Nearshore Navigation and Communication Based on Deliberate EM Signals

and

Theoretical, Numerical and Observational Studies of Coastal Ocean Electrodynamics

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Introduction

This project began with an effort to understand and utilize environmental and deliberately produced electromagnetic (EM) signals in the coastal ocean. Our studies were undertaken to provide a means to communicate with and guide autonomous underwater vehicles (AUV) and other autonomous sensor systems, such as moored instruments. There is a need for non-acoustical methods to navigate and control AUVs, communicate with autonomous instruments, and detect submerged and buried objects in shallow water. In principle, extremely low-frequency EM signals (< 1 kHz) can be used for these purposes. In practice, however, not enough is known to predict reliable signal-to-noise ratios for particular applications. This is both because the propagation paths in the coastal environment are complex and because the background environmental fields are not well understood. Clearly, a comprehensive numerical model is needed to determine the effects of various complications encountered in the littoral region.

We undertook an effort to develop a numerical model that includes many EM influences, such as environmental noise, seabed electrical conductivity, variable bottom depth and coastline, and deliberate EM signals. Our goal is to understand these factors well enough to reliably estimate signal-to-noise ratios in planning coastal EM operations and to improve basic understanding of EM propagation and environmental noise in the coastal waters and to make and interpret sensitive EM measurements. The project had two components: 1) theoretical and numerical studies and 2) instrument construction and field observations.

Theoretical and Numerical Studies

The immediate objectives were to study the fundamental generation and propagation of EM fields in realistic shallow coastal environments having non-uniform, three-dimensional geometries and to examine various sources of environmental noise expected for such regions. The environmental EM noise included fields generated by external sources in the ionosphere and magnetosphere, by the dynamo action of the ocean flow, and by artificial sources, such as from the 50/60-Hz power grids.

The approach was to combine theory with numerical modeling. A primary element was the development of a frequency-domain, finite difference/volume numerical model capable of calculating the generation and propagation of EM fields due to arbitrary sources in the presence of the strong land/air/sea conductivity contrasts and complicated 3D geometry of the realistic coastal ocean and land/sea/air environment.

Rather than use the standard Maxwell equations, a formulation in terms of electromagnetic gauge potentials was used from which the electric and magnetic fields were calculated in postprocessing. Gauge potentials have been exploited successfully in numerical models with applications ranging from scattering problems [in which the EM fields are wavelike, e.g., Biro and Preis (1989)] to low-frequency geophysical induction problems [in which the process is diffusive, e.g., Badea et al. (2001)]. Advantages of the gauge formulation for our applications are several; it can be written in a way such that the potentials are everywhere continuous, it can be discretized on finite difference grids similar to those used by the ocean modeling community, gradients of conductivity (rather than resistivity) are used, and it allows arbitrary (including static) sources. Although it is a frequency-domain model it can be used to calculate the EM fields generated by arbitrary time-dependent ocean flow on the continental shelves as the associated EM fields are essentially in static adjustment.

We have called the model MOED (Model for Ocean ElectroDynamics) as its primary intended use is to calculate the generation and propagation of low-frequency (< 1 kHz) EM fields in or near the ocean. But as displacement currents have been included at little extra cost (and for stability considerations) it is equally capable of tackling more general high-frequency cases.

We have combined several different previous versions of the model (optimized for particular cases) into one versatile model with appropriate switch-controlled options. For example, we have modified the formerly regular (possibly non-uniform) grid to allow for general orthogonal curvilinear coordinates such that MOED can accept ocean model (e.g., SCRUM/ROMS) data on native curvilnear or spherical coordinate grids. This allows MOED to calculate the ocean generated EM fields as well as to use the particular model configuration in calculations involving atmospheric or artificial sources such that a consistent EM data set is added to the ocean model one. MOED now has several switches that can be used to improve performance. MOED, even in its fully versatile mode allowing displacement and conduction currents and no limiting assumptions, is quite fast (a fully coupled simultaneous solution of all four gauge potentials with 50K gridpoints typically takes one minute on a 550-MHz PC) and the user does not need to consider these switches for many problems. But depending on the case, there are often approximations that are exceedingly valid and for very large problems the switches are used to greatly increase the performance. MOED has been rewritten for maximum modularity and user-friendliness. It is entirely interfaced by MATLAB and plotting routines are also included in the distribution.

MOED has been validated in a diverse variety of cases ranging from the simplest, for which there is an analytical solution (e.g., Fig. A1), to complicated geometries with extremely high parameter contrasts, in which case the results are inspected for correct behavior (e.g., Fig A2).

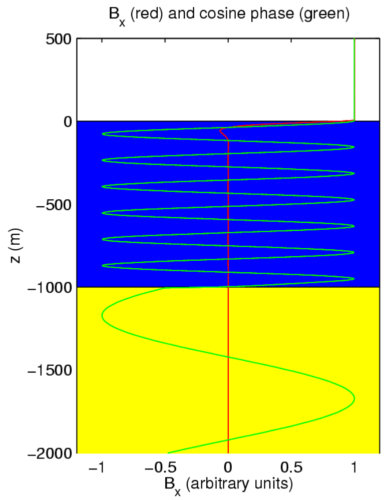

Figure A1: MOED solution for a 100-Hz horizontal magnetic field B_x (specified to have unit value at an altitude of 20 km) propagating down through the atmosphere (white), ocean (blue), and sediments (yellow). The model and theoretical solutions are essentially identical and show the exponential attenuation once the water is entered (real(B_x) in red) as well as the dependence of wavelength on conductivity (phase(B_x) is in green). For these parameters, theoretical skin depth is about 25 m and wavelength is about 160 m. Conductivities used for air/sea/sediments were 4 x 10^{-13}/4/0.1 S/m.

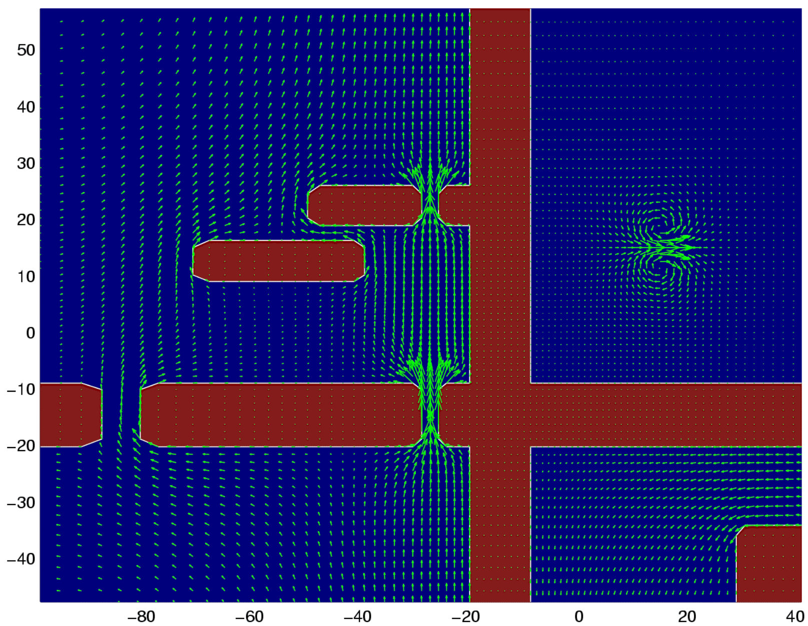

Figure A2: A 10-Hz dipole source in upper right seawater tank couples inductively through insulating walls to neighboring tanks, two of which are coupled galvanically with channels. MOED simulations such as this are done to test for correct behavior and non-divergence in the vectors of electric current density (green) under complicated geometries and coupling scenarios. Vectors in the source tank are reduced for display.

Another important accomplishment (Tyler 2001b) has been an extension of the current theory of oceanic motional induction focusing on the non-local electric currents that historically have been poorly understood. While the ocean generated EM fields locally associated with the flow are well described by the theory of Sanford (1971), the ocean flow also generates electric currents closing non-locally in horizontal planes. Understanding the latter process is important primarily because the non-local electric currents are responsible for the component of the ocean generated magnetic field reaching outside of the ocean and because offshore flows generate EM fields on the shelf through these non-local electric currents.

With E. Maier-Reimer we have successfully performed a Helmholtz decomposition of the flow-dependent forcing vectors responsible for non-local electric currents generated by ocean circulation. This decomposition allows us to identify the components of ocean circulation responsible for the generation of these non-local electric currents.

With the help of a student (E. Peery), we have organized a global set of intercomparable time series from historical coastal geomagnetic observatory records together with processing scripts. We will use this to estimate the electric currents in coastal waters generated by ionospheric, magnetospheric, and oceanic sources. We have also written software to calculate automatically the ocean electrical conductivity, main magnetic field, and sediment conductance using, respectively, ocean climatologies of salinity and temperature, the IGRF main field model, and the global sediment conductance data of M. Everett.

Aside from the published paper (Tyler 2001a), two related papers (Tyler 2001b, Tyler and Sanford 2001) were presented by Tyler at the MARELEC 2001 (Marine Electromagnetics) conference in Stockholm in 2002 and appear in the proceedings. A paper treating the Schumann propagation described above and following these results concerning the coastal effect described above is in preparation.

Results from the theoretical analysis of ocean generated non-local electric currents (Tyler 2001a, b) have important significance here. The first concerns a rigorous constraint on the time scales for magnetic diffusion in the ocean; the longest time scale is expected for the non-local currents. Because there is a vast reduction in computational expense when the EM fields are known to be in approximate static adjustment with the flow field, it is important to be able to consistently evaluate this approximation. This was done by casting the EM induction equation onto geopotential surface, including the flow constraints, and then performing scale analyses. By comparing the speed of information propagation for a dynamical class of flow with the speed of ‘lateral’ magnetic diffusion (that involves propagation along the air and seafloor interfaces), constraints on the ‘instantaneousness’ of the EM adjustment were obtained. In the terminology of magnetohydrodynamics, this amounts to deciding whether the process falls into either the magnetic diffusive or frozen flux regimes. As it turns out, no oceanic processes are clearly in the frozen flux regime, some processes like deep-water barotropic Rossby waves and tides straddle the separtrix of the two regimes, and (fortunately) all flow processes resolved in coastal ocean circulation models fall into the magnetic diffusive regime. The last result indicates that when calculating the EM fields generated by the flows of these models, there is no benefit in not using the less expensive static EM formulation.

Another significant theoretical result is subtler. It illuminates an intrinsic inefficiency in the generation of non-local electric currents by geostrophic flow. This results because the non-local currents depend on the gradient of the ratio of the Coriolis parameter and radial main magnetic field. As both are axis aligned dipole fields to first order, the ratio is similarly constant and the gradient vanishes. This should mean that while offshore flows such as tides may lead to strong electric fields on the shelf, the effect of offshore geostrophic flows is secondary.

Concerning the development and use of MOED, we report the following results. The numerical implementation using gauge potentials appears for these applications to be an efficient, reliable, and versatile method to calculate the EM fields. Aside from validation studies, we have also used MOED in a variety of applications including oceanic, atmospheric, and artificial sources. For example, aside from conventional EM applications such as vessel detection, there are a growing number of new or expanded applications including underwater navigation and communication, mine counter measures, and marine petroleum and methane hydrate exploration. A recurring uncertainty in these applications concerns the inadequate understanding of environmental EM fields in the coastal ocean.

We have simulated the return electric currents in the ocean associated with the Global Circuit and observe that while these currents are typically very weak, they become significant in certain straits where they are highly concentrated. Even in those cases, however, these currents are not of primary relevance to the work here as they are primarily depth-uniform DC currents.

We have also simulated the well-known 'coastal effect' involving the amplification and distortion of magnetotelluric currents due to the strong coastal conductivity contrast. Alongshore magnetotelluric currents tend to be amplified around peninsulas with an opposite effect near bays. On/offshore magnetotelluric currents, conversely, can be stronger in bays than around peninsulas. The basic well-known effect of these currents being concentrated in shallow water is confirmed in our results.

We are preparing a paper on the propagation of atmospheric Schumann resonant EM fields into the coastal environment. While there is typically a dearth of appropriate observations with which to compare our model results, Soderberg's (1969) observations provide a useful data set. He made observations of the horizontal components of the electric field at various depths in the Sea of Cortez at a location about 12 km offshore where the water depth was about 310 m. Atmospheric EM fields propagating directly down from the sea surface should show a frequency-dependent exponential decay (similar to that seen in Fig. 1) consistent with theory. Because Schumann resonances (the lowest frequencies are about 8 and 14 Hz) provide peaks in the energy spectra with undoubtable atmospheric sources, it was useful to concentrate on these frequencies. The amplitudes indeed decayed according to theory over most of the water column but as the seafloor was approached the amplitudes increased. He interpreted (correctly, we think) this result as follows. Unlike the open ocean, atmospheric EM fields can propagate into the ocean both from the surface and also through the seafloor by entering the coastal lands and propagating under the sea while refracting back up into the ocean. Hence when this seafloor propagation path is viable the minimum energy level in the water column will not necessarily be at the seafloor but at an intermediate depth that depends on sediment conductivity and distance to shore. Using the observed 14-Hz energy minimum depth of about 240 m and the distance to shore (12 km), he inferred a bulk sediment conductivity of 0.76 mS/m. Applying a 14-Hz Schumann source in MOED while using this sediment conductivity value and a similar configuration, we calculate an energy minimum depth very similar to what he observed. With MOED, we have been able to support and extend his initial conjecture. We have included information about the importance of the orientation of the incident atmospheric fields as well as frequency-dependent effects.

Related Projects

We are supported by the NSF International Program to continue collaboration with the German Climate Computing Center/Max Planck Institute for Meteorology in Hamburg. This collaboration started with J. Oberhuber and involved adding subroutines to the OPYC ocean circulation model to calculate the EM fields generated by large-scale ocean circulation and resulted in several publications (e.g., Tyler et al. 1997). Since Oberhuber's departure from the institute, our collaboration has proceeded with E. Maier-Reimer, with whom we have continued similar EM calculations using the HOPE ocean circulation model.

R. Tyler received an award for related work from the NASA New Investigator Program. In this work we used theory and numerical models to calculate the magnetic fields at land and satellite locations produced by global ocean tides. A paper on this work was published in *Science* (Tyler et al. 2002).

Theoretical, Numerical and Observational Studies of Coastal Ocean Electrodynamics

Electromagnetic Field Measurement in the Sea

The long-term goal is to develop and use unique geo-electromagnetic measurement systems to characterize littoral environment magnetic and electric noise spectra and signal propagation characteristics. The primary technical objectives of this task relate to the development and use of electric and magnetic measurement systems to characterize EM noise and signal propagation phenomena in shallow water environments. Specific objectives include:

- Develop methods to predict and measure EM propagation in the littoral region
- Develop a comprehensive littoral electromagnetic spectral database
- Develop an empirical database to characterize electromagnetic propagation phenomena in SZ/VSW environments and verify theoretical propagation models

The overall technical approach for the electromagnetic measurements system consists of the following:

- Refine a comprehensive numerical model that determines the 3-D behavior of EM propagation in the wedge-shaped region of the near shore environment (MOED)
- Collaborate with investigators from the Coastal Systems Station in experiments with their wide band magnetic spectrometer, the Magnetic Induction Data Acquisition System (MIDAS)

Discussion

It is appreciated that one of the ‘bottlenecks’ in understanding low-frequency electrodynamical processes in the solid earth, oceans, and lower atmosphere is the limitation of current numerical models capable of simulating realistic three-dimensional aspects of these phenomena. The limits have been set primarily by the computational demands of such calculations as well as by the numerical implementation of the Maxwell equations, which can be at times obtuse when compared to formulations such as the heat equation that afford simple, intuitive numerical implementation based on simple flux conservations. Elsewhere we discuss the advantages of formulations based on the electromagnetic gauge potentials (Tyler et al. 2004, Tyler et al. 2003). This formulation appears to offer several advantages. Some, for instance the continuity of these potentials (as opposed to the discontinuous electric field), are well known. Others, however, do not appear, at least explicitly, to have been previously examined. For frequency-domain studies, we note that the gauge formulation can be written as a generic set of coupled elliptic equations, allowing a simple, modular numerical approach using simple conservation principles. More importantly, by writing the governing equations using gauge potentials an extra degree of freedom is introduced into the system. We show that this extra degree of freedom can be exploited to increase performance, accuracy, and simplicity. We have implemented the gauge approach in the three-dimensional numerical model MOED (Model for Ocean ElectroDynamics). MOED has now been used in a variety of applications and has been freely distributed to colleagues in academia and industry.

Given the importance of littoral magnetic environment characterization to the successful use of electromagnetic sensor systems, a significant effort toward development of an underwater electromagnetic spectrometer system was initiated this year. This effort involved conceptual design, development and construction of the MIDAS to measure environmental magnetic noise spectra and the SWEFS to measure the corresponding electric field noise. In addition a test was conducted to collect high-frequency geomagnetic noise spectra and test the MIDAS equipment and software for the Littoral Environment Geo-Electromagnetic Measurement. The MIDAS system consists of a digitizer, the data acquisition software, unique cables and connectors, and three sets of the most precise magnetic sensors. The high-frequency induction coil sensors (10–200 KHz) were used in injunction with low noise Digital Signal Processor (DSP) based portable eight channel digitizers with an effective resolution of 16 bits and a maximum sampling rate of 1.0 MHz.

Deployments of E and B Sensor Arrays, Coastal Systems Station, Panama City, FL

SWEFS was deployed in St. Andrews Bay near CSS in August 2003 in conjunction with a MIDAS deployment.

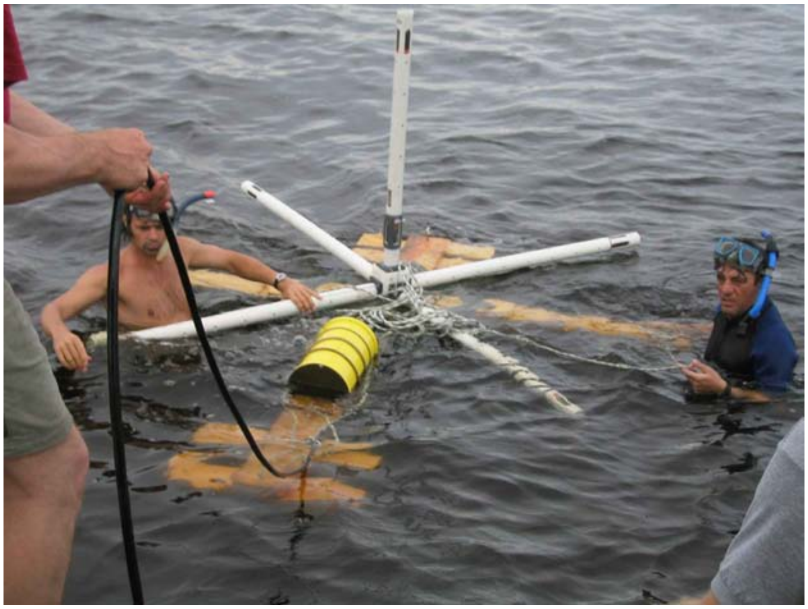

Figure B1: SWEFS electrode arms (PVC pipes) and amplifier in yellow pressure case.

The magnetic data were acquired using three high-frequency induction coils orthogonal sensors along with three signal conditioners during a six-second-time interval. The record length for the discrete Fourier transform (DFT) operation for these spectra calculations was 0.01 second and the number of averages was 600.

At present there is a paucity of quantitative magnetic noise spectrum data available with respect to littoral environments. Furthermore, there are no littoral ocean measurement systems or methodologies presently available 'off the shelf' to perform the correlated environmental magnetic spectrum measurements.

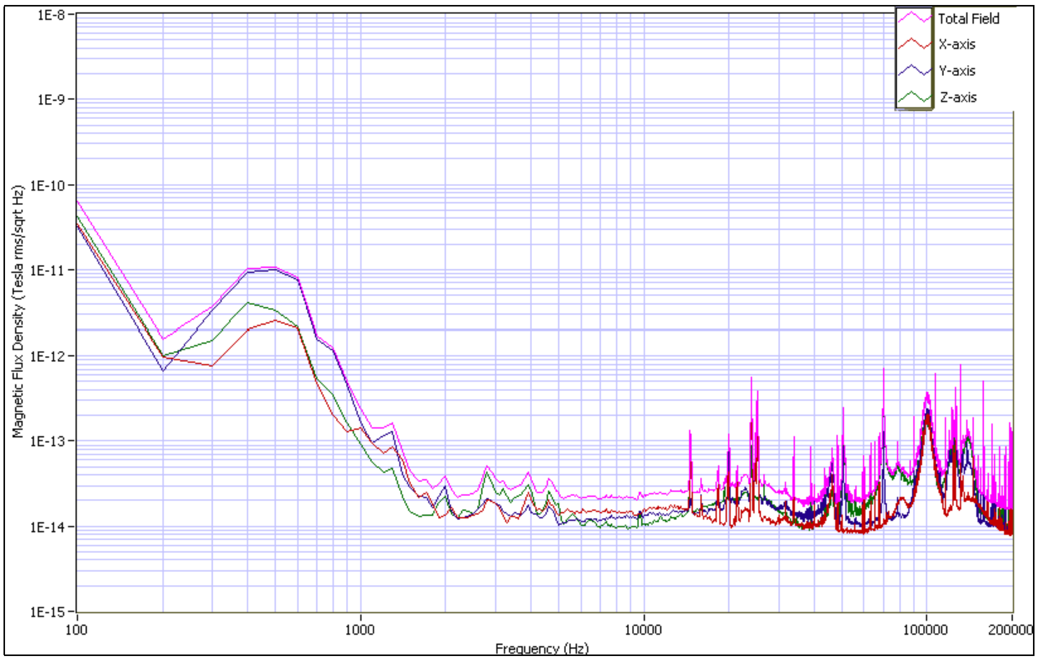

Figure B2. Magnetic flux density spectra of X, Y, and Z components and total field from high-frequency sensors from August 2003 Coastal Systems Station deployment.

Deployments of E and B Sensor Arrays, Puget Sound, WA

A joint electromagnetic field measurements test was conducted by personnel from Naval Surface Warfare Center, Panama City (NSWC-PC), and the Applied Physics Laboratory, University of Washington (APL-UW), in Utsalady Bay on the north end of Camano Island in Washington State (Fig B3). The test was conducted June 17–20, 2004. The first three days of the test period consisted of submerging the electric field and magnetic field sensors to desired depth (3.51 m) and making simultaneous electric field and magnetic induction measurements (Fig. B4). The last day was used to measure the vector components of the extremely low frequency (ELF) magnetic induction.

Figure 5: (left panel) E-field system being prepared for deployment. (right panel) B-field instrumentation being assembled prior to deployment on R/V Miller.

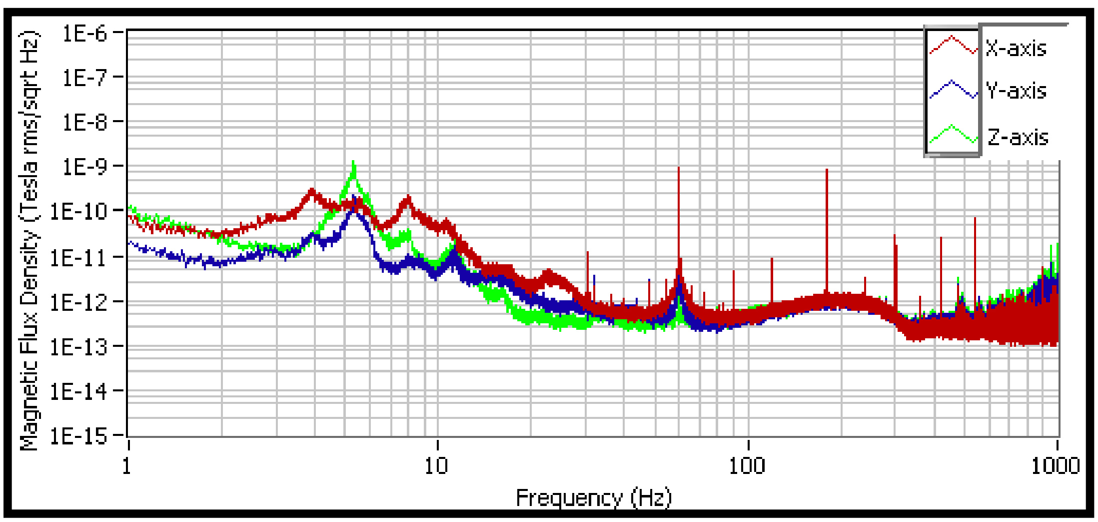

Figure B4: Magnetic induction spectral density display of X, Y, and Z axes from low-frequency sensors. The X-axis is pointing approximately –0.15 degree from magnetic north. The Y-axis is pointing west, and the Z-axis is pointing down.

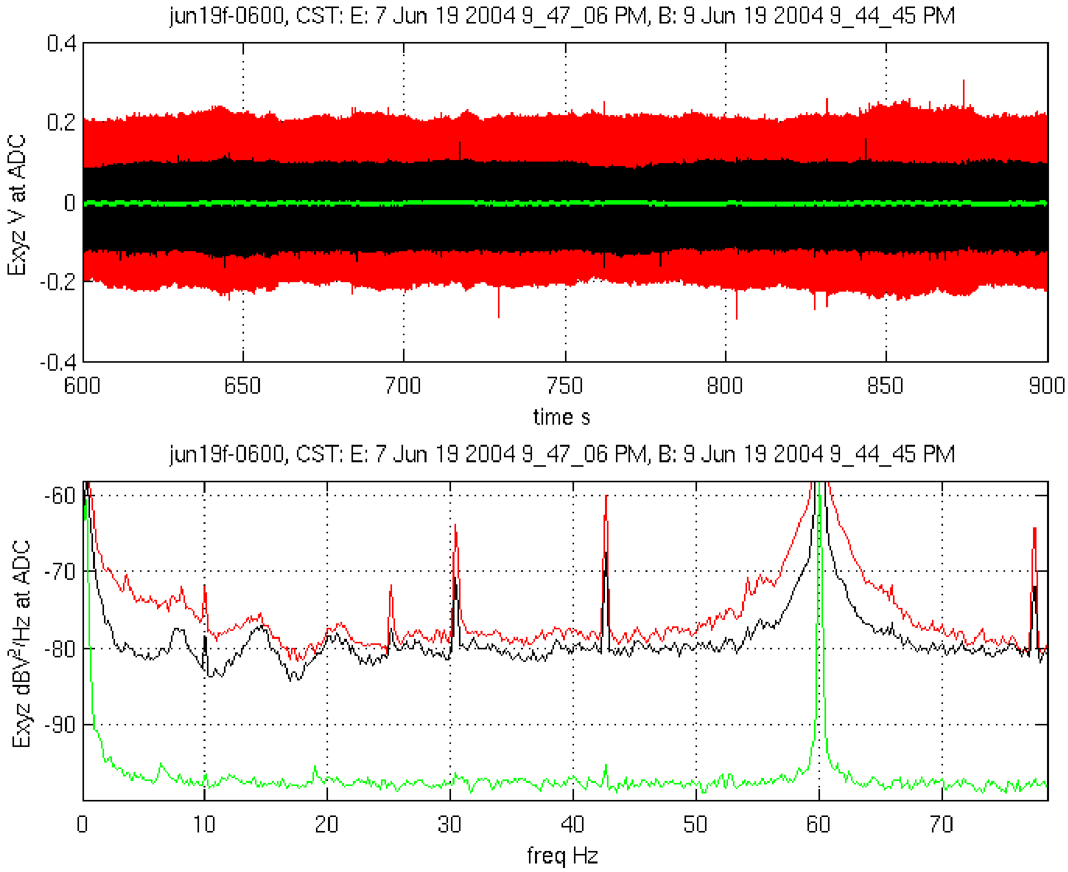

Figure B5: Examples of time series of X (red), Y (black) and Z (green) electrode voltage differences and the corresponding power spectra. The electrodes were separated 2.4 m in the horizontal and 0.8 m in the vertical. The voltages are dB re: 1 V at the ADC. The gain of the preamp was 80 dB. Thus –100 dB in the figure corresponds to –180 dB or 1 nV/sqrtHz at the electrodes. Note the much weaker 60-Hz line in the vertical electrode pair.

The Schumann resonance peaks 8, 14, 21, and 28 Hz are prominent, as are some unexpected, narrow but weak peaks at 25, 30, 42, and 78 Hz (Fig. B5). There is very little of these signals in the vertical E-field. Of course, there is the large 60-Hz power grid line; the p-p amplitude range of the time series is caused by this line. The cusps around the line are orders of magnitude smaller than the peak.

We have explored the processing of simultaneous measurements of electric and magnetic data in terms of polarization for power line frequencies and using a singular value decomposition (SVD) method. First, considering the X-Y polarizations (Fig. B6). The features of note are the general orthogonality and ellipticity of the B and E fields. The signals at multiples of 1, 3, and 5 times the 60-Hz line are band-passed and plotted in polar form of amplitude vs. phase. The 60-Hz line shows the expected orthogonal relation between E and B for a propagating signal. The weakness of the vertical component indicates that the power grid signals are horizontally polarized.

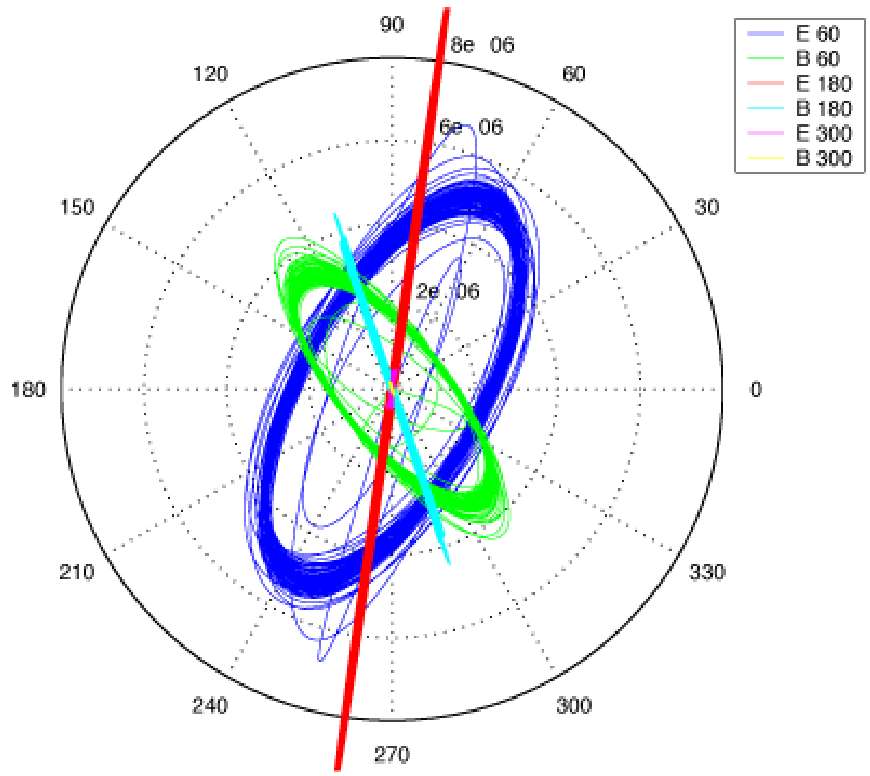

Figure B6: Example of E and B field polarization ellipses at odd harmonics: 60, 180, and 300 Hz.

Figure B7 shows the modal behavior of Utsalady data band-pass filtered near 60 Hz. The singular value decomposition (SVD) method replaces the original six time series of E and B data with three new time series (right panels) associated with three modes (left panels) of co-variability. The first mode (top) shows E (blue) orthogonal to B (red) and indicates downward propagation of energy. The second mode (middle) contains a similar orthogonal pair but is associated with upward propagation of energy. The third mode (bottom) is statistically insignificant noise. There is a dominant propagation of energy down from the surface. But as there is also a mode propagating from the seafloor that may be a reflection or a propagation path from the beach through the sediments under the ocean or due to direct contact of the ocean with grounded sources from nearby residences.

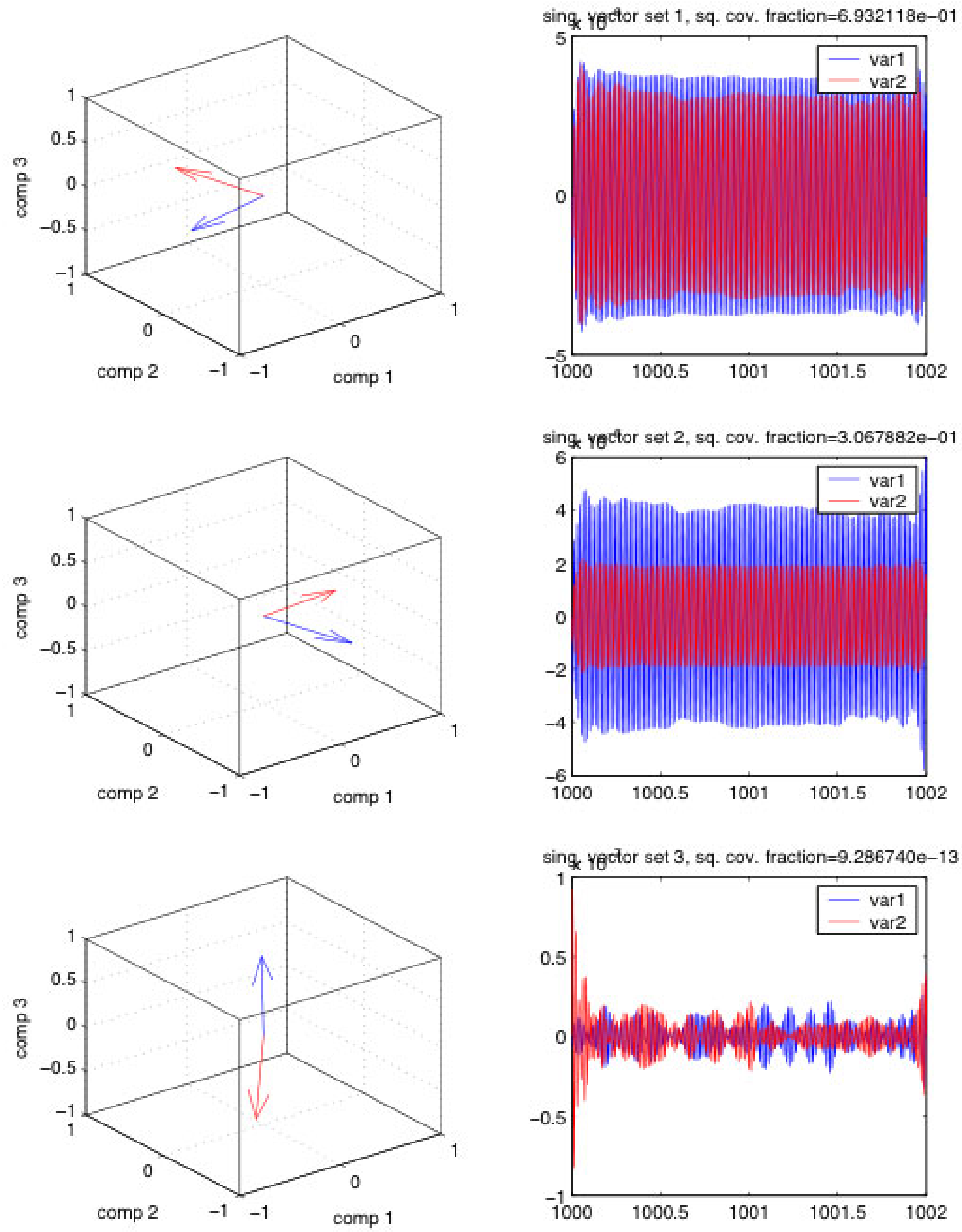

*Figure B7: Singular value decomposition of **E** and **B** from Utsalady Bay observations separating downward and upward propagation modes.*

Theory and Modeling

Several publications related to the model MOED (Model for Ocean ElectroDynamics) are now available to academic and defense research agencies around the world.

- Three-dimensional modeling of ocean electrodynamics using gauged potentials, Robert H. Tyler, Frederic Vivier, and Sheghui Li. *Geophys. J. Int*. (2004) **158**, 874–887
- Simulations of magnetic fields generated by the Antarctic Circumpolar Current at satellite altitude: Can geomagnetic measurements be used to monitor the flow? Frederic Vivier, Robert H. Tyler, and Ernst Maier-Reimer, *Geophys. Res. Letters*, (2004) **31**, L10306, doi:10.1029/2004GL019804.

In other unpublished work, theoretical work and MOED simulations have been combined to suggest several interesting opportunities of relevance to naval operations.

- Simulations indicate that it may be feasible to illuminate buried objects using EM radiation from a seafloor source. The EM fields travel through the sediments and illuminate the object from below. This is better than illuminating the object from above because the ratio of amplitudes between the scattered to primary fields increases to order one. Although without further description of background noise levels, the feasibility is difficult to determine. Current simulations suggest that while the EM detectors must be close (within a range of the order of a few times the dimension of the target), the source may typically be a kilometer or more away.
- Theory and modeling studies have suggested that there may be a significant opportunity for exploiting "PLHR" in naval detection and navigation applications. Power-line harmonic radiation (PLHR) refers to the stray EM radiation in the atmosphere due to the 50/60-Hz (and harmonics) power grids over the globe. Particularly, the odd harmonics of PLHR are large in amplitude and apparently uniform over large areas. As these fields refract into the ocean, they provide a somewhat ideal source of plane wave EM radiation from above, which can be used to illuminate targets or possibly be used as a navigation grid.

The E-field technology developed and utilized in this program has opened new opportunities. Other programs have been initiated to exploit the advances. For example, the technology is behind a new concept of making electrical conductivity profiles from seafloor installations in an NSF Science and Technology Center in which APL-UW is a partner. A proposal for new ocean EM sensors was submitted to ONR in response to the PLUS BAA. Another example is the installation of this project's SWEFS onto a neutrally buoyant float for NAVAIR.

MOED has been made available on a web site and is being used the CSS personnel. In addition, it is being used by investigators at Information Systems Laboratory, Inc., in support of research at SSC San Diego.

Related Projects

There are several ongoing projects sponsored by ONR or the Navy that will directly benefit from this effort:

1. The development of very sensitive EF systems has been supported by NAVAIR in the form of a neutrally buoyant float supporting a 3-axis EF array
2. An EF component to PLUSnet, the UARC response to ONR's BAA Persistent Littoral Undersea Surveillance
3. A NAVAIR program to evaluate EF opportunities

While developing state-of-the-art ocean electric field sensors and numerical models, we became acquainted with advanced technology for ocean EF measurements. Tim Fristedt joined us for two years as a postdoc. Tim earned his Ph.D. from Stockholm University but was also on the staff of the Swedish Defence Agency (FOI). We tested his technology against our current gear and determined that we could increase our sensitivity with the carbon fiber electrodes and low-noise amplifiers developed by FOI. We built our first instrument with this technology for our measurements of ambient EF in the Puget Sound. It was also used in the joint E-field and B-field measurements with CSS colleagues in St. Andrews Bay off Panama City, FL. We called the device the Shallow Water E-Field Sensor (SWEFS).

During the field experiment in Florida there was lightning all around us. Lightning is a prominent feature of both the E and B measurements. It is hard to find a quiet time series that is long enough for analysis. As a result, we have planned a second experiment in Puget Sound where lightning in the summer is a rare event.

Between the SWEFS deployments with CSS, we built an EF sensor system for a neutrally buoyant float (Eric D'Asaro's Mixed Layer Float, MLF II). We called this device the Floating E-field Research Platform (FERP). This NAVAIR funded program was operated off Pt. Loma, CA, in October 2004. For this experiment there was a towed EF source operated by Sweden's FOI. This project required an onboard data acquisition system, also a requirement for an autonomous SWEFS, as proposed to and funded by the recent ONR DURIP.

All data sets are being analyzed to quantify and describe the environmental EM noise, especially in the ELFE region, say below 10's of Hz. In particular, we want to identify spectral "windows" where deliberate EM signaling can have superior signal-to-noise. For example, gaps between the Schumann resonance peaks are candidates, as are frequencies that are not near the harmonics of the power line frequencies.

We have an ongoing collaboration with the Swedish Defense Agency that provides Tyler with opportunities to work with FOI yearly and Sanford with access to their technology and observations. For example, FOI plans to provide us with a source for electric field that will support the future work.

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13. ABSTRACT *(Maximum 200 words)*

This project began with an effort to understand and utilize environmental and deliberately produced electromagnetic (EM) signals in the coastal ocean. Our studies were undertaken to provide a means to communicate with and guide autonomous underwater vehicles (AUV) and other autonomous sensor systems, such as moored instruments. There is a need for non-acoustical methods to navigate and control AUVs, communicate with autonomous instruments, and detect submerged and buried objects in shallow water. In principle, extremely low-frequency EM signals (< 1 kHz) can be used for these purposes. In practice, however, not enough is known to predict reliable signal-to-noise ratios for particular applications. This is both because the propagation paths in the coastal environment are complex and because the background environmental fields are not well understood. Clearly, a comprehensive numerical model is needed to determine the effects of various complications encountered in the littoral region.

We undertook an effort to develop a numerical model that includes many EM influences, such as environmental noise, seabed electrical conductivity, variable bottom depth and coastline, and deliberate EM signals. Our goal is to understand these factors well enough to reliably estimate signal-to-noise ratios in planning coastal EM operations and to improve basic understanding of EM propagation and environmental noise in the coastal waters and to make and interpret sensitive EM measurements. The project had two components: 1) theoretical and numerical studies and 2) instrument construction and field observations.

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