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# Modeling and Experimental Support for Detection of Linear Conductors Task Authorization 3: Electromagnetic Propagation Model Upgrade

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Research Centre (SRC)**

**Revision 1.1  
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## 1 Introduction

There is an ongoing research program at Defence Research and Development Canada (DRDC) Suffield Research Centre (SRC) to explore electromagnetic (EM) scattering from linear conductors to better understand the physical phenomena governing this effect. The purpose of this contract is to provide technical expertise to supplement the efforts at DRDC by furthering the research on EM scattering through experimental and theoretical means.

The need to detect linear conductors is pertinent to military and commercial interests. A number of commercial applications would benefit from a reliable method to detect buried infrastructure such as wires, pipes, rods and other infrastructure critical to the delivery of crucial services to consumers. Detection of these conductors would help to significantly reduce the number of occurrences resulting in interruptions to power, water and communications services that result from excavation operations. This would directly result in time and money savings for businesses and consumers alike and help alleviate associated safety and environmental concerns.

A principal consideration in many of the detection schemes proposed and examined (C-CORE 2013, 2016) is the propagation of transmitted EM fields over different ground types. The International Telecommunications Union (ITU) developed a software application called GRWAVE that calculates these parameters (International Telecommunications Union 2007). This software was originally developed over three decades ago using the FORTRAN programming language. There is a need for a modernized version of this software that can be incorporated into different linear conduction detection models. The original GRWAVE software has been translated into C-Sharp (C#), a modern programming language, and has been given a graphical user interface (GUI) for ease of use. The outputs of this new software compare favourably to those of the original ITU version.

This work has been carried out under Task Authorization (TA) 3 entitled “Electromagnetic Propagation Model Upgrade.” This TA is authorized under contract No. W7702-175832/001/EDM with DRDC Suffield.

### 1.1 Scope

This report provides an overview of the work carried out to translate the existing FORTRAN code into a modern programming language, C#. The program structure is outlined at a high level and the constituent functions have been described. Comparisons between the outputs from the two versions have been made. Suggestions for further enhancement of this software are also presented.

### 1.2 Definitions

Acronym	Definition
AM	Amplitude Modulation
DLL	Dynamic Link Library
DRDC	Defence Research and Development Canada
EM	Electromagnetic
GUI	Graphical User Interface



Acronym	Definition
ITU	International Telecommunications Union
PC	Personal Computer
SRC	Suffield Research Centre
TA	Task Authorization

## 2 Background

Broadcast transmissions between 10 kHz and 30 MHz are affected by the properties of the ground, the curvature of the earth and tropospheric conditions, which often refract the signals. Propagation can take place directly over intermediate paths between transmitter and receiver according to Sommerfeld theory, or as a surface or creeping wave over long paths beyond the optical horizon. Paths involving reflections from the ionosphere are not considered in this report. Moreover, it is assumed that the earth is a smooth homogeneous sphere, which is a serious simplification.

The original theory for this model was developed by Rotheram (1981a, 1981b) and this was itself based on a large body of previous work. This led to the development of computer code, called GRWAVE, which calculates the electric field at a distance from a transmitter. The transmitter and receiver can be located at different heights above the earth's surface. The code also takes into account the ground properties through specification of the ground permittivity and conductivity. It is assumed that the refractive index of the air falls off with height exponentially and this typically causes rays to be refracted downwards slightly, so that the effective radius of the earth is increased over its physical value.

As is well known, AM broadcast transmitters are vertically polarized. The transmitting antenna is usually a vertical monopole placed over a horizontal set of wires, which form a good approximation to a perfectly conducting ground plane. Therefore, the antenna can be regarded as a vertical dipole formed by the monopole and its image in the ground plane: the charges associated with the image are opposite in sign to those on the monopole. The propagating electromagnetic waves pass over the earth and induce currents in it. When the earth is highly conducting, the entire process can be handled by image theory. Then it is clear that the electric field, some distance away from the transmitter and near the earth's surface, will be almost vertical but at long distances, rays will be refracted around the curvature of the earth and that this is likely to lead to enhanced signal attenuation. Finite conductivity of the ground changes this picture in that significant horizontal electric fields are created in the direction of propagation. These are associated with the induced currents. Ground dissipation tends to increase attenuation but enhances the surface wave components, which are desirable to penetrate beyond the horizon.

In the AM band, ionospheric propagation (or skywave effect) is not usually present during the day because signals at frequencies less than 1 MHz tend to be absorbed because of a high collision rate between ionospheric electrons and the neutral atmosphere. However, at night the ionospheric layers tend to rise into a less dense atmosphere and the collision frequency of the electrons is usually sufficiently small to allow propagation over hundreds of kilometers. Thus reliable communication must be based on ground wave propagation.

At HF frequencies of a few megahertz, propagation around the surface of the earth and long distance communication by refraction is not effective using the ground wave. This is why Marconi employed low frequencies (Belrose 1995). However, high frequencies penetrate the lower ionospheric layers and tend to be reflected by ionospheric layers at heights between 100 km and 450 km. Therefore, HF antennas are usually designed for ionospheric propagation, which implies that the radiated power should be directed partly upwards. This can be achieved using horizontally polarized antennas over a ground plane. It is important to note that the image of a horizontal antenna in a perfectly conducting plane constitutes another horizontal antenna with charges and currents in the opposite sense to the physical antenna.

Therefore, at some distance from the transmitter and near the ground, the fields tend to cancel and ground wave communication is typically very poor even over highly conducting ground.

The extension of the theory to non-homogeneous ground and obstacles is described by Millington and Isted (1950) and this has been combined with GRWAVE and topographical maps by several workers (Whittington and Thomas 1992; Crego García 2009; Barclay 2008). GRWAVE can be executed from another program, written in another language, such as MATLAB (Crego García 2009). This is possible because GRWAVE can be executed using the command prompt and reads input data from a file; output data can also be written to a file. These files permit the parameters and propagation information to be transferred to and from the primary program.

GRWAVE is freely available from the International Telecommunications Union (ITU)<sup>1</sup> (International Telecommunications Union 2007). They supply the source and executable codes. In addition they suggest ground permittivity and conductivity data for different soils. The principal factor affecting the soil parameters is the moisture content.

The GRWAVE source code is written in archaic FORTRAN. Structures, such as IF-THEN-ELSE-ENDIF, are rarely employed. The executable was compiled using a 16-bit compiler. The executable will run on a 32-bit personal computer with a Microsoft Windows operating system but not directly on a 64-bit machine. Evidently the project is the result of several iterations, which include modifications for various FORTRAN compilers. It is not likely that it would compile and run easily, even using a modern FORTRAN compiler. Therefore, the program has been re-written in C#, which offers the possibility of easily creating a GRWAVE-64 assembly (Dynamically Linked Library (DLL)), which can be called by a GUI written in C#, C++ or Visual Basic.

The primary objective of this work is to translate the source code into a working version in C#. The results from this are compared with those from the 16-bit executable version. Secondary objectives are the replacement of the unstructured code and verification that the FORTRAN source code matches the executable outputs and contains no obvious errors.

The source code refers to three reports, SRI, SRII and SRIII, where SR seems to refer to Steve Rotheram. The first two reports are probably Rotheram (1981a, 1981b) but there seems to be no information about the third, which seems to have been very comprehensive; its apparent unavailability is unfortunate.

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<sup>1</sup> <http://www.itu.int/en/ITU-R/study-groups/rsg3/Pages/iono-tropo-spheric.aspx>

### 3 GRWAVE Code and Translation

#### 3.1 Original GRWAVE

The ITU download includes the source code, the executable, a manual and an example input file. The code includes a set of default parameters. For example, the default frequency is 1 MHz and the ground type is salt water with a relative permittivity of 75 and a conductivity of 5 S/m. The antenna heights (of the base above ground) are 50 m for the transmitter and 100 m for the notional receiver. On a computer based on the 386 processor, new input information can be entered on the command line in the command prompt window. It is not necessary to enter all the parameters but just those that need changing from the default values. Similarly, the input information can be read from a file by entering:

```
GRWAVE < InputFile.txt
```

The output can also be routed to a file, using a command, such as:

```
GRWAVE <InputFile.txt >OutputFile.txt
```

One of the input variables is an integer DEBUG. If this is set to 2, a large set of intermediate values are output and these enable quite detailed comparisons to be made between the values created by the existing original program and those from a new version in another language, say.

For example, to run the default input values but to store the detailed output in the file "OutputFile.txt", the file "Inputfile.txt", should contain the following:

```
IDEBUG 2  
  
GO  
  
STOP
```

More generally, to change ground properties, the station heights, the polarization to horizontal and the frequency, the input file might contain:

```
EPSLON 3  
  
SIGMA 0.0001  
  
HTT 0  
  
HRR 0  
  
IDEBUG 2  
  
IPOLRN 2
```

FREQ 30

GO

STOP

For vertical polarization IPOLRN should be set to 1.

Though the original GRWAVE was designed for a 16-bit machine, the program floating point variables are typically 64-bit (“double”). Complex numbers are typically a pair of “double”. In a 16-bit machine “float” and “double” are implemented in software, whereas in a 64-bit machine they are implemented in hardware. Therefore, the 64-bit machine is much faster and GRWAVE, which formerly took minutes to run, now takes less than one second.

In the new C# program, all floating point variables are “double”. This implies that we should expect the results to be very close to within at least 6 or 7 decimal places. To facilitate comparisons, the new program employs similar constant values as the original, even though some of these are clearly approximate (such as the speed of light). Some disparities will be discussed below.

### 3.2 The FORTRAN Code

The original FORTRAN program dates from 1985. There are a number of functions at the end of the program that are redundant from our perspective; these deal with character and number handling. The elimination of these yields 32 functions and subroutines covering about 50 pages of code. Some of this code represents verbose FORTRAN outputs and is not required, so that the task was tractable.

Early FORTRAN did not lend itself to structured programming and the GRWAVE code is no exception. The occurrence of many GOTO statements in GRWAVE is a characteristic of poor technique but this is typical of the time. However, it can sometimes be difficult to translate this type of unstructured code.

In 1985 and earlier, compilers were not particularly intelligent so that the authors adopted methods to increase runtime speeds by introducing an excess of variables, which represented partial calculations that would have been repeated in the code. This affects readability.

The programming style is such that the relationship of a variable to a physical quantity tends to be easily lost. Short variable names were employed, as was customary, and these tend to be difficult to relate to theory.

The new code has been developed in Microsoft’s Visual Studio and uses Windows forms with the same set of default input variables as the original. This calls a class GRWAVE, which performs the calculation of the electric field along a path between the transmitter and receiver in the presence of a conducting earth. The output is a file of electric fields, which can be used to compare the results either with ITU graphs or digital output from other sources. The calculated electric field is the component matching the polarization

of the transmitting antenna. The original GRWAVE permitted the simultaneous calculation for several pairs of transmitters and receivers but the new version is for just one transmitter and receiver.

Several FORTRAN COMMON blocks are employed and some of these have been replaced by classes that contain the input static variables, such as the input variables. (For example, the COMMON block “BUGGER” is replaced by the input class noted above.) This ensures that these variables can be accessed throughout the program. In the original code, there is no attempt to group the variables or sub-programs in a rational way.

The program first attempts to use the residue approach, which is appropriate to the far field. The field at the maximum distance is calculated and then the distance is progressively decremented until the residue method is not valid. At this point, the calculations switch to the Sommerfeld approach and the field is calculated at the nearest distance followed by increments until the distance is equal to that where the residue approach is valid. For large transmitter and receiver heights, the calculations are based on geometrical optics theory and include reflection from the ground.

### 3.3 Structural Changes

As noted, the new program is written in C#, which closely resembles C and C++. The code in PROF is only a few lines and this subroutine is only used once. Therefore, the code has been transferred to the new routine “Grwave”. The same applies to the subroutine MODIFY. Code for ABS2 has been included with the complex number routines; this is worthwhile because ABS2 is employed a number of times in the original code; it returns the square of the absolute value of a complex number.

During translation attempts were made to replace the unstructured code but this was with limited success because it was often difficult to understand and follow the code. Nevertheless, some important routines, such as the residue calculation, have been entirely recoded.

### 3.4 GRWAVE FORTRAN Subroutines and Functions

Table 1 provides a list of the original FORTRAN routines, along with the relationships to the common blocks. The names of these routines and the names of variables within them have mostly been retained. The relationships of the routines and common blocks are listed in Table 2.

Table 1. GRWAVE routines and common blocks.

Number	Name	Functionality	Blocks
R-1	Program ROTHRM	Main program. Sets default input values and reads actual values.  Calls: GRWAVE	INTGR REAL
R-2	GRWAVE	Computes field strength-distance variation for a homogeneous curved earth with exponentially decreasing refractive index.  Calls: PROF, MODIFY, RESIDH, GEOMOP	BUGGER EARTH BROCK

Number	Name	Functionality	Blocks
R-3	PROF	Reads the surface refractivity NS in N-units and height scale in km for the exponential refractivity variation and computes related parameters.	BUGGER
R-4	MODIFY	Modifies the values of psi0, del, and k0 for vertical polarization.	BUGGER
R-5	ABS2	Computes the square of the modulus of a complex variable.	-
R-6	BTLC	Computes the basic transmission loss constant (in dB) assuming perfectly conducting ground near the aerials	-
R-7	PFUNCS	Computes the function P and its first N derivatives.	BUGGER PEES PEXCIT EARTH
R-8	TPOINT	Computes the turning point of the differential equation.  Calls: PFUNCS.	BUGGER
R-9	ZXI	Function used in PSTART.	-
R-10	ZPSI	Function used in PSTART.	-
R-11	RUNKT1	Performs a single step of the 4 <sup>th</sup> order Runge-Kutta method.	-
R-12	RUNKT2	Integrates the N first order equations.  Calls: RUNKT1	BUGGER STEP
R-13	BLOCK DATA	Weights and abscissae for 16 point Gaussian quadrature, etc.	-
R-14	PINT	Computes the phase integral and derivatives.  Calls PFUNCS.	BUGGER PEES QUAD16
R-15	PSTART	Computes an initial value for the propagation constant, p0[m], derived from a uniform approximation based on an Airy integral.  Calls: RUNKT2, TPOINT, PINT, ZXI, ZPSI.	BUGGER PEES PEXCIT AIRYS HCHITE
R-16	HFI	Seems to find part of a differential equation.  Calls: HIFITAU, PFUNCS.	BUGGER PEES STEP
R-17	HR	See above.  Calls: HRTAU, PFUNCS.	BUGGER PEES STEP
R-18	EIGEN	Computes the propagation constant p0[m] and excitation factor for the m <sup>th</sup> mode.  Calls: PSTART, TPOINT, PFUNCS, RUNKT2.	BUGGER PEES PEXCIT TURNPT
R-19	NEWHTG	Computes the height-gain function. If the integration fails, use another routine in RESIDH.	BUGGER HCHITE

Number	Name	Functionality	Blocks
		Calls: RUNKT2.	
R-20	HEIGHT	Another way of getting the height-gain function.  Calls: RUNKT2.	BUGGER HTGAIN HCHITE TURNPT
R-21	GHIGHT	See above.  Calls: RUNKT2.	BUGGER HTGAIN HCHITE
R-22	SORT	A sorting routine.	-
R-23	RESIDH	Computes the field strength-distance variations using the residue series for elevated terminals.  Calls: EIGEN, SORT, HEIGHT, GHIGHT	BUGGER PEXCIT HTGAIN HCHITE BROCK
R-24	W	Update of information from CCIR. Corrects for lack of convergence of the asymptotic series near origin.	BUGGER
R-25	JCALC	Computes a set of function J[m] with argument tau.	BUGGER
R-26	JRCALC	Computes an array JRP, which is used by FLATX3.  Calls: JCALC.	BUGGER
R-27	YCALC	Computes arrays YD and YR used in FLATX3.  Calls: PFUNCS.	BUGGER PEES PEXCIT
R-28	FLATX3	Computes field strength-distance variation for terminals close to the surface at short ranges. A series generalization of the Sommerfeld flat earth theory is used.  Calls: YCALC, JRCALC, JCALC.	BUGGER BROCK
R-29	PINTAB	Computes the phase integral and its first or second derivative with respect to P0[m]. It uses Gaussian quadrature.  Calls: PFUNCS.	BUGGER QUAD16 PEES
R-30	COMINT	Computes combinations of phase integrals used in RAY.  Calls: PINT, PINTAB.	BUGGER
R-31	RAY	Computes the components of the direct ray. These components are used in stationary phase integrations.  Calls: PFUNCS, COMINT, TPOINT	BUGGER PEES
R-32	GEOMOP	Computes the field using geometrical optics.  Calls: BTLC, FLATX3, PFUNCS, RAY.	BUGGER BROCK PEES PEXCIT

### 3.5 Results

It has been possible to obtain close agreement between the detailed outputs from the original program and the new version for all variables except those involving the height-gain functionality, which occurs in the Sommerfeld calculation. This is in spite of significant efforts. Therefore, the transmitter and receiver heights have been restricted to zero, so that this problem does not occur. Strictly, this implies that the program should only be used for vertical polarization because a horizontal dipole placed directly on a perfectly conducting surface will not radiate. In the program, it is simply assumed that the field strength at a distance of 1 km is 300 mV/m.

To relate the results of GRWAVE to transmitter power, we note that, according to the ITU (2007), the electric field at a distance of 1 km from a short vertical dipole in free space radiating a power of 1 kW is 300 mV/m. Therefore, in decibels, the power relative to 1  $\mu\text{V/m}$  is  $20 \log_{10}(3 \times 10^5) = 109.54 \text{ dB}$ , which is in fact returned by GRWAVE at this distance. The electric field can be deduced for any transmitter radiated power by multiplying the result from GRWAVE by the square root of the power (in kW) and correcting for the antenna gain. For example, the gain of a half wave dipole (or vertical quarter wave monopole set directly over a ground plane) is 2.15 dB.

The output from the new version of the program, which we call GRWAVE-64, has been compared with the output from the original GRWAVE for zero heights and combinations of all parameters in Table 2. There,  $\epsilon$  is the relative permittivity and  $\sigma$  is the conductivity.

Table 2. Comparison Parameters.

Parameter	Values
Frequencies (MHZ)	1.0, 5.0, 30.0
Polarizations	V, H
Grounds	Very Dry: $\epsilon = 3, \sigma = 0.0001 \text{ S/m}$ Very Wet: $\epsilon = 40, \sigma = 0.03 \text{ S/m}$ Sea Water: $\epsilon = 70, \sigma = 5.0 \text{ S/m}$

For vertical polarization, the agreement is excellent with a maximum discrepancy of less than 0.1 dB. In horizontal polarization, the discrepancy is up to about 1 dB at close range but it is not known if this is significant because the transmitter height is zero.

Note that the results from the original GRWAVE are included as part of the deliverable package, in a file called FORTRANTestData.7z. The new GRWAVE-64 program is in a file called NewGRWAVE.7z. The comparisons can therefore be made by running GRWAVE-64 and comparing them to the output files of the original GRWAVE. A screenshot of the GRWAVE-64 GUI is shown in Figure 1.

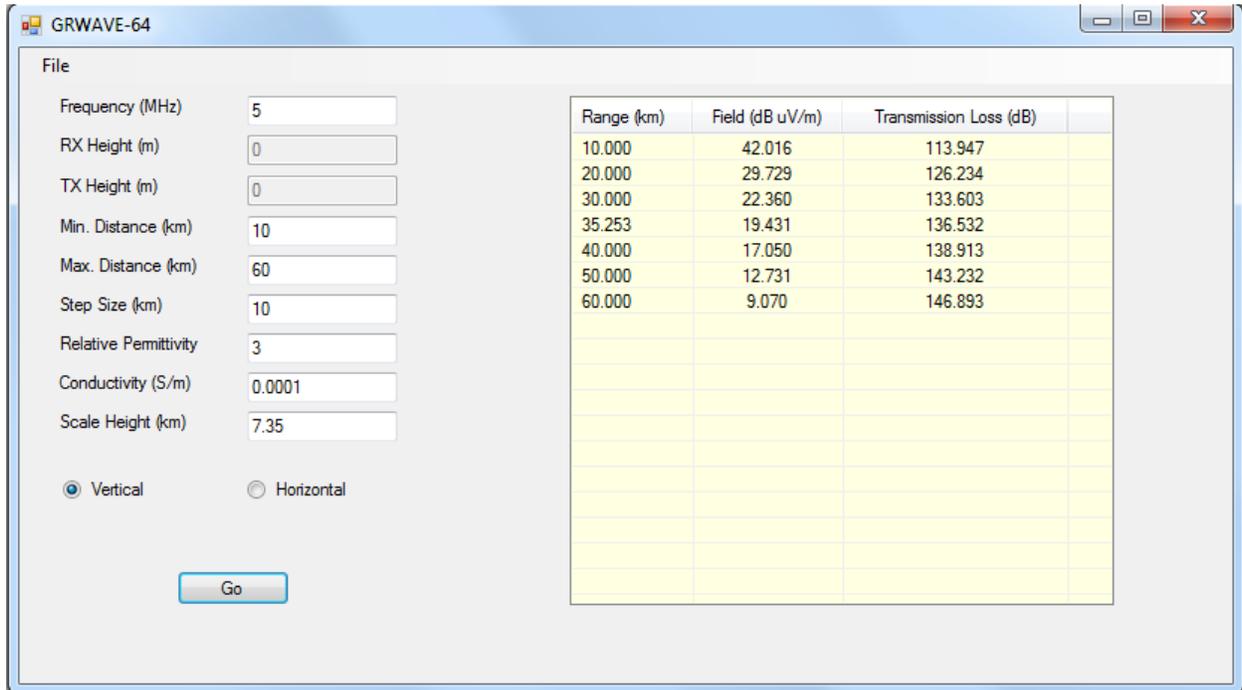


Figure 1. Screenshot of GRWAVE-64.

## 4 Conclusions and Recommendations

The FORTRAN program GRWAVE has been successfully translated, though only for zero transmitter and receiver heights. This is useful for applications in which the ground is reasonably flat and for signals in the AM broadcast band, which are always vertically polarized. The new code, GRWAVE-64, runs on 64-bit personal computers running the Microsoft Windows 10 operating system and should be a useful module in EM applications for locating linear conductors.

However, much of the code is still unstructured and it is desirable to replace this with structured programming. This much enhances the readability and comparison of the code with theory. The restriction on zero height should also be removed, if at all possible.

Finally, we note that there are other ground wave codes, such as Li et al. (2013), and it would be useful to compare the outputs from this independently, as it might be a convenient substitute for GRWAVE-64.

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A principal consideration in many of the detection schemes proposed and examined is the propagation of transmitted EM fields over different ground types. The International Telecommunications Union (ITU) developed a software application called GRWAVE that calculates these parameters. This software was originally developed over three decades ago using the FORTRAN programming language. There is a need for a modernized version of this software that can be incorporated into different linear conduction detection models. The original GRWAVE software has been translated into C-Sharp (C#), a modern programming language, and has been given a graphical user interface (GUI) for ease of use. The outputs of this new software compare favourably to those of the original ITU version for the noted cases.