present, and the user wants to cut straight to the comparison, select *Import* and type ***900***. If the user wants to see the process of creating the 900.CAL using 900.RAW, 900.TC and 900.RG (it's a fast process), select *Create*. Type ***900*** for the transmission file, choose ***4*** layers, type in any appropriate title, and say *Yes* to import raw field data. The next three files all have the name ***900***.

The program should now display the time-calibration information. After pressing ***Return***, the range-gain estimation takes place. Depending on the number of records in the file and the speed of the computer, this may take a few moments. A message tells the user when the process is completed. Press ***Return*** again to proceed to the direct arrival elimination. For this data, the early part of the trace should be zeroed to sample #82. This is achieved by moving the blue line with the Right Arrow key until the number 82 is displayed, and then pressing ***Return***.

The screen should now show the model parameters for four layers. If the 900.MOD file was *Import*ed, the parameters will be filled out. If the model was *Create*d, the parameter values will need to be input. Try the following:

Layer 1:	$\kappa'=3.55$,	$\kappa''=0.00$,	$\sigma=0.25$,	thickness=0.39;
Layer 2:	$\kappa'=4.00$,	$\kappa''=0.03$,	$\sigma=0.10$,	thickness=0.37;
Layer 3:	$\kappa'=4.10$,	$\kappa''=0.08$,	$\sigma=1.10$,	thickness=0.88;
Layer 4:	$\kappa'=5.20$,	$\kappa''=0.15$,	$\sigma=1.50$;	

Use the default values of Δt (0.143) and first (0.0). The values of last and offset should be changed to 32 and -6.8, respectively. A final ***Return*** or two will take the program to the graphics screen showing the comparison.

Notice that although the field (red) and modeled (yellow) traces are somewhat similar, they have significant differences. Go back to the parameter screen and change the offset to -5.2. Use ***Alt-R*** to change the coupling ratio to 1.7. Now a return to the comparison should snow it to be better (figure 2). Evidently, the 900 MHz antenna output in air is modified to a dominant frequency of about 590 MHz when it is on dry sand. The frequency spectra comparison of this case is shown in figure 1.

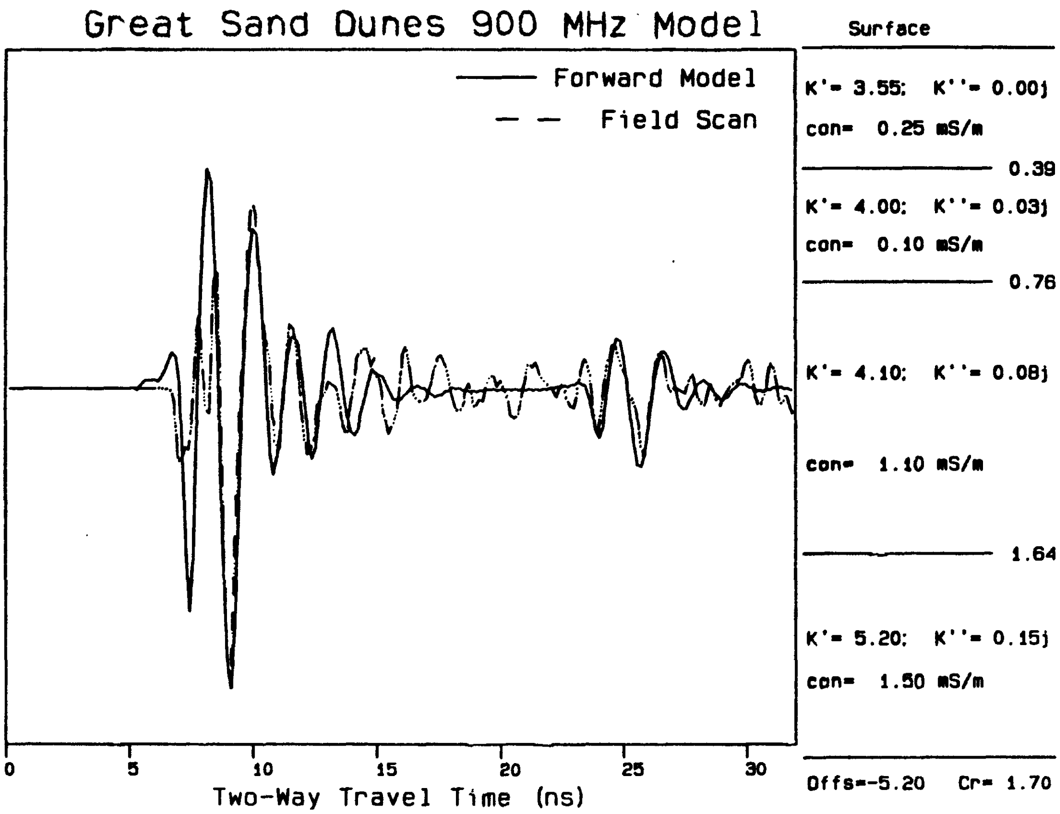

Figure 2. The primary display screen showing a comparison of model synthetic data and field data. The model is displayed to the right, with parameters shown for each layer. Numbers to the right of the layer boundary lines are depths in meters.

Next, return to the parameter screen and select ***Alt-V***. Study the information window and return to the graphical comparison. Now it is possible to move to different parameters (highlighted in red) and interactively change them. Press ***Return*** or ***Enter*** to see their effect. This is a major feature of the program. Press ***Esc*** to return to the parameter screen.

A useful trick for comparing various matches between the field and modeled traces is to first turn on the *Power difference* option within the ***Alt-O*** menu, and then select ***Alt-V*** to change parameters interactively on the graphics screen. The match with the lowest power difference may be the best. (This is certainly not always the case. With this dataset, if κ' for layer two is decreased to 3.8 the power difference decreases, but the match is not improved. This is because the direct arrival interferes with the first reflection, making it lower in amplitude than it likely should be.) For this dataset, it is interesting to try different combinations of coupling ratio and offset, or maybe a thin layer between layers two and three. Only the user's judgement can determine the best fit.

From the parameter screen, Press ***F10*** to leave the program.

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