ELECTROMAGNETIC MATCHED FIELD PROCESSING FOR SOURCE LOCALIZATION

Donald F. Gingras[1] *Peter Gerstoft*[2] *Neil L. Gerr*[3]

[1]Naval Command, Control and Ocean Surveillance Center, San Diego, California 92152, USA
[2] SACLANT Undersea Research Centre, 19138 La Spezia, Italy
[3] Office of Naval Research, Arlington, Virginia 22217, USA

ABSTRACT

Matched field processing (MFP) refers to signal and array processing techniques in which, rather than a planewave arrival model, complex-valued (amplitude and phase) field predictions for propagating signals are used. Matched field processing has been successfully applied in ocean acoustics. In this paper the extension of MFP to the electromagnetic domain, i.e., electromagnetic (EM) MFP (EM-MFP) is described. Simulations of EM-MFP in the tropospheric setting suggest that, under suitable conditions, EM-MFP methods can enable EM sources to be both detected/localized and used as sources of opportunity for estimating the environmental parameters that determine EM propagation

1. INTRODUCTION

Recent research on array processing for ocean acoustics has included a significant effort to use precise full wave propagation models and efficient parameter search algorithms in order to jointly estimate both signal source location and environmental parameters. In ocean acoustics these methods are referred to as Matched-Field Processing (MFP) because they exploit the full-field structure of signals propagating in the waveguide. MFP is a generalization of plane wave beamforming wherein the "steering or replica" vector is derived from a solution of the wave equation for a point source. Because the plane wave model is not generally an appropriate model for acoustic signals propagating in the ocean waveguide MFP provides improved localization performance for this application [1, 2].

MFP methods for joint source localization and environmental parameter estimation have not previously been applied in the electromagnetic domain. In this paper the extension of MFP to the electromagnetic domain is described, i.e., electromagnetic MFP (EM-MFP), as a means for simultaneously localizing an EM source and estimating the environmental parameters associated with the propagation of the source signal. While methods for estimating environmental parameters using EM field measurements have been successful and there are a number of papers on this subject, in the previous work the source-receiver geometry was known and in fact controlled so as to optimize information about environmental parameters.

Early work in acoustic MFP typically treated cases in which it was assumed that all parameters except for two (e.g., source range and depth for MFP using a vertical array) were known without error. Solution then involved computing the so-called range-depth "ambiguity function", a two-dimensional surface whose maximum, generally found by visual inspection or exhaustive search, formed the source location estimate. In what follows such a case in the setting of EM-MFP is considered along with a more complicated case in which the environmental parameters that determine propagation are also unknown. Solution in the latter case requires sophisticated search techniques to find the global maximum in a space of dimension greater than two.

1.1. Array Data for Ocean-MFP and EM-MFP

MFP in ocean acoustics typically employs a vertical array of hydrophones of sufficient length to "adequately" sample the acoustic field over some portion of the water column. Vertical antenna arrays have also been employed in the electromagnetic domain. Webster [3] used a vertical array containing 16 antenna elements spanning 666 wavelengths at 16.65 GHz to estimate the time-varying multipath arrival structure (multipath amplitude and angles-of-arrival). Webster's results indicate that (1) the angle-of-arrival structure was rich in that there were always at least five different path arrivals and (2) the angle-of-arrival structure was time-varying. The first observation strongly suggests that there is information in the arrival structure that can be exploited, through EM-MFP, for the purpose of source location and environmental parameter estimation. The second observation implies that for EM-MFP it will not be sufficient to use *a priori* environmental parameters for source location estimation. Rather, EM-MFP is likely to require the joint estimation of these parameters. Furthermore for EM-MFP to be of utility in an operational setting the estimation will have to be conducted on a time scale consistent with the time-varying nature of the EM channel.

2. OBJECTIVE FUNCTION AND SEARCH METHOD

The objective function provides a measure of similarity between the observed signal field and the predicted signal field, where the observed signal field is the vector-valued array data and the predictions are based on the forward propagation model and environmental parameters. The linear Bartlett processor is perhaps most popular and only this will be used. This processor expresses the linear correlation of the observed and computed field. Whether acoustic or electromagnetic, the MFP objective function is generated as follows: Windowed time-series from the array are

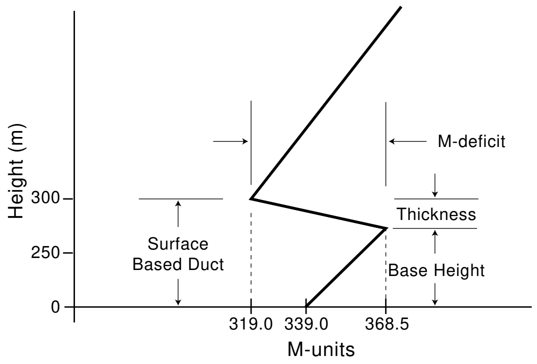

Figure 1. Modified vertical refractivity for a tri-linear profile.

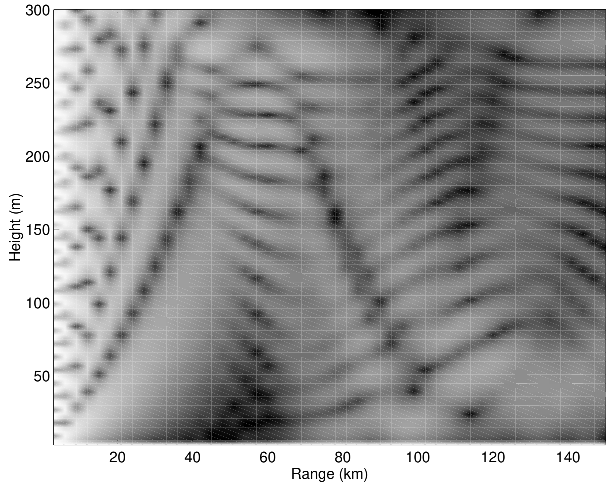

Figure 2. Coverage diagram showing propagation loss as a function of height and range for the tri-linear refractivity profile, RF emitter at 50 m, the frequency is 1 GHz. The transmission loss scale is from less than 100 dB (white) to greater than 150 dB (black).

Fourier transformed to form frequency domain data vectors $\mathbf{d}^l(\omega)$ where ω denotes frequency and l the time window. The dimension of the data vectors equals the number of antenna elements. The outer-products of the data vectors are averaged to form the sample covariance matrix

$$\hat{\mathbf{R}}(\omega) = (1/L)\sum_{l=1}^{L} \mathbf{d}^l(\omega)\mathbf{d}^l(\omega)^* \tag{1}$$

where * denotes conjugate transpose and L is the number of time "snapshots." The normalized Bartlett objective function is then

$$P_{BT}(\mathbf{m};\omega) = \frac{\mathbf{w}^*(\mathbf{m})\hat{\mathbf{R}}(\omega)\mathbf{w}(\mathbf{m})}{\|\mathbf{w}(\mathbf{m})\|^2}. \tag{2}$$

where $\mathbf{w}(\mathbf{m})$ (referred to as the replica vector) is the vector of signal field predictions computed using a forward propagation model and the parameter vector $\mathbf{m}$. A number of other objective functions have been investigated for acoustic MFP (see [1, 2] for a summary of these) but, in general, the Bartlett processors have been found to be the most useful.

2.1. Global Search Algorithms for MFP

In early work in acoustic MFP a two-dimensional range-depth ambiguity surface was thought to be adequate for source localization with a vertical array in a known propagation environment. Such use of a two-dimensional ambiguity surface was predicated on the implicit assumption that all but two (source location) parameters were known. In that special case the parameter search was carried out only over the two unknown parameters by plotting the value of the objective function over the range of feasible values for source location. Not surprisingly, in cases where the environmental parameters were in fact well known the ambiguity surface contained a well defined maximum and the associated source location estimates were accurate. If the environmental parameters were not well known then the parameters used to generate the ambiguity surface differed substantially from those of the actual waveguide. In the event of such "mismatch " the ambiguity surface generally contained a number of sidelobes close in amplitude to the maximum and source location estimation could not be accomplished with any certainty. In that case there were essentially more than two unknown parameters and so as a remedy to mismatch the maximum of the objective function in an augmented parameter space of dimension greater than two must be found. This requires an efficient global search algorithm.

In Section 3.2, simulation results will be presented for parameter estimation first via a two-dimensional ambiguity function and then in a space of higher dimension using a global optimization technique referred to as "genetic algorithms." The basic principle of GA is simple: From all possible parameter vectors, an initial population of q members is randomly selected. The "fitness" of each member is computed on the basis of the value of the objective function. Based on the fitness of the members a set of "parents" are selected and through a randomization a set of "children" is produced. These children replace the least fit of the original population and the process iterates to develop an overall more fit population. A more detailed description of genetic algorithms and their application to parameter estimation is given in [5].

3. TROPOSPHERIC SIMULATIONS

This section presents a discussion of the computer simulations of EM-MFP in the tropospheric setting. The simulations are of three general types. First, all environmental parameters are assumed to be known and a range-height ambiguity surface is generated for estimating the unknown source location parameters. Second, knowledge of environmental parameters is not assumed and the refractivity profile parameters are estimated assuming that the source location is known. Third, the refractivity profile parameters are estimated simultaneously with the source location parameters. In the second and third cases estimation involves global search using genetic algorithms.

In all simulations, the synthetic array data were generated for a scenario with the following general characteristics:

Source Signal: The synthetic signal simulated an omni-

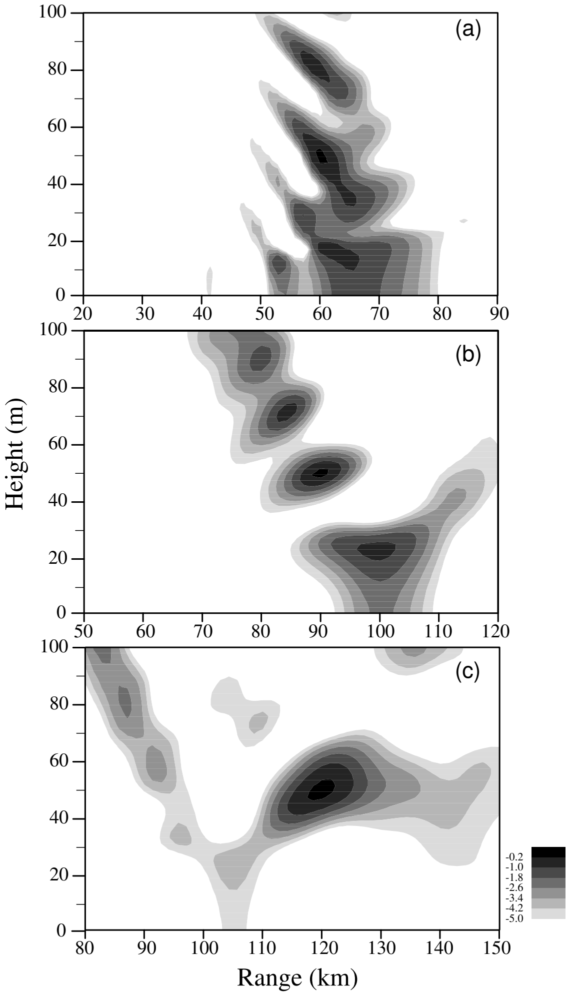

Figure 3. Range-height ambiguity surfaces for the known environment case, receive antenna aperture was 98 m, actual source locations were a height of 50 m and range of: (a) 60 km, (b) 90 km, and (c) 120 km.

directional point source with horizontal polarization at a frequency of 1 GHz. Source ranges were 60, 90 or 120 km and source height was 50 m. Receive Antenna: The receive antenna was a vertical array that contained 50 omnidirectional elements. Two configurations were considered: (1) element spacing of 2 m, first element at 2 m above mean sea level (MSL) and total aperture of 98 m, and (2) element spacing of 1 m, first element at 1 m above MSL and total aperture of 49 m. Propagation Environment: The propagation environment (refractivity profile in modified M-units) used for all synthetic cases was that of a surface duct caused by an elevated trapping layer, see Fig. 1. A tri-linear refractivity profile was used to characterize the environment. The tri-linear profile is represented by three parameters which define the trapping layer: layer base height, layer thickness and the M-deficit (decrease in refractivity over the layer in M-units). Propagation Code: The Terrain Parabolic Equation Model (TPEM) was used for all simulations [4]. TPEM is based on the split-step Fourier transform to solve the parabolic wave equation, which has been shown to be numerically efficient. Objective Function: In all cases the objective function used was the Bartlett processor [1, 2]. The synthetic signal data at each receive antenna element was generated using TPEM based on the source signal, receive element location, and propagation environment. The replica vectors were also generated using the TPEM propagation model.

In this paper the extension of MFP to the electromagnetic domain, i.e., electromagnetic MFP (EM-MFP), as a means for simultaneously localizing an EM source and estimating the environmental parameters associated with the EM propagation is considered. Solution in the case of unknown source location (range and height for a vertical array) is developed via exhaustive search of the so-called ambiguity surface. For the case of unknown environmental parameters (three refractivity parameters: M-deficit, base-height and layer thickness) exhaustive search was not feasible, particularly if source location was also unknown (five parameters total). In this paper genetic algorithms are used to solve these more difficult cases.

Figure 2 illustrates the propagation loss coverage diagram for a range-independent terrain for a source at 50 m with a frequency of 1 GHz computed using TPEM. From this figure it is seen that the dominant component of the propagation is two beams of energy that are reflected by the upper boundary of the surface duct at a range of about 50 km and again reflected by the surface at a range of about 100 km. These beams dominate the propagation in the lower 300 m of the atmosphere.

3.1. Known Environment

Figure 3 gives the ambiguity surfaces computed when the receiver array contained 50 elements spanning the first 98 m of the atmosphere with the source at a height of 50 m. For Fig. 3a the source was located at a range of 60 km from the receiver array. Significant ambiguity in source height is noted in that there are sidelobes at 15 m and 80 m at the source range with the largest sidelobe only 0.5 dB below the maximum. However, there were basically no ambiguities in range over the search region from 20 km to 90 km. Figures 3 b and c illustrate source location estimation when the source location was at ranges of 90 km and 120 km, respectively. The results for the source located at 90 km are fairly similar to those obtained when the source was located at 60 km, though in this case the sidelobes were displaced in both range and height (whereas for the 60 km case the sidelobes were only displaced in height) and the largest sidelobe was 0.8 dB below the maximum. Figure 3c illustrates the results for a source at 120 km. The results for the source at 120 km are the best in that the largest sidelobe was 2.6 dB below the maximum.

3.2. Unknown Environment

If the environment is not known it is in general not possible to estimate the source position. Figure 4 shows how strong the source range depends on the 3 environmental parameter. Using a wrong parameter can seriously degrade the performance and give a wrong estimate of the source location. In order not to be trapped in any local minimum it is better to optimize all important parameters simultaneously,

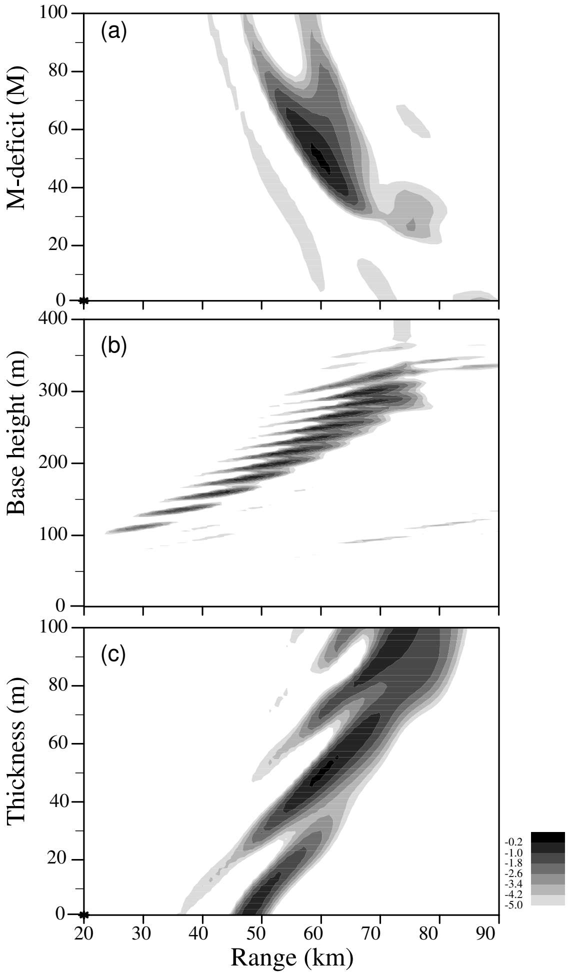

Figure 4. Ambiguity function, source range vs (a) M–deficit, (b) base-height, and (c) thickness.

this is here done by the globally convergent genetic algorithm [5]. The result of this genetic algorithm is not only the minimum value, but also from each candidate model vector, visited durring the optimization, is weighted with its objective function, this corresponds to an Monte Carlo integration of the likelihood function and is an estimate of the *a posteriori* probability distribution.

Figure 5 illustrates the *a posteriori* distributions for the five estimated parameters using an antenna aperture of 98 m. The source location distributions are well defined unimodal distributions with maxima located very close to the actual source location values. The distributions for the three M–profile parameters, as in Case B where the source location was known, are well defined and close to the actual values. All five parameter estimates are close to the actual values and confidence is quite high for all of the parameters except the layer thickness.

4. RESULTS AND CONCLUSIONS

The potential for EM-MFP in the tropospheric setting was evaluated using synthetic data. The simulation results suggest that, under suitable conditions, electromagnetic MFP

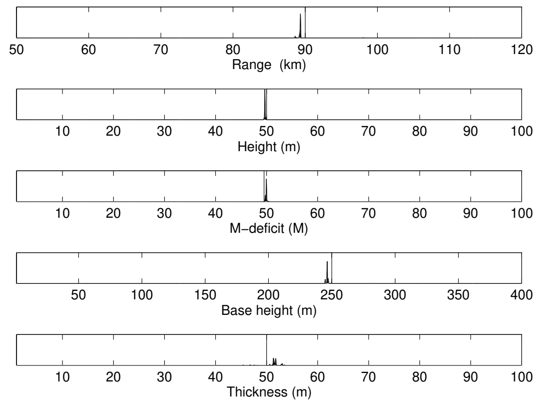

Figure 5. GA estimated *a posteriori* distributions for source range, source height, M-deficit, base-height, and layer thickness, antenna aperture was 98 m.

methods can enable EM signal sources to be simultaneously localized and used as sources of opportunity for estimating refractivity. The specific case considered was that of passive localization of a 1 GHz emitter at 50 m height and 60/90/120 km range in a surface duct environment with a vertical 50-element antenna of length 98 m. EM-MFP was carried out using the TPEM propagation code and Bartlett processor.

A more throughout examination of EM-MFP can be found in Ref. [6].

Even though promising, these results are preliminary and far more needs to be done before EM-MFP can be thought to be of real utility. Of potential interest would be EM-MFP in other EM propagation settings, with emitters at other frequencies and with bandwidth, using other antenna configurations, and in noise. Ultimately, evaluation of EM-MFP using real field data is required.

REFERENCES

[1] A.B. Baggeroer, W.A. Kuperman, and P.N. Mikhalevsky, “An overview of matched field methods in ocean acoustics,” IEEE J. Oceanic Engr. **18**, 401–424 (1993).

[2] A. Tolstoy, *Matched Field Processing for Underwater Acoustics*, World Scientific, Singapore, 1993.

[3] A.R. Webster and T.S. Merritt, “Multipath angles-of-arrival on a terrestrial microwave link,” IEEE Trans. Comm. **38**, 25–30 (1990).

[4] A.E. Barrios, “A terrain parabolic equation model for propagation in the troposphere,” IEEE Trans. Antennas Propagat., **42**, 90–98 (1994).

[5] P. Gerstoft, “Inversion of seismoacoustic data using genetic algorithms and *a posteriori* probability distributions,” J. Acoust. Soc. Am. **95**, 770–782 (1994).

[6] D.F. Gingras, P. Gerstoft and N.L. Gerr “Electromagnetic Matched field processing: Basic concepts and Tropospheric simulations,” IEEE trans. on antenna and propagation, accepted October 1996.