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ELF CODE FOR HORIZONTALLY STRATIFIED MEDIA

Extension of the 2-layer conducting half space (Weaver) model

M. Birsan

Defence R&D Canada

Technical Memorandum
DREA TM 2000 - 151
February 2001

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ELF code for horizontally stratified media

Extension of the 2-layer conducting half space (Weaver) model

Marius Birsan

Defence Research Establishment Atlantic

Technical Memorandum

DREA TM 2000 - 151

February 2001

Author

Marius Birsan

Approved by

Ron Kuwahara

Section Head DREA/Electromagnetics

Approved for release by

Kirk Foster

Chair, Document Revue Panel

Abstract

KHERNER3 is a program written in FORTRAN 77 for the computation of extremely low frequency (ELF) electromagnetic fields from an electric dipole source. The electric source is located in the upper layer of a two-layer conducting half-space. In a marine environment, this model corresponds to a single semi-infinite conducting seabed. For a better modeling of electromagnetic propagation in shallow water, the program was modified to accept an arbitrary number of conducting layers. A multi-layer structure translates into a correction factor for the conductivity of the bottom layer in the previous two-layer conducting half-space model. The correction is a function of the (complex) incidence angle and it was introduced directly in the numerical integration of 1-D field integrals in the wave number region.

Résumé

KHERNER3 est un programme écrit en FORTRAN 77 pour le calcul de champs électromagnétiques de fréquence extrêmement basse (ELF) dont la source est un doublet électrique . Cette source est située dans la couche supérieure d'un demi-espace conducteur à deux couches. Dans un environnement marin, ce modèle correspond à un fond marin conducteur semi-infini à une seule couche. Pour une meilleure modélisation de la propagation électromagnétique en eau peu profonde, le programme a été modifié de façon à accepter un nombre arbitraire de couches conductrices. Une structure multicouche se traduit par un facteur de correction de la conductivité de la couche inférieure de l'ancien modèle du demi-espace conducteur à deux couches. La correction est fonction de l'angle d'incidence (complexe) et elle a été directement incorporée à l'intégration numérique des intégrales du champ unidimensionnel dans la région du nombre d'ondes.

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Executive summary

The computation of extremely low frequency (ELF) electromagnetic fields in seawater is of prime importance in detection and evaluation of magnetic and electric signals from ships, and underwater communications between submerged vessels. During past years, the Electromagnetics Section at DREA wrote a program (KHERNER3) that computes the electromagnetic field from a horizontal mono-frequency dipole. In this program, the electromagnetic field is produced by an electric dipole located in the upper layer of a two layer conducting half-space. For the marine environment this means that a single conducting layer models the bottom of the sea. For certain applications this model works well, but for others (with different sediment layers) it represents a coarse approximation.

In this report we describe how the KHERNER3 program was modified in the sense that the sea bottom can be modeled by an arbitrary number of layers, each one with different conductivity and thickness. The purpose of this work was to extend the capabilities of the KHERNER3 program for a more accurate modeling of the marine environment.

For this work we used the FORTRAN 77 version of the KHERNER3 program. Formatted files accomplish all input and output. As mentioned, this version admits only one infinite conducting layer as a model for seabed. The new version, which could be appropriately called KHERNER_N, can treat any number of layers. Preserving the features of the former version of the code, KHERNER_N also accepts as input piecewise linearly varying conductivity and depth parameters for each of the bottom layers.

The numerics of KHERNER_N are based on the analytical solution of the electromagnetic field proposed by Weaver corrected for the additional reflections from a parallel stratified seabed consisting of N homogeneous slabs. The most notable difference in the N layer model is that the bottom conductivity becomes a complex number, while it is a real number in the previous model.

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Sommaire

Le calcul de champs électromagnétiques de fréquence extrêmement basse (ELF) dans l'eau de mer est primordial pour la détection et l'évaluation des signaux magnétiques et électriques venant de navires et pour les communications sous-marines entre engins submergés. Par le passé, la Section de l'électromagnétisme du CRDA a écrit un programme (KHERNER3) qui calcule le champ électromagnétique à partir d'un doublet horizontal à fréquence unique. Dans ce programme, le champ électromagnétique est produit par un doublet électrique situé dans la couche supérieure d'un demi-espace conducteur à deux couches. Pour l'environnement marin, cela veut dire qu'une seule couche conductrice modélise le fond marin. Pour certaines applications, ce modèle fonctionne bien, mais pour d'autres (ayant des couches sédimentaires différentes), il représente une approximation grossière.

Dans le présent rapport, nous décrivons comment le programme KHERNER3 a été modifié de façon que le fond marin puisse être modélisé par un nombre arbitraire de couches, ayant chacune une conductivité et une épaisseur différentes. Ces travaux avaient pour but d'augmenter les capacités du programme KHERNER3 en vue d'une modélisation plus exacte de l'environnement marin.

À cette fin, nous avons utilisé la version en FORTRAN 77 du programme KHERNER3. Des fichiers formatés accomplissent toutes les entrées et sorties. Comme nous l'avons déjà dit, cette version n'admet qu'une seule couche conductrice infinie comme modèle du fond marin. La nouvelle version, qui pourrait être appelée de façon appropriée KHERNER_N, peut traiter un nombre quelconque de couches. Tout en conservant les caractéristiques de l'ancienne version du code, KHERNER_N accepte également comme entrées des paramètres de conductivité et de profondeur à variation linéaire pour chacune des couches du fond.

Les calculs de KHERNER_N sont basés sur la résolution analytique du champ électromagnétique proposée par Weaver avec correction des réflexions additionnelles venant d'un fond marin constitué de N couches parallèles homogènes. La différence la plus marquante du modèle à N couches est que la conductivité du fond devient un nombre complexe, tandis que dans l'ancien modèle c'était un nombre réel.

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1. Introduction

Several sources of electric currents present on a ship generate underwater electromagnetic fields. Most of them are underwater currents such as the ripple in the current of the impressed cathodic protection, modulation of the dc shaft current, corrosion currents, and leakage of ac currents from power systems on board. The computation of extremely low frequency (ELF) electromagnetic fields in seawater is of prime importance in detection and evaluation of magnetic and electric signals from ships and submarines, and underwater communications between submerged vessels. During past years, the Electromagnetic Group at DREA wrote a program (KHERNER3) that computes the electromagnetic field from a horizontal mono-frequency dipole. The computer code is based on the mathematical model developed by J. T. Weaver [1]. In this model, the electromagnetic field is produced by an electric dipole located in the upper layer of a two layer conducting half-space. For the marine environment this means that a single conducting layer models the bottom of the sea.

The model of a single infinite conducting layer for the seabed is a good approximation for deep waters where the electrical thickness of the water stratum is large. In the shallow water case, the conductivity of the bottom becomes an important parameter. Since the propagation in shallow water is one of the most important problems of interest, an N-planar homogeneous layer model as depicted in Fig. 1 should be considered. This is the case of a more general problem of a lithosphere with conductivity that is a function of the vertical co-ordinate, that varies discontinuously from layer to layer. The sea boundary of the horizontally layered region is characterized by generalized reflection coefficients or response functions obtained with a one dimensional recurrence formula similar to that derived and used for downward traveling wave [2]. Note that in transmission from the air (wave number k_0) into the earth or seawater (wave number k_1) the ratio (k_1/k_0) is large so that the electromagnetic field is a locally plane wave propagating normally to the surface. Also the plane wave impedance is determined only by the conductivity and frequency and does not depend on the incident wave structure.

This situation is very different when the primary field is generated by a horizontal dipole in the seawater above the surface of the lithosphere. Transmission is now from a region with large wave number into one with a much smaller wave number so that the field transmitted into the lithosphere, even when represented by elementary plane waves, bends away from and not towards the normal. Furthermore, the field in the seawater now includes a surface wave in addition to any partially reflected wave.

The surface impedance of a stratified conducting medium is seen to be an important quantity. In a large measure it determines the propagation constants for waves gliding along its surface. The calculated impedance or conductivity, as a related parameter, of sea boundary of the horizontally layered region will introduce a correction in the field values obtained using the previously coded two-layer conducting half space (Weaver) model. As mentioned, the effect of the bottom conductivity is more important in shallow waters. Thus the correction of the electromagnetic field introduced by a N-layer model are intended to be used where sensors are mounted on the sea bottom, or where the source is so close to the sea bottom that it significantly alters the distribution of electric currents generated by the source.

2. Electric source over stratified media

In calculations of the reflection from stratified media, the meaningful physical standpoint is to consider the source a localized distribution of current. An example is a horizontal line source of electric current. The propagation model is illustrated in figure 1. To facilitate application of the theory outlined in the present chapter, a four-layer model for the conducting half space is considered. This approach does not limit the generality of the model and in principle any number of layers can be added to the computer code. The very first and last layers of the propagation model are air ($\sigma_0 = 0$) and the lithosphere, respectively. These layers are semi-infinite. Next layer from the top is seawater. The x and y directions denote the horizontal plane. This is the plane in which the structure is uniform in its electromagnetic parameters. The z direction is the vertical direction pointing downwards in which the structure varies in its properties. The origin of this Cartesian reference frame is located on the interface of air and seawater, yielding positive z values in the layers of interest. The electromagnetic properties of each layer are considered to be homogeneous, linear and isotropic. It is understood that the magnetic permeability μ_i for each layer can be replaced by the constant μ. A model composed of two or three such homogeneous layers is often an adequate representation for the earth's crust.

Since we are considering time-harmonic cases, it is noted that the time factor $\exp(j\omega t)$ is used for the field quantities in the frequency domain and is omitted throughout.

The present section reviews the effect of stratification on electromagnetic fields for those cases in which both the dipole source and the field point are in the top layer of the stratified conductor. The problem is discussed in details by Wait [2]. To calculate the surface impedance, or a related parameter, for a stratified conductor is a tedious business. In many cases, however, the conduction currents are large compared with the displacement currents in each of the strata. Under these situations, the propagation constants γ_i ($i = 1,2,3,4$) have a phase angle of $\pi/4$ radians:

$$\gamma_i = i\alpha_i + \beta_i = (i\omega\mu\sigma_i)^{1/2} \tag{1}$$

For these cases, and with the specialization mentioned above, the effect of stratification may be accounted for by introducing an effective surface impedance, Z_e, with a corresponding propagation constant. In order to relate the reflected and transmitted fields to the incident field, it is necessary to express the complete field as the linear superposition of two component parts – the one of electric type or E-polarized with the electric field in the plane of incidence, the second of magnetic type or H-polarized with the magnetic field in the plane of incidence.

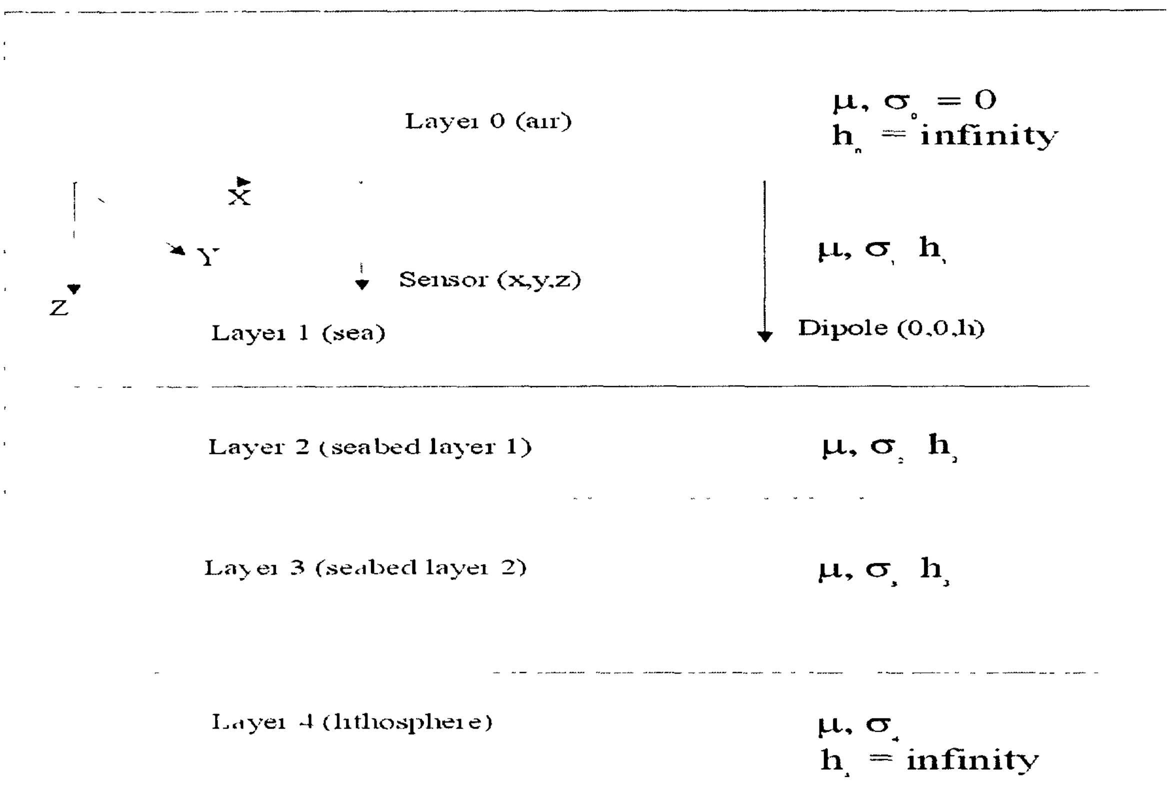

Figure 1. *Propagation model*

For the case when the electric vector is perpendicular to the plane of incidence, the surface admittance at the water-seabed boundary may be defined by:

$$Y_e = \frac{\left(u^2 + i\omega\mu\sigma_e\right)^{1/2}}{i\omega\mu} = \frac{\left(u^2 + i\omega\mu\sigma_2\right)^{1/2}}{i\omega\mu} Q_2 = -\left[\frac{H_{1x}}{E_{1y}}\right]_{z=h_2} \tag{2}$$

where Q_2 is the correction of the characteristic admittance of seabed to account for the presence of the lower layers. Similar relations exist for the seabed impedance, Z_e, in the case of the E-polarized field, and it is interesting to note that $Y_e Z_e \neq 1$ (see [2]).

Once the effective conductivity of seabed is calculated for the two separate cases, the problem reduces to the previously known results for the two-layer conducting half-space, substituting σ_2 with σ_e, the new conductivity of the bottom. Explicitly, it follows from (2) that:

(3)
$$\sigma_e = \sigma_2 Q_2^2 + u^2 \left(Q_2^2 - 1\right) / i\omega\mu$$

for the H-polarized field. In this equation, 'u' can take any value and it can be identified with $k_2 \sin\theta$, where θ is the (complex) angle of incidence and $k_2 = -i\,\gamma_2$. Q_2 can be calculated using the downward recursion rule, applied here for a three-layer sea bottom:

$$Q_2 = \frac{Y_3 + N_2 \tanh u_2 h_2}{Y_3 \tanh u_2 h_2 + N_2} \quad , \quad N_2 = \frac{u_2}{i\omega\mu} , \quad u_2 = \left(u^2 + i\omega\mu\sigma_2\right)^{1/2}$$

$$Y_3 = \frac{\left(u^2 + i\omega\mu\sigma_3\right)^{1/2}}{i\omega\mu} Q_3$$

$$Q_3 = \frac{Y_4 + N_3 \tanh u_3 h_3}{Y_4 \tanh u_3 h_3 + N_3} \quad , \quad N_3 = \frac{u_3}{i\omega\mu} , \quad u_3 = \left(u^2 + i\omega\mu\sigma_3\right)^{1/2}$$

$$Y_4 = \frac{\left(u^2 + i\omega\mu\sigma_4\right)^{1/2}}{i\omega\mu}$$

The value of the effective conductivity of the seabed in both cases of E and H field polarization becomes complex and depends on the continuous variable 'u'. When the symbol 'u' is identified with $k_2 \sin\theta$, the effective admittance (2) is given by a single set E and H of plane waves of angle of incidence θ. From this point of view, the multilayer bottom conductivity will affect the reflection coefficient at the seawater – seabed interface at every angle of incidence.

It must be remembered that an incident plane wave in a lossy medium must be treated with great care. Strictly speaking, a plane wave incident in a lossy medium is not physically meaningful because the electromagnetic field increases exponentially without limit as the source is approached. However, in the limited context of one or more infinite parallel planar boundaries, it is useful to make use of such an incident plane wave.

3. Software implementation

The existing KHERNER3 code implements the two-layer conducting half space (Weaver) model. In this model, σ_1 is the conductivity of seawater and σ_2 is the conductivity of seabed (figure 1). Into the code, the variable depending on bottom conductivity is $\varepsilon = \sigma_2/\sigma_1$, which is a constant real number. To account for a layered bottom structure, this variable was corrected:

(4)

$$\varepsilon(u) = \frac{\sigma_2}{\sigma_1} corr_{E,H}(u)$$

where, for example, in the H-polarized case:

$$corr_H(u) = \frac{\sigma_e}{\sigma_2} = Q_2^2 + u^2\left(Q_2^2 - 1\right)/i\omega\mu\,\sigma_2$$

The correction factors of the bottom conductivity for any value of 'u' is calculated in a new subroutine introduced into the KHERNER_N program. The subroutine is also a function of frequency, conductivity of three layers and height of two layers (the third layer is infinite). Once the conductivity correction is calculated for a certain wave number 'u', the new bottom reflection coefficient is calculated and then the field terms depending on ε are obtained by numerical integration in the wave number region. Because of the two cases considered above, there is a need to separate the field components during the computation: the field of electric type includes Ex, Ez and By; the field of magnetic type consists of Bx, Bz and Ey.

For sources close to the water-bottom interface, the propagation is possible by lateral waves through a less lossy medium. The influence of the layered structure on the propagation constant becomes important. A study of the Poynting vector in both regions [3], seawater and seabed, shows that the field from the horizontal dipole in the sea enters the adjacent lithosphere only in a narrow cone directly below the dipole. Actually, the maximum depth of penetration into region 2 is well approximated at low frequency by the formula:

$$z_{\max} \cong \left(\frac{\sigma_2}{\sigma_1}\right)^{1/2} R/2.718$$

where R is the distance from the source.

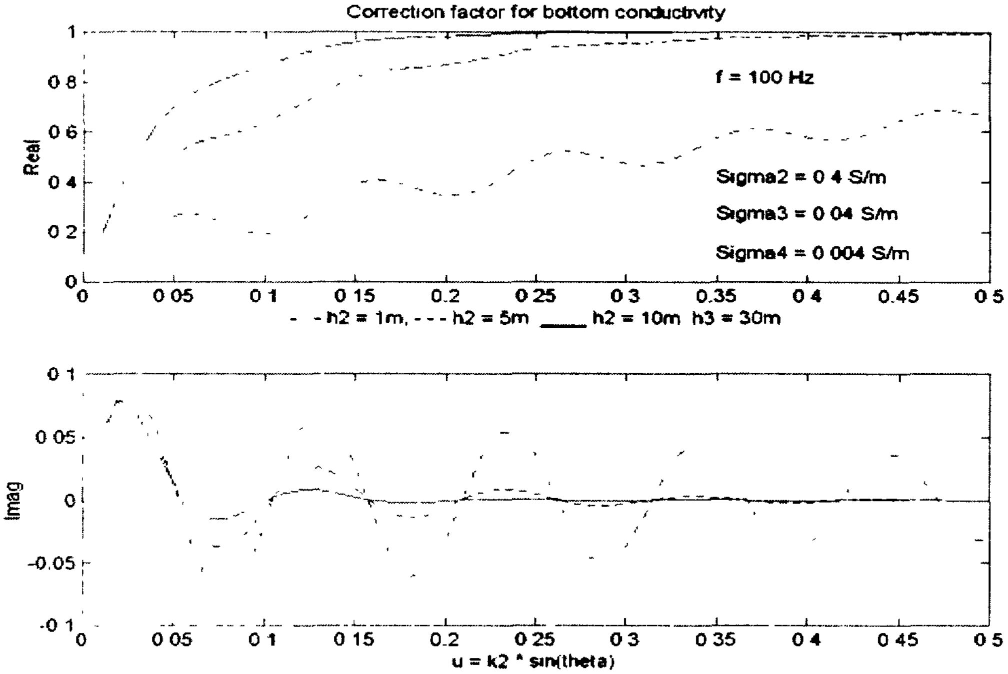

Figure 2. Correction factor for ε as a function of u

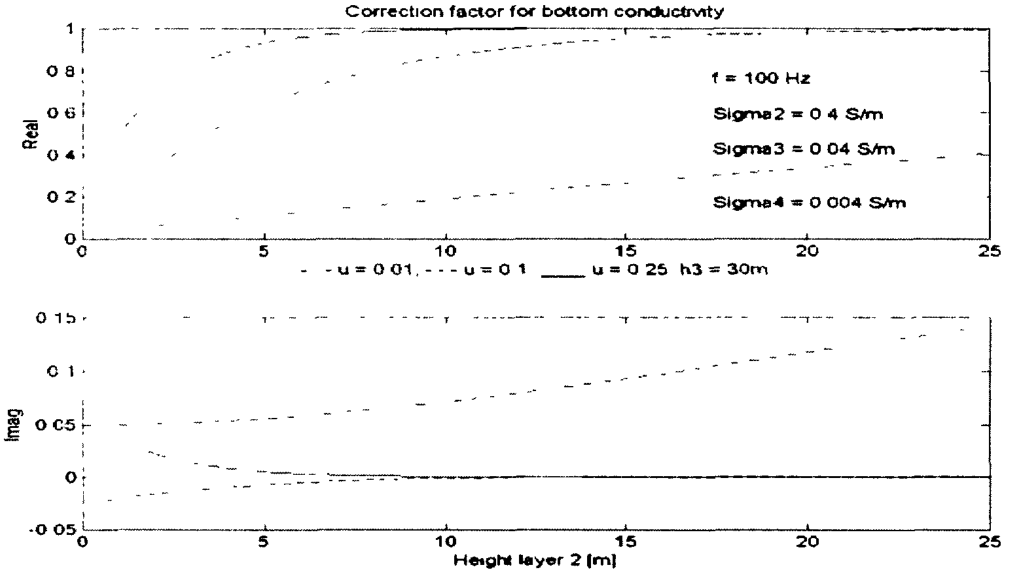

Figure 3. Correction factor for ε as a function of h2

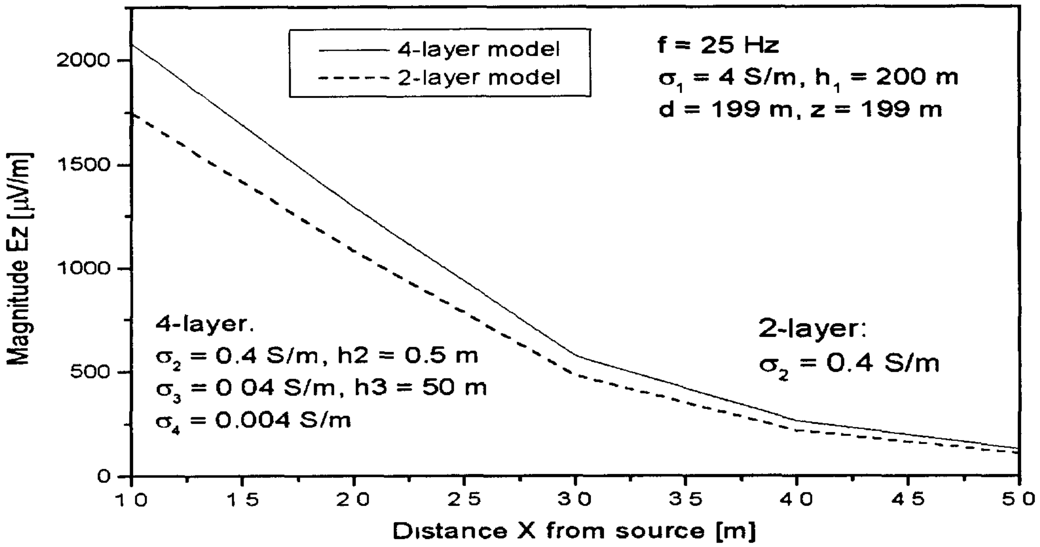

Figure 4. Influence of stratified bottom on electric field (infinite small dipole)

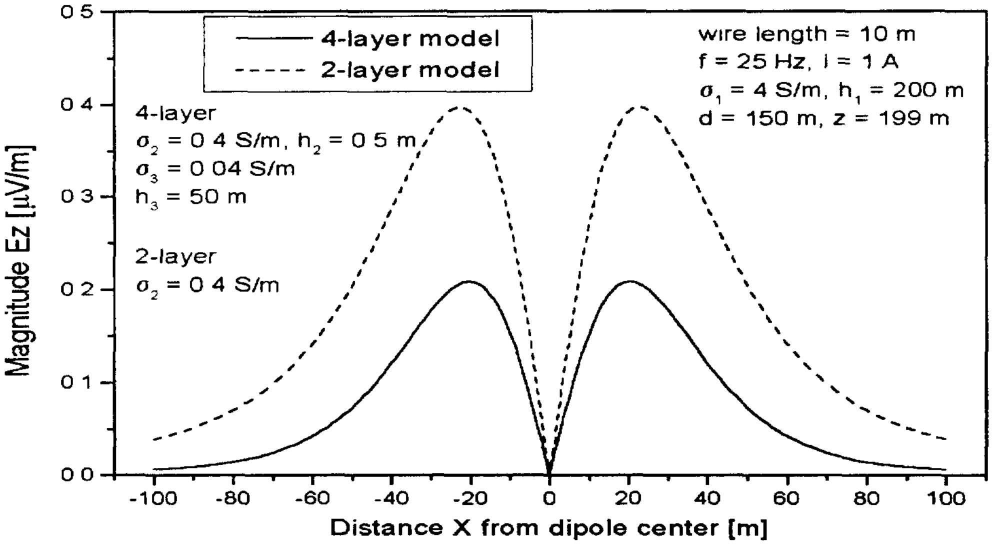

Figure 5. Influence of stratified bottom on electric field (long wire)

Thus, it is expected that the correction factor would have a greater contribution for small angles of incidence. As shown in Fig. 2, the correction factor (of magnetic type) depends also on the thickness of the first bottom layer. With incidence angle θ, it goes rapidly to unity for a layer 10 m high, but still it has a significant contribution to decreasing the bottom conductivity for a 1-m height layer.

The variation of the correction factor (of magnetic type) with the height of the bottom first layer for certain values of the parameter 'u' is illustrated in Fig. 3. As an example of electromagnetic field computation, Figure 4 shows the difference between the two models when the electric field produced by an infinite small dipole having 1 A-m electric moment is calculated. The source and the sensor are close together (1 to 5 m apart) and placed on the sea bottom. To eliminate the influence of the seawater-air interface, the sea depth was set to 200m. In the two-layer model, the bottom has a conductivity of 0.4 S/m. In the four-layer model, this conductivity is assigned to a thin 0.5 m layer of sediment covering a thicker layer (50 m) with much lower conductivity (0.04 S/m). The fourth layer is the lithosphere with a typical conductivity of 0.004 S/m.

The last example is presented in figure 5 where the same component of the electric field, Ez, is calculated for a more realistic situation. The electric dipole is 10 m long (I = 1 A), located at 150 m depth, and moves over the sensor placed very close to the bottom (1 m). The results show a considerable influence of the bottom conductivity on the magnitude of electric field. On the contrary, when the X component of the electric field is calculated, the results are only slightly different for the two models.

To verify the consistency of the new model, the sensor and the dipole were moved away from the bottom. In this case, the 2-layer and 4-layer models give identical results.

3.1 Data input and output

At runtime, KHERNER_N will open and read a file with the name *'layedt.def'*. This file must be edited by the user and defines the problem. The format of this file preserves the features of the KHERNER3 input file with a few modifications. The format is best illustrated by an example shown in Fig. 6. The first 20 lines of the input file define the parameters of the electromagnetic propagation problem, and the last line controls the printing and tolerance. All the 20 parameters can vary in steps (column 3) starting from an initial value (column 1) up to a final value (column 2). The total number of loops is given in column 5. At each step (loop) a new problem is defined. If several parameters are imposed to vary, each of them will vary independently according to the priority assigned in column 4.

Parameters 17 – 20 and 4 correspond to the geometry of the new model and they can also be incremented in steps.

```
0.00        0.00        0.00        0.00        1.00          !  1. Range orientation [deg]
200.00      200.00      0.000       0.000       1.00          !  2. Sea depth [m]
4.000       4.000       0.000       0.000       1.00          !  3. Sigma1 seawater [S/m]
0.004       0.004       0.000       0.000       1.00          !  4. Sigma4 lithosphere [S/m]
25.00       25.00       0.000       0.000       1.00          !  5. Frequency [Hz]
1.00        1.00        0.000       0.000       1.00          !  6. Dipole current [A] or [Am]
0.00        0.00        0.000       0.000       1.00          !  7. X       |
0.00        0.00        0.00        0.00        1.00          !  8. Y       | Dipole
199.0       199.0       0.000       0.000       1.00          !  9. Z       |
0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 1.00          ! 10. Angle   |
0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 1.00          ! 11. Ship heading [deg] from X axis
0.00        0.00        0.00        0.00        1.00          ! 12. Length dipole [m]
1.00        30.00       1.00        1.00        30.00         ! 13. X       |
0.00        0.00        0.00        0.00        1.00          ! 14. Y       | Sensor
199.00      199.00      0.00        0.00        1.00          ! 15. Z       |
0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 1.00          ! 16. Angle   |
0.4         0.4         0.00        0.00        1.00          ! 17. Sigma2 1st layer [S/m]
0.50        0.50        0.00        0.00        1.00          ! 18. Height 1st layer [m]
0.04        0.04        0.00        0.00        1.00          ! 19. Sigma3 2nd layer [S/m]
30.00       30.00       0.00        0.00        1.00          ! 20. Height 2nd layer [m]
1.000       0.1000E02 0.10E04   7.00

==========================================================================================
Example of input file to WEAVER_N. This file shall always have the generic name layedt.def.
*** First 20 lines with:
start       final       step        priority    number of
value       value       value                   loops
*** Last line contains:
iprint      n0          tol        nr. of iteratins
==========================================================================================
```

Figure 6. *The format of input file*

4. Concluding remarks

In reference [1], Weaver solved the problem of the electromagnetic field for an electric dipole located in the upper layer of a two-layer conducting half-space model. The mathematical formulation contains 2 parameters, 'f' and 'g' (equation 50 in [1]), which are the reflection coefficients from the air-seawater and seawater-seabed interfaces, respectively. In the present contribution, the parameter 'g' was corrected to account for an arbitrary number of layers in a horizontally stratified sea bottom.

The parameter 'f' does not depend on conductivity because $\sigma_{air} = 0$. Following a similar approach to the one presented here, it is possible to modify this parameter to account for an arbitrary number of layers above the seawater layer. In this case the electric source can be located in any conducting layer of an n-layer horizontally stratified model. Such a model would be appropriate for example in modeling the electromagnetic propagation in the Arctic Ocean when the electric source is in the seawater covered by ice.

5. References

1. Weaver, J. T., "The Quasi-static Field of an Electric Dipole Embedded in a Two-Layer Conducting Half-Space", Can. J. Phys. 45, 1981, 1967.

2. Wait, J. R., "Electromagnetic Waves in Stratified Media", Pergamon Press, 1962.

3. King R. W. P. and Wu T. T., “Electromagnetics” 1, 51 (1981).

List of symbols/abbreviations/acronyms/initialisms

DND	Department of National Defense
DREA	Defense Research Establishment Atlantic
ELF	Extremely Low Frequency

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Dr. Peter Sigray

Department of Passive Sonar, Seismology and Magnetics

FOA Defense Research Establishment

SE-172 90 Stockholm, Sweden

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KHERNER3 is a program written in FORTRAN 77 for the computation of extremely low frequency (ELF) electromagnetic fields from an electric dipole source. The electric source is located in the upper layer of a two-layer conducting half-space. In a marine environment, this model corresponds to a single semi-infinite conducting seabed. For a better modeling of electromagnetic propagation in shallow water, the program was modified to accept an arbitrary number of conducting layers. A multi-layer structure translates into a correction factor for the conductivity of the bottom layer in the previous two-layer conducting half-space model. The correction is a function of the (complex) incidence angle and it was introduced directly in the numerical integration of 1-D field integrals in the wave number region.

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Electromagnetic propagation, stratified media, ELF, wavenumber integration

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