Envelope Sensing Decon

Jon F. Claerbout

Classical deconvolution is a process which uses the spectrum of the data but ignores the envelope of the data. Wiggins' MED deconvolution is sensitive to the envelope of the output seismic traces but ignores the spectrum. Unlike classical decon, MED tells you what color is best to use to display your seismic traces. In practice, and perhaps in theory, MED cannot achieve the reliability of classical decon. In this paper it is shown how the envelope-sensing, color-defining properties of MED can be built into a stable minimum-squares framework.

Levinson-Robinson Decon (The Classic Case)

Let y_t define the data input to an undetermined filter a_t and let x_t denote the output of the filter. In matrix form this may be written as for example

$$\mathbf{x} \quad = \quad \begin{bmatrix} x_0 \\ x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} \quad = \quad \begin{bmatrix} y_0 & 0 & 0 \\ y_1 & y_0 & 0 \\ y_2 & y_1 & y_0 \\ 0 & y_2 & y_1 \\ 0 & 0 & y_2 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \end{bmatrix} \quad = \quad \mathbf{Y}\,\mathbf{a} \tag{1}$$

In the classical prediction error problem, one defines the filter $\mathbf{a}$ by minimizing the energy in the output subject to the constraint that the filter be causal, that is

$$\min_{\mathbf{a}} \quad \mathbf{x}^T \mathbf{x} \qquad \textit{subject to} \quad \begin{cases} a_0 = 1 \\ a_t = 0 \;\; \textit{if } t < 0 \end{cases} \tag{2}$$

The resulting filter $\mathbf{a}$ has some very remarkable properties which are well documented in the classical literature. Let us note only that the output x_t of this filter is known to have a white spectrum independent of the spectrum of the input to the filter. Likewise the output

x_t is independent of *any* minimum phase pre-filter. Thus it can be said that classical decon corrects for variations in seismometers, and more importantly, for lateral variations in the resonance of the soil layer.

Against this process it may be said that no one wants to look at a white output. The bandwidth depends on the Nyquist frequency which in turn is almost an accidentally determined parameter. The process is incomplete in that it leaves the processing geophysicist with a number of further judgements to be made. The display spectrum must be non-white, but what should it be?

A popular approach is to try out several band pass filters and use some subjective criterion to select the best. Against this approach it may be said that the decon has filled the holes in the spectrum. The bottom of any hole in the spectrum of a received wave is almost certain to be filled with noise, and it seems inappropriate to amplify it to the level of the rest of the information. Furthermore, big peaks in the spectrum are forced down, which may be inappropriate because these big peaks may represent the strongest signal in the downgoing wave.

There are other popular indirect means of limiting the bandwidth of the output data. For example, a prediction error filter may be gapped. Alternately, some white noise may be added to the spectral matrix which is to be inverted. These means of limiting the output bandwidth share the characteristic of requiring human judgement to select a central parameter. And the output is significantly sensitive to the parameter. An attractive feature of classic decon, namely invariance of output to soil prefilters, is lost when classic decon is modified in these ways to limit bandwidth. To preserve this feature, the filter must be defined in terms of properties of the *output* not properties of the *input* or the transfer function itself.

Predictive deconvolution has a seductive theoretical basis in which one imagines observed signals being created by occasional "innovations" convolved with an unknown system response. A few innocent sounding assumptions lead to a magical method of determining the unknown system response and being able to deconvolve to uncover the hidden innovations. When you test it you are disappointed to discover innovations coming out at every point on the time axis. If you double the density of sampling the continuum, you get double the innovations. Perhaps what you really wanted was not the innovations but the gaps between them!

Minimum Entropy Deconvolution

Ralph Wiggins broke new ground in seismic deconvolution when he introduced what he called *minimum entropy deconvolution.* This process is not a minimum power process. Instead it is an iterative process which tries to increase the output signal where it is large and decrease it where it is small. Thus it tries to create both innovations and the gaps between them. Like pure Levinson-Robinson decon, the spectrum of the output is wholly independent of the spectrum of the input, so the output is (within reasonable limitations) independent of the random prefilters which we have come to associate with soil layers. But the MED process, unlike any of the classical decons, has a new attractive feature that it tells you what is the best spectrum to use in the display of the data. Furthermore, it overcomes the "minimum phase" assumption of classical decon. A claim for MED is that it is able to find the waveform, minimum phase or not, which is common to a group of seismograms. This may be true or not, but in my mind, a more important factor is that MED is able to find, in the presence of noise, the most appropriate inverse filter to apply to the data. To sum up, MED almost seems to be the answer to seismologist's dreams.

It is an observed fact that Wiggins' MED has not replaced traditional decons in the processing industry. I don't like to be the one to say what is wrong with MED, but I worked on it a long time, so I should know, and I'm not sure I do. I can guess that the problem may begin with the fact that the MED concept is based on an instability. You start with bumps and encourage them to grow. If the data happens to constrain the situation well enough, you end out with a good answer. If not, you don't. I found the MED concept so seductive that I tried to use it to solve more general estimation problems, such as filling in missing traces. There the immodesty of MED quickly becomes an embarrassment unless the data constraints truly overdetermine the situation in all ways, something not generally known in advance.

Envelope Sensing Deconvolution

When you set out to minimize a sum of squares, you never know how the residuals will distribute themselves. One thing you can say though without any real knowledge of the problem at hand is that the residuals will avoid concentration if the constraints allow. The reason for this is that for a fixed amount of residual, the sum *squared* residual is least if the residual is able to distribute itself uniformly over all available locations.

Imagine somehow we know the envelope that the correctly deconvolved seismogram should have. We need not be very precise about the definition of envelope. We could guess that the envelope of the input data will roughly match the envelope of correctly deconvolved data. It would be very nice to use as the envelope the statistical expectation of x_t^2

call it $E(x_t^2)$ if that were known. The idea is to minimize the sum

$$\min_{\mathbf{a}} \sum_t \frac{x_t^2}{E(x_t^2)} \tag{3}$$

The reason for introducing the inverse envelope squared as a weighting function in the sum of residuals is to set the stage so that the answer will be good when the terms in the sum (3) turn out to be uniformly distributed. It will be nice to see x_t^2 fluctuating about its expectation.

Form a diagonal matrix with the inverse of the squared envelope along the diagonal. *Envelope sensing decon* is now defined by placing this diagonal matrix strategically between the $\mathbf{x}^T$ and the $\mathbf{x}$ in (2), namely

$$\min_{\mathbf{b}} \quad \mathbf{x}^T \mathbf{diag}\left[\frac{1}{E\,|x_t^2|}\right]\mathbf{x} \qquad \textit{subject to} \quad \begin{cases} b_0 = 1 \\ b_t = 0 \;\; \textit{if}\; t<0 \end{cases} \tag{4}$$

If I succeed in convincing you that this is the right thing to do, then you can say that classical decon assumes that the expected output trace has a constant envelope. That is what you might expect from a stationary independent Gaussian signal generator.

Both envelope decon and classical decon try to make the envelope of the output seismogram vanish everywhere. Both are prevented by the constraint $f_0 = 1$. Classical decon squeezes down the squared envelope with a uniform weighting function of time. Envelope decon squeezes down harder where the expected envelope is small and barely squeezes at all where the envelope is expected to be large. So envelope decon has something the flavor of Wiggins' MED, without the tendency to instability.

Finally we must address the issue of where we are to get our information about the envelope. As soon as you accept the idea that envelope sensing decon is an improvement on classical decon, then you already have some idea how well you must know the envelope. Any estimate better than a constant will be an improvement. Our first estimate comes from theory of spherical divergence correction and earth Q. To do better, we consider AGC of our input observations. To do even better, we consider AGC of our deconvolved outputs. It is too early to say how much smoothing is appropriate or whether there are any serious dangers with feeding an insufficiently smooth envelope back in for another iteration.

Before proceeding we must consider another central aspect of the correct formulation of the deconvolution problem.

Pre-Whitening

Suppose you had prior knowledge of the best spectrum to use to display some output traces. Call it $E\,|X_\omega|^2$ where X_ω is the Fourier transform of x_t. The classical deconvolution problem is to minimize the total energy in the time domain, namely $\mathbf{x}^T\mathbf{x}$. This is exactly the same as the total energy in the frequency domain, namely $\mathbf{X}^*\mathbf{X}$. Instead of minimizing that we should try instead

$$\min_{\mathbf{b}} \quad \mathbf{X}^* \,\mathbf{diag}\left(\frac{1}{E\,|X_\omega|^2}\right)\mathbf{X} \qquad \textit{subject to} \quad \begin{cases} b_0 = 1 \\ b_t = 0 \quad if\ t<0 \end{cases} \tag{5}$$

The idea is of course the same, but this time it is in the frequency domain. Since least squares residuals tend to be uniformly distributed, this is setting up the problem so that the answer tends to fluctuate about its expected value.

From a practical point of view, the minimization (5) is particularly easy to achieve. We can simply define an $\mathbf{X}'$ by scaling $\mathbf{X}$ inversely to its expected magnitude. This is called prewhitening. Then use a traditional program to solve the unweighted minimization of $\mathbf{X}'$ to find a filter $\mathbf{b}$. The final output traces are $\mathbf{Yb}$.

But where do we find the essential ingredient $E\,|X_\omega|$? The classical decon problem assumes this is white. It's easy to find an improvement on that. For starters we could use a uniform spectrum from 10 to 100 Hz. We could get a better guess by using the average spectrum of the seismograms recorded nearby. We can further improve on that by using the spectrum of these seismograms *after humanly chosen filters were applied.* It seems that we are almost prescribing the spectrum of the output. Is this circular reasoning? Perhaps so, but probably not if we go back and incorporate the concepts of envelope sensing decon which clearly offer the ability to learn what is the appropriate spectrum of the output.

It is easy to make prior statements about the spectrum of a seismogram, but a lot harder to make prior statements about the envelope. The prior statements which we can make about envelopes are very weak statements. It remains to be established that envelope estimates drawn from the data sample itself can be used to successfully bootstrap to a happy end.

Envelope Sensing Decon with Pre-Whitening

We need to formulate the problem in some domain where we are simultaneously able to deal with envelopes and spectra. Since the constraints are in the time domain, let us use the time domain. First, let us find a time domain expression of the idea that prewhitening is an essential aspect of the problem. I have looked at a lot of seismograms in my life and can suggest a global prewhitening filter given by the filter coefficients (1.0, -.8). The auto correlation of this filter is (-.8, 1.64, -.8). Construct a tridiagonal matrix $\mathbf{T}$ with this auto correlation on the diagonal. Our time domain definition of the prewhitened decon filter is

$$\min_{\mathbf{b}} \quad \mathbf{x}^T \mathbf{T} \mathbf{x} \qquad \textit{subject to} \quad \begin{cases} b_0 = 1 \\ b_t = 0 \ \ \textit{if} \ t < 0 \end{cases} \tag{6a}$$

The way to include envelope sensitivity is to scale the three diagonals of the matrix $\mathbf{T}$ by the inverse of the envelope. For rapidly variable envelopes we may need to take some care in the method of creation of $\mathbf{T}$ so that we ensure positivity. There are several easy ways to assure positivity, but more study is needed to see which is best. It is an interesting issue whether to do gain control before, after, or during whitening.

We are now prepared to state the general formulation of envelope-sensing, prewhitened decon. It is clear that what we need is uniform residuals in both time domain and frequency domain. Somehow we must know, or be able to estimate, the statistical expectation of the outer product $\mathbf{x}\mathbf{x}^T$. So the envelope-sensing, prewhitened decon is defined by

$$\min_{\mathbf{b}} \ \mathbf{x}^T E(\mathbf{x}\mathbf{x}^T)^{-1} \mathbf{x} \qquad \textit{subject to} \quad b_0 = 1 \tag{6b}$$

I have dropped the requirement of causality, because it does not seem to be an essential aspect of the problem. You can always add causality constraints if you wish.

Notice that the matrix $E(\mathbf{x}\mathbf{x}^T)$ is big. If the seismogram $\mathbf{x}$ has N time points, then the matrix has N^2 elements. This matrix is at the heart of the matter. It contains a lot of information about $\mathbf{x}$. For example $\mathbf{x}$ could have a time variable spectrum (earth Q) and the information would be encoded in the elements of the matrix.

Perhaps the best name for the techniques being proposed would be *non-stationary deconvolution*. But this term is already used. In my understanding, it implies learning to cope with non-stationarity. It does not imply the deliberate attempt to extract information from variations in the envelope of the seismic traces. Next remains the chore of demonstrating that we actually can, without circular reasoning, bootstrap ourselves up to useful estimates of the required covariance matrix.

The Example of Gain Control

Spherical divergence correction of reflection seismic data is the scaling up of late arrivals to account for the spreading of the wavefront. This correction tends to bring the data to a somewhat uniform amplitude. We would like to have a good definition of information density of seismic data, but we don't. Whatever information is, it is somewhat uniformly distributed along the time axis. It may not be strictly uniformly distributed on the time axis, but it is a lot more uniform than the data envelope. So spherical divergence correction is a very crude transformation from data to information. The most universal (least particularized) gain correction is simply multiplication by time t. Thus the output x_t is given in terms of the input y_t by

$$x_t \quad = \quad t \ y_t \tag{7}$$

Automatic gain control (AGC) is defined by using some time window in which to estimate the signal strength. Let us use $<|y_t|>$ to denote some sort of local smoothing of the magnitude (or maybe root mean square) of the data. Henceforth, for convenience, we omit explicit statement of time dependence by the subscript t. Thus the output of AGC is defined by

$$x \quad = \quad \frac{y}{<|y|>} \tag{8}$$

An interesting issue is how the envelope of a seismogram should be defined. I have no quarrel with the familiar definition involving Hilbert transforms, provided that the data is a stationary Gaussian variable. But for data containing transients, it makes more sense to first preprocess with AGC (saving the gain function), then compute the Hilbert envelope, then undo the AGC.

It is a good idea to combine (7) with (8) to obtain

$$x \quad = \quad \frac{t\,y}{<|t\,y|>} \tag{9}$$

Notice that (9) contains both (7) and (8) as special cases. If the smoothing window is broad, tending to global, then the denominator tends to a constant, so (9) tends to (7). If the smoothing window is local, then t tends to a constant in the window, and its presence in the denominator cancels its presence in the numerator, so (9) tends to (8). Whenever you are averaging numbers, it is very nice if the numbers are all the same size because then your answer is almost independent of the many averaging methods which you might select. That is why (9) is better than (8). The denominator average is over variables which are more likely to be the same size.

Let us define $<<|y|>>$ as a more heavily averaged estimate of the envelope. The extra averaging need not be imagined being on the time axis, it could be over some local space coordinates. Call this a *regional* estimate. Let us rewrite (9) replacing the universal envelope estimate $1/t$ by the regional estimate $<<|y|>>$.

$$x \quad = \quad \frac{1}{<<|y|>>} \; \frac{1}{< \dfrac{|y|}{<<|y|>>} >} \; y \tag{10}$$

The *local* is embedded in the *regional* which is embedded in the *global*, which in turn is embedded in the *universal*. It is interesting to think of incorporating a global <<< >>> stage to the averaging in (10). There is probably some clever mathematical way to go from local to universal in a continuous way rather than through a clumsy discrete set of jumps. We could try to gain control the gain controlled trace. Let x_n denote an nth order AGCed trace. Thus

$$x_{n+1} \quad = \quad \frac{x_n}{<|x_n|>} \tag{11}$$

Consider (11) in the limit $n \to \infty$. Suppose convergence is attained so that $x_{\infty+1} = x_\infty$. Then equation (11) says that the divisor envelope is exactly the time independent constant +1. So (11) doesn't seem to be the way to do the job. What is the most sensible way to embed local information inside more regional information ? I don't know yet.

Embedding Local Deconvolution in Regional Deconvolution

Looking back to the gain control question, the goal seems to have been to remove regional behavior without distorting local behavior. With deconvolution, the goal seems to be somewhat the opposite. We wish to replace very local effects, like soil resonance and shot waveform variation, with a regionally averaged filter. Having done so, output traces will have the same spectrum. The main thing we do with seismic data is to observe time shifts from trace to trace, something most easily done on traces of the same spectrum.

Let *Factor* denote the process of spectral factorization, that is, let the function *Factor*(*spectrum*) take as its argument a spectrum, and return as value the Fourier transform of a minimum-phase causal time function with the input spectrum. A sensible approach to deconvolution is to obtain the output X_ω from the input Y_ω by

$$X \quad = \quad Factor\left[\frac{\ll Y^* \, Y \gg}{< Y^* \, Y >} \right] \, Y \tag{12}$$

When the averaging defined by << >> is global, then the numerator in (12) is a constant, and the output X is white, independent of the spectrum of the input. Alternately, going to the limit that the smoothing window of << >> equals that of < >, then the output equals the input. Recalling the point of (10) which is to reduce biasing effects in averaging, we are motivated to improve upon (12) by using instead

$$X \quad = \quad \frac{1}{Factor\left[< \dfrac{Y^* \, Y}{<< Y^* \, Y \gg} > \right]} \, Y \tag{13}$$

Now that we have seen how the *local* is embedded in the *regional*, we would like to see how it in turn is embedded in the *global*, which in turn is embedded in the *universal*. Let us define a function *DeconFilt*( ).

$$\textit{filter} = \textit{DeconFilt}(\textit{time series}) \tag{14a}$$

$$(\textit{filter})\ \textit{convolve}\ (\textit{time series}) = \textit{whitened time series} \tag{14b}$$

The process of computing a deconvolution filter is basically that of computing the spectrum of the time series, smoothing it, inverting it, and finding a causal minimum phase wavelet with that spectrum. Let "*" denote convolution. The amount of smoothing of the spectrum can be indicated as shown in the following table

Smoothing Type	Operation		Output
local	$DeconFilt<y> * y$	=	white
regional	$DeconFilt<<y>> * y$	=	fairly white
global	$DeconFilt<<<y>>> * y$	≈	(1,−.8) * y
universal	$DeconFilt<<<<y>>>> * y$	=	y

Making use of this notation, (13) can be expressed by

$$x = DeconFilt<DeconFilt<<y>> * y> * y \tag{15}$$

To help understand that (15) really is equal to (13), consider first the specialization of (15) when "<< >>" is taken to be "<<<< >>>>". Then the table shows that x comes out white, as it should. Next consider the specialization of (15) when "<< >>" is taken to be "< >". Since $DeconFilt<white> = delta\ function$, then x comes out equal to y, as it should. Deeper embedding of the form of (15) is demonstrated by going to one higher order.

$$x = DeconFilt<DeconFilt\ll DeconFilt<<<y>>> * y\gg * y> * y \tag{16}$$

It is curious to note the similarity of this functional form to the $f(f(f \ldots (f(x)) \cdots)$ situation described by Hofstadter.

I was planning to alternate *AGC* with *DeconFilt*, but now I'm not sure that that is exactly what is required either.

Shaping Filter Approach

The foregoing ideas offer philosophical attractions and ambiguities. They seem to completely avoid the issue of requiring the geophysicist to specify some "desired output". You just seem to get the "desired output" without ever having to say what it was you wanted ! Whether this will work out in practice remains to be seen. So far even the algorithm is not even adequately specific to program.

An alternate, more traditional approach is to specify a desired output. Wiggins pointed out that this may be stated in terms of the current best estimated output. That is, the desired output may be the third power of the input. I'll now offer a variation on this theme, which is my current favorite prospect for implementation. My desired output is that the present output should be larger where it already exceeds its local envelope, and it should be smaller where it is less than its present envelope. Unfortunately I must express this concept in specific mathematical form, and I really don't know how to do it in a wholly non-subjective way. Define

$$e \quad = \quad Envelope(x) \tag{17}$$

My desired output is

$$desired\ output \quad = \quad x + \Delta x \quad = \quad \frac{e}{<e>} x \tag{18}$$

The algorithm is initialized by

$$x \quad = \quad Copy(y) \tag{19a}$$

Iteration proceeds with

$$\min_b \sum_{channel} \sum_t w_t \frac{\left[\frac{e}{<e>} x - y * b \right]^2}{<<e>>} \tag{19b}$$

To understand the subjective choice of weighting functions w_t, it helps to think of (19) as a minimization of relative error

$$\sum\sum w_t \left[\frac{\Delta x}{x} \right]^2 \tag{20}$$

Notice that no prewhitening is done, nor does any seem to be required. No one would like a white spectrum for x_t but there seems to be no objection to a white spectrum for the relative error $\Delta x / e$.

Possibility of Using the Burg Algorithm

The Burg algorithm provides an intriguing superstructure in which to attempt to embed both the AGC and the whitening. Notice that new weighting functions, obviously the gain control, can be used between each stage of the whitening. But I don't understand it yet. The best person I know to tackle the job of estimating a covariance matrix is John Burg, but he isn't here, so eventually we may have to tackle it ourselves.

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Search for oil aided by computer research

Geophysics professor Jon Claerbout, who helps guide the search for oil deposits all over the world from his computer laboratory at Stanford, helps link the School of Earth Sciences and the international oil industry.

Oil companies and prospecting contractors finance Claerbout's work by subscribing to the Stanford Exploration Project, a novel program of university research funding.

Essentially Claerbout takes seismic data from explosive soundings and produces clearer pictures of underground formations than had been possible before. His technique is unique in that it treats the soundwaves produced by the explosions in a way that is different from conventional techniques. He estimates that oil companies around the world spend some $3 million producing seismic data for exploration.

When Claerbout first developed his technique in 1970 he could not get government grants to support his work. He felt, however, that industry would eventually value his research, so when he came to Stanford from the Massachusetts Institute of Technology, he approached the industry for support.

Instead of trying to get a large sum from just a few companies, he decided to get small amounts from a large number of firms. Today his project receives identical contributions of $14,000 a year from 34 firms; 25 in the United States and nine from Europe and Japan.

The money is used to pay for the computer bank, operating costs, and student stipends. Claerbout in turn provides each company with semi-annual progress reports and copies of all related student dissertations.

Claerbout said he has no further need to actively seek subscribers. "They know about us because they're aware of the work in their field," he said. "They come to us because it is to their advantage.

Since its inception at Stanford in 1973, this form of sponsorship has been successfully copied by about 10 other groups at universities across the nation.

Many companies benefit from the Stanford project even though they are not subscribers. They just wait until the results are published. Members, however, have the advantage of learning about projects as they proceed. They don't have to wait until the student theses are published.

Oil prospectors sound individual locations by exploding dynamite and measuring the seismic reverberations. Multiple seismic measurements taken over the surface of a particular site can be correlated to produce a picture of underground rock patterns. Claerbout likens it to seeing mountains underground.

Wherever there are shapes that might indicate the presense of oil, the prospectors aim their drills.

Amos Nur, Claerbout's colleague in geophysics, created a similar and related subscription program four years ago, called the Stanford Rock Physics Project. Nur and his doctoral student team began studying the effects local temperatures and pressure characteristics have on the practical interpretation of Claerbout's computer maps.

Individual geographic locations have individual rock composition characteristics, and particular temperature and pressure conditions. These characteristics affect the sounding measurements used to draw the maps. Consequently, these factors should be considered in interpreting the maps.

Jon Claerbout

The Nur research team also works with information and material from specific prospecting locations. And they use their cumulative research results to create generally applicable theories of map interpretation.

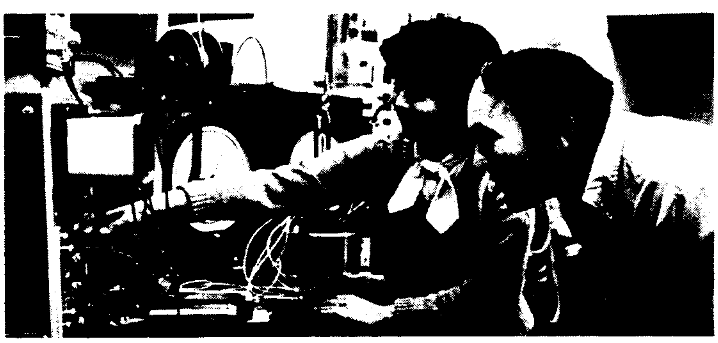
Nur's research is more expensive because it requires the use of large and sophisticated machinery to test various rock and mineral samples. His subscribers pay $15,000 a year for what amounts to only one-third the cost of the work.

The federal Department of Energy and the National Science Foundation contribute the remaining two-thirds funding. Nur said these agencies share Rock Physics Project information differently than the private corporation subscribers. "Grant programs are designed to bring research to the general public," he said. "Unlike the individual professionals who have a real technical interest in our work, the grant programs have no continuing immediate application for the information."

Nur sends progress reports to the Department of Energy according to very specific reporting procedures. Yearly reports, dissertations by project students and abstracts of articles written for the *Journal of Geophysical Research* and *Geophysics* are submitted to both grant providers.

The private subscribers receive, additionally, semiannual compilations of findings and, when specifically requested, data from particular research locations.

Students in Claerbout's and Nur's program interact with each other frequently. "The system is related and open," said Nur, "and I think we all find that very exciting."



Carol Tosaya and Amos M. Nur.

These subscription programs are naturally vulnerable to the inevitable danger of academics working at exclusively private research.

University researchers have traditionally frowned on private funding arrangements, in an effort to avoid dependence on the competitive and product-oriented business world. Academic scientists dislike working on practical business problems rather than on pure research because they are afraid their findings might become the property of particular corporations, rather than contributions to the open pool of scientific information.

Claerbout said he has avoided the problem by the nature of his program.

First, there are many different companies involved. Although the research involves a rather specific method, the number of financiers, including businesses in competition with each other, precludes the study of any particular business's problems.

Second, Claerbout said there is no classified information. All reports are published, and no company who wants to join the projects is excluded.

Third, Claerbout's research team regularly criticizes certain subscribers in the reports. Because much of the raw seismic data comes from the companies that perform explosive soundings, the researchers continually find fault with the procedures those companies use to get the information.

Claerbout said the companies accept criticism because they ultimately value the long-term benefits of continuing involvement in the subscription program.

"It helps to do such long-term research," said Claerbout, "because we all feel an obligation to be fair to one another for a long period."

Finally, Claerbout said the information in his reports comprises ideas, not specific computer programs or actual maps of oil and mineral deposits.

"My method can be used in any area of seismology, not just petroleum exploration," Claerbout explained. "Nuclear explosion seismology and earthquake seismology are other applications."

"Also, there are many alternative procedures for clarifying underground maps. All the good ideas didn't originate here."

As government and university research money becomes harder to find, academic researchers increasingly seek private financing. Science-minded businesses are particularly interested in university research, and they are often financially better equipped to underwrite it than government agencies or university administrations.

Claerbout said he prefers private support to government support. "It's fun to work with these companies," he said, "because their geophysicists are highly professional. And they will really use the information. Ultimately, they will drill a hole in search of oil."

—Mary Duenwald,
News Service Student Intern.