THE APPLICATION OF INVERSE METHODS TO THE OCEAN ENVIRONMENT

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Year end Report

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Subj: RETURNED GRANTEE/CONTRACTOR TECHNICAL REPORTS

1. This confirms our conversations of 27 Feb 97 and 11 Jul 97. Enclosed are a number of technical reports which were returned to our agency for lack of clear distribution availability statement. This confirms that all reports are unclassified and are "APPROVED FOR PUBLIC RELEASE" with no restrictions.

2. Please contact me if you require additional information. My e-mail is *silverr@onr.navy.mil* and my phone is (206) 625-3196.

ROBERT J. SILVERMAN

INTRODUCTION

This is the final report on the research contract, "The Application of Inverse Methods to the Ocean Environment," for the period, November 1, 1994 through October 31, 1995.

Under support of this and other research funding, we have developed and implemented an inversion theory for imaging reflectors in a host medium and estimating the changes in medium parameters across those reflectors.

This is a research project in the Center for Wave Phenomena, an interdisciplinary educational and research program at the Colorado School of Mines; the principal investigator is the director of that center.

Technology Transfer

A major source of funding for the Center for Wave Phenomena is a consortium project supported by thirty-two companies in the oil industry: explorers/producers, seismic data processors and computer companies. We would like to believe that the success of our program in this this period of dramatic contraction in the industry we serve is a measure of the quality, relevance and potential applicability of our research in finding energy reserves.

The Center also has support from the Ocean Acoustics Branch of ONR, the ACTI program, providing partnership between the energy industry and the national labs (Livermore, Los Alamos, Oak Ridge), the Army Research Office, the Gas Research Institute, and the Foundation of the Society of Exploration Geophysicists.

Papers

There was one paper produced partially under the support of this project during the current year,

Migration Velocity Analysis, Zhenyue Liu, CWP-168, Ph. D. Thesis, previously sent to ONR.

A brief excerpt of this paper was presented in our consortium project review. That excerpt is attached because it addresses the research completed in the current project year, only.

Test on Marmousi Data of Velocity Analysis by Perturbation, Zhenyue Liu and Norman Bleistein, appearing in the CWP Annual Project Review, CWP-185.

Presentations

Presentations on our research on this project were presented at the following international meetings.

Velocity Analysis by Perturbation, by Liu and Bleistein, Expanded Abstracts, Society of Exploration Geophysicists, October 1994, p. 1191. (Presented by Liu.)

Mathematical Analysis of Residual Moveout and Velocity Analysis, Zhenyue Liu and Norman Bleistein, Abstracts, International Geophysical Conference and Exposition, St. Petersburg, Russia, July 1995. (Presented by Bleistein.)

Mathematical Analysis of Residual Moveout and Velocity Analysis, Zhenyue Liu and Norman Bleistein, Workshop on Inverse Methods, Institute for Mathematical Analysis, University of Minnesota, March, 1995. (Presented by Bleistein.)

Mathematical Analysis of Residual Moveout and Velocity Analysis, Zhenyue Liu and Norman Bleistein, Workshop on Inverse Methods, International Meeting of the Society of Exploration Geophysicists, Houston, October, 1995. (Presented by Bleistein.)

This talk was also a "fill-in" for an absent speaker at a workshop on inversion at the International Congress of Industrial and Applied Mathematics in Hamburg, Germany, July, 1995.

BACKGROUND

As noted above, this research is part of a larger integrated research project on the application of inverse methods to map the interior of the earth with sources on land or in the ocean. As such, we concentrate on modeling and inversion in acoustic and elastic media (although our methods are just as valid in electromagnetic media). The emphasis is on inversion of data from multi-source/multi-receiver arrays to produce a reflector map of the probed medium and to estimate the changes in medium parameters across those reflectors. Since our concentration is on reflection, refraction and diffraction, are methods are naturally *high frequency methods.*

Inverse problems are inherently nonlinear. The wave equation(s) governing the forward problem involve products of the unknown medium parameters and the unknown propagating fields in the interior of the medium. Hence, it is necessary to solve these problems by iterative and/or recursive methods. Our methods back propagate the observed data into the unknown medium, using "background" propagation parameters in this process. As new information about the unknown parameters is gained, the background can be revised to produce a (presumably) more accurate picture of the unknown medium. Over the years, we have extended our methods through a hierarchy of progressively more realistic source/receiver configurations and progressively more complex background media.

The primary relevance of our work to ONR is the application to mapping the seabed, seamine detection, and nondestructive evaluation—imaging of flaws in solids—where the method is known as *synthetic aperture focusing technique* or SAFT. In the seismic inverse problem, when the sources and receivers are buried (located in wells), the method is called *diffraction tomography.*

A major stumbling block for all inversion techniques is getting good background propagation speeds because the observed data on the upper surface must be "propagated" back into the subsurface using this background. Poor estimates of background speed yield misplaced reflectors and poor estimates of the change in medium parameters across them. Furthermore, amplitude control in an absolute sense is extremely impractical; amplitude control in a relative sense—from one experiment to the next—is a more realistic goal. Thus, there is a need for a method to estimate background velocities that does not require precise amplitude information.

The interest in the oil industry for this technique stems from the need to properly place possible oil or gas prospects. For seabed mapping, this type of velocity analysis is crucial to proper mapping of the seabed in regions of complex structure. Sonar signals, for example, can "tunnel" through the shallow part of the seabed, arriving back at the receiver location before reflections that have propagated totally within the ocean. Thus, a knowledge of the seabed in regions of complex structure is a necessary requirement for proper interpretation of such returns.

In flaw characterization there is a similar need for proper position and sizing of cracks and inclusions in solids. Similarly, more accurate location and imaging of tumors and other anomalies in human tissue would provide a dramatic improvement in non-invasive analysis of medical problems.

Another important military application is the location of sea mines. While the location of floating mines might not require the precision velocity analysis of our research, the location of mines that have sunk or been buried in the seabed will require this kind of precision. While the "reflector" in this case may be more like a point scatterer, it requires only a minor change in our processing algorithms to image point scatterers rather than reflectors. Such modifications have been described in Bleistein [1988], partially supported by the Mathematics Branch of ONR under this program.

With the graduate student partially supported by this project, the principal investigator has been working on various approaches to "velocity analysis," a technique for obtaining a reasonable accurate (low wave number) propagation speed to use in the computer implementation of the inversion. As noted above, we specifically use methods that do not rely on accurate amplitude in the data acquisition. Thus, our methods use only the reflector mapping property of our inversion and not on its parameter estimation capability. In the seismic exploration literature, methods that provide reflector maps are called "migration" rather than inversion, although the distinction between the two terms has blurred in recent years. However, in our papers, we often refer to migration rather than inversion to emphasize to the reader that this component of our more general inversion techniques can be carried out with standard migration algorithms that have little regard for amplitude accuracy. Often, these have the advantage of requiring less CPU, although our inversion and comparable Kirchhoff migration codes have similar run times.

Briefly, the idea behind our method is as follows. It depends on the fact that there is multiple coverage of the unknown medium with a suite of experiments of one of the following types:

1. common shot experiment—fixed source and a line of receivers;
2. common offset experiment—fixed distance between source and receiver, many experiments.

Note that for the latter, one need only reorder the data in the suite of experiments of the former type. The former type is more typical. A ship with a towed array of receivers sets off a source—dynamite or mechanical—at uniform intervals as it moves in a line in the ocean. The latter type is more popular for processing because the suite of traces at different midpoints and one offset illuminates the entire survey region while the suite of traces at one source and all receivers would illuminate only a small portion of the medium below the receiver array.

Suppose that the background propagation speed is known down to a particular reflector and the objective is to get a "best guess" for the average background in the layer between that level and a next reflector. Choose a transverse position (trace location) where the reflector is imaged by more than one common shot inversion or by more than one common offset inversion. For each inversion, the illumination will require different refractions at the upper interfaces and different traveltimes to the reflection point under investigation. Thus, the output of that trace will show the reflection point in question at the same depth for all experiments, only if the "right" propagation speed is used above the reflector; for the wrong propagation speed, the different outputs will show the "same" reflection point at different depths. It is the curvature of this ensemble of erroneous depths that we exploit to determine the velocity recursively through progressively deeper layers in the Earth. Note that this technique depends upon a certain degree of coherency in this *common image gather* of outputs; it is necessary to "see" the images of a common reflection point and distinguish them from the clutter of multiple images and noise. When the velocity is determined in a particular layer, the data is processed through that layer to the next reflector and the method is repeated, either below the new reflector or laterally, until the entire medium is covered by blocks in which the velocity analysis has been carried out and a reflector map has been produced. The method within a layer is iterative, correcting the curvature of the multiple images of a common reflection point until they agree within some error criterion; the method is recursive in that it moves progressively deeper into the host medium starting from the upper surface.

A complete discussion of this iteration/recursion procedure and the interface smoothing can be found in Liu and Bleistein [1991] and Liu [1995], and is described in more detail in previous renewal proposals. References to related work can also be found in those papers, as well.

More recently [Liu and Bleistein, 1992], this research project has focused on the analytical relationship between the apparent curvature of the erroneous positions as function of the offset of the source and receiver and the error in velocity. For horizontal reflectors, this technique does not require the iterations of the former method; one reads off the "correct" velocity from the curvature of the arrival time as a function of the offset between source and receiver. For small lateral variations in velocity, a perturbation method allows us to solve for an approximate laterally varying background velocity, as well.

The analysis of [Liu and Bleistein, 1992] has also been extended to take account of velocity gradients. This work is described in Liu and Bleistein, [1993]. As part of this more recent analysis, we also provide sensivity and error estimates for this type of velocity analysis. A shortcoming of that method was that it still relied on a near hyperbolic curvature of the ensemble of images of the same depth point on the reflector as a function of offset.

Work in this project year

The work completed in the current project year makes significant improvement on the previous method used to update the velocity in the iterative part of the algorithm. This is achieved by deriving an expression for the functional derivative of image depths with respect to parameters characterizing the mean velocity or mean components of velocity gradient in a given layer in the subsurface. That expression is described in Liu and Bleistein [1995] (attached) and in detail in the Ph.D. thesis, Liu [1995].

The most difficult test of this data was carried out on the Marmousi data, a test data set produced for the oil industry by the Institut Français du Petróle in 1988 [Versteeg and Grau, 1991]. The physical model for this data set is shown in Figure 2 in the attached paper. It shows over 200 layers. This velocity analysis method produced a background model shown in Figure 5 containing only 19 layers. This model was produced in a "blind test," assuming no *a priori* knowledge of the model in the test. Figure 6 shows a comparison of the true velocity with the derived velocity on three vertical lines. One can see that the derived background velocity has lower frequency content than the true velocity. This is to be expected. Since we are using traveltime information to derive the background velocity, we are limited to distinguishing changes over "many" (at least three) wavelengths at the dominant frequency of the data. However, one can also see in this comparison that the method has produced a velocity with a nonzero vertical component of gradient in some layers, in part, as partial compensation for loss of detail. In fact, there were cases of nonzero horizontal gradient, as well.

The output produced by inverting the Marmousi data with the background derived by this velocity analysis is shown in Figure 7, while the inversion produced with the true velocity model as background is shown in Figure 8.

The only region in which the output of Figure 8 is significantly better than that of Figure 7 is below the midpoint at 6km at a depth of 2.5km and below. In this region, this approach to velocity analysis has failed. The explanation for this is provided in Liu [1995] and in the attached paper. It is a consequence of the fact that there are multiple arrivals at this depth and a lack of coherency in our images of a common reflector point from data at different offsets. This was first reported in Geoltrain, and Brac [1991]. This lack of coherency at depth can be seen in Figure 10. As a comparison, Liu shows in Figure 12 that the same lack of coherency occurs when one uses the true velocity rather than the derived velocity, confirming that this anomaly is not peculiar to our method, but is inherent in the data. Thus, we need to improve the basic approach to obtain a better background velocity in this one region.

The results in the remainder of Figure 7 are extremely good, at least as good or better than any blind tests reported in a survey article on processing of the Marmousi data [Versteeg, R., 1994].

In the PROPOSED RESEARCH section of last year's proposal, we set the Marmousi data set as a benchmark for our inversion. We also noted last year that we needed a better ray tracing code to achieve this end. That code was developed under other support. We believe that we have substantially succeeded in meeting the goal to develop a velocity analysis method to deal with data of this degree of complexity, although, as noted here, there is still further work to be done.

REFERENCES

Beylkin, G., 1985, Imaging of discontinuities in the inverse scattering problem by inversion of a causal generalized Radon transform: J. Math. Phys., 26, 99-108.

Bleistein, N., 1987, On the Imaging of Reflectors in the Earth: Geophysics, 52, 931-942.

Bleistein, N., 1989, Large wave number aperture limited Fourier inversion: Wave Motion, 11, 113-136 (CWP-063R).

Bleistein, N., and Cohen, J.K., 1991, An alternative approach to the Cagniard deHoop method: (CWP-098P) Geophysical Prospecting, 40, 619-649, 1992.

Burridge, R., M. V. de Hoop, and D. Miller, 1995, Multi-parameter inversion in anisotropic media using the generalised Radon Transform: Schlumberger-Doll Research, Rigefield, CT and Shlumberger Cambridge Research Report

Cohen, J. K., F. G. Hagin, and N. Bleistein, 1985a, Computational and Asymptotic Aspects of Velocity Inversion: Geophysics, 50, 8, 1985.

Cohen, J. K., F. G. Hagin, and N. Bleistein, 1985b, Three Dimensional Born Inversion with an Arbitrary Reference, Geophysics, 50, 1689-1700.

Cohen, J. K., F. G. Hagin, and N. Bleistein, 1987, Two-and-one-half Dimensional Born Inversion, with J. K. Cohen and F. G. Hagin, Geophysics, 52, 26-36, 1987.

Geoltrain, S., and J. Brac, 1991, Can we image complex structures with finite-difference traveltimes?: Expanded Abstracts, International Meetin of the Society of Exploration Geophysicists, Houston, November, 1991, 1110-1113.

Gray, S. H., and W. P. May, Kirchhoff migration using eikonal equation traveltimes, Geophysics, 59, 5, 810-817.

ten Kroode, A. P. E., D. -J. Smit, and A. R. Verdel, 1995, Linearized asymptotic inversion in the presence of caustics (extended version): Shell Research Publication 1295, Koninklijke/Shell Exploratie en Produktie Laboratorium, Rijswijk, The Netherlands.

Liu, Z., 1995, Migration Velocity Analysis: Center for Wave Phenomena Rsearch Report, CWP-168, Ph. D. Thesis, previously sent to ONR.

Liu, Z., and N. Bleistein, 1991, Velocity analysis by inversion: CWP-104.

Liu, Z., and N. Bleistein, 1992, Velocity analysis by residual moveout: Center for Wave Phenomena Report, CWP-123, Colorado School of Mines, Golden, CO.

Liu, Z., and N. Bleistein, 1993, Velocity analysis by perturbation: Center for Wave Phenomena Report CWP-135, Colorado School of Mines, Golden, CO.

Liu, Z., and N. Bleistein, 1995, Test on Marmousi Data of Velocity Analysis by Perturbation: appearing in the CWP Annual Project Review, CWP-185.

Maslov, V. P., 1972, Théorie des Perturbations et des Méthodes Asymptotiques: Dunod, Paris.

Maslov, V. P., and Fedoriuk, M. V., 1981, Semi-classical Approximation in Quantum Mechanics: Reidel, Dordrecht.

Versteeg, R., 1994, The Marmousi experience: velocity model determination on a synthetic complex data set: The Leading EDGE, 13, 191-199.

Versteeg, R., and G. Grau, 1991, The Marmousi Experiment, Proceedings of a workship on practical aspects of seismic data inversion held at the 52nd EAEG meeting (Copenhagen, 1990): EAEG, Zeist; ISBN 90-73781-01-9.