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RAYLEIGH WAVE REJECTION BY OPTIMUM FILTERING OF VERTICAL ARRAYS

7 October 1966

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Washington, D. C.

By

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EARTH SCIENCES DIVISION
TELEDYNE INDUSTRIES, INC.

Under

Project VELA UNIFORM

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RAYLEIGH WAVE REJECTION BY OPTIMUM FILTERING OF VERTICAL ARRAYS

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ABSTRACT

Rayleigh Wave Rejection by Optimum Filtering of Vertical Arrays

By

Wm. C. Dean

Optimum array processes such as the maximum likelihood filters are usually derived from the cross correlation matrix of the time series outputs of the array. With a vertical array, however, the correlations of both the incoming P-wave signals and Rayleigh wave noise are predictable from the structure. This paper presents the theory of maximum likelihood filters in vertical arrays which can provide undistorted estimates of the signal or the various Rayleigh modes with the other modes cancelled out.

The performance of these optimum processes will be dependent upon the validity of the underlying assumptions such as horizontal bedding, known instrument calibration, and knowledge of both P and S velocities with depth. Examples are shown of the performance of the optimum filters using synthesized data where the underlying assumptions are satisfied. Then these same optimum filters are applied to data from the UBO vertical array.

I. THEORY

Vertical arrays offer some intriguing advantages over other arrangements of seismometers. Assuming the noise to be composed of Rayleigh waves and perhaps some mantle-propagating P-waves, and assuming the signals to be teleseismic P-waves, the noise and signals will be recorded by a vertical array with some rather special characteristics.

We can imagine that each mode of Rayleigh wave noise possesses a random character common to noise functions in general. However for each Rayleigh wave mode the response versus depth and frequency relative to its response on the surface is predictable. Because the relative depth variation is predictable, the vertical array can be summed to cancel the Rayleigh modes. In contrast the noise over a surface array is more unpredictable and more variable and, therefore, more difficult to cancel by array summation.

Normally we compute the attenuation of each Rayleigh wave mode relative to the surface continuously with the depth for several particular frequencies.[1,2,3,4,5,6] We are thus calculating mode attenuation (and sign) versus depth with frequency as a parameter. However, we could convert many such computations into attenuation versus frequency with depth as a parameter. Naturally, the particular depths we choose would be the levels where a seismometer was recording in the vertical array. In this manner we can compute a frequency response, $H_{km}(\omega)$, where

$$H_{km}(\omega) = \frac{\text{response at the mth depth}}{\text{response at the surface}} \tag{1}$$

for the kth higher mode. These Rayleigh modes must obey these frequency relationships, $H_{km}(\omega)$, not only in an average sense integrated over time, but also in a transient sense for each instant of time. Otherwise these noise modes would not be surface waves.

The waveform for any of the modes at depth will be either in phase or 180° out of phase with that at the surface. Hence the filter response, $H_{km}(\omega)$, will be an even, real function as must its transform in the time domain. In other words, these filters are phaseless.

In a similar way teleseismic signals, and whatever mantle P-wave noise may be present, will possess very definite delay (i.e., filter) relationships between the various outputs of a vertical array. Let us assume that the signal waveform, $s(t)$, is the same at all levels and further that the surface reflection coefficient is unity and the reflected waveform is the same as the incident waveform. Then if the signal recording on the surface is $2\ s(t)$, the signal recording from the mth level seismometer is given by

$$z_m(t) = s(t + T_m) + s(t - T_m) \qquad (2)$$

where T_m is the one way travel time for the signal from the mth level to the surface. The frequency equivalent of the above time equation is

$$Z_m(\omega) = S(\omega) \quad 2\cos(\omega T_m). \qquad (3)$$

Thus, similar to that applied to the Rayleigh modes, the filtering applied to the signals is also phaseless.

We will define the noise mode, n_k, as follows:

n_1 = the signal mode, s , plus any mantle P-wave noise with velocity and reflection properties identical to those of the signals;

n_2 = the fundamental Rayleigh mode

n_3 = the first higher Rayleigh mode

n_k = the k-2 higher Rayleigh mode

The composition of each of the vertical array outputs is given by

$$z_1(t) = \sum_{k=1} h_{1k}(\tau) * n_k(t) \quad ; \quad Z_1(\omega) = \sum_k H_{1k}(\omega)\, N_k(\omega)$$

$$z_2(t) = \sum_k h_{2k}(\tau) * n_k(t) \quad ; \quad Z_2(\omega) = \sum_k H_{2k}(\omega)\, N_k(\omega) \qquad (4)$$

$$\vdots \qquad\qquad\qquad\qquad \vdots$$

$$z_m(t) = \sum_k h_{mk}(\tau) * n_k(t) \quad ; \quad Z_m(\omega) = \sum_k H_{mk}(\omega)\, N_k(\omega).$$

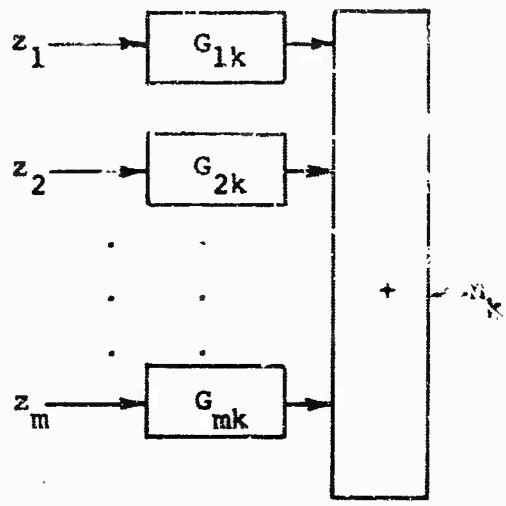
where these equations can be expressed either as functions of frequency, ω , or time, t. For time equations, the operation (*) implies convolution between the h's and the n's. The first recording level, $z_1(t)$, may be, but is not necessarily on the surface of the ground.

In matrix form we have

$$Z = HN. \qquad (5)$$

The vector of vertical array outputs, Z, is measured. The matri of filter relations, H, is computable from the structure. The problem is to determine each member of the unknown vector of noise modes, n, by a filtering process just as a seismometer would record the mode on the surface with the other modes absent.

If the number, m, of recording levels is less than the number, k, of noise modes present, (m,k), then the system is underdetermined. In this case the noise modes cannot all be separated from each other. If m = k, we have a determined system with just enough recording levels to find all modes. If the number of recording levels is greater than the number of modes present. the system is overdetermined. In this case all modes can be separated with the extra measurements used to overcome the effects failure of assumptions, errors in calibrations, and instability of the optimum filters. The following schematic illustrates the optimum filters, G_{1k}:



Each of the m input channels must be filtered and these results added to produce each desired noise mode in the output. Thus the solution leads to a matrix rather than a vector of optimum filters.

The filtering operation is therefore

$$GZ = GHN = IN = N \tag{6}$$

where I is the identity matrix. The solution $G = H^{-1}$ will not do since we especially want to find solutions when H is not square. Consequently, we let

$$G = (H^T H)^{-1} H^T \tag{7}$$

for which the operation GZ gives

$$GZ = (H^T H)^{-1} H^T HN = IN = N \tag{8}$$

as desired.

Our method will be to solve these equations for the optimum filter matrix, $G(\omega)$, in frequency for several reasons. First, the well log analysis yields the $H(\omega)$ filter matrix for the Rayleigh modes in terms of period or frequency.[2,3,4] Second, not all Rayleigh modes are present at all frequencies. For example, only the fundamental mode can be expected to exist at the lowest frequencies. Finally, the solutions of the matrix equations are independent of each other at the different frequencies. Thus the inversions of the matrices which are not expected to be larger than 10 x 10 are readily handled on even the smaller digital computers.

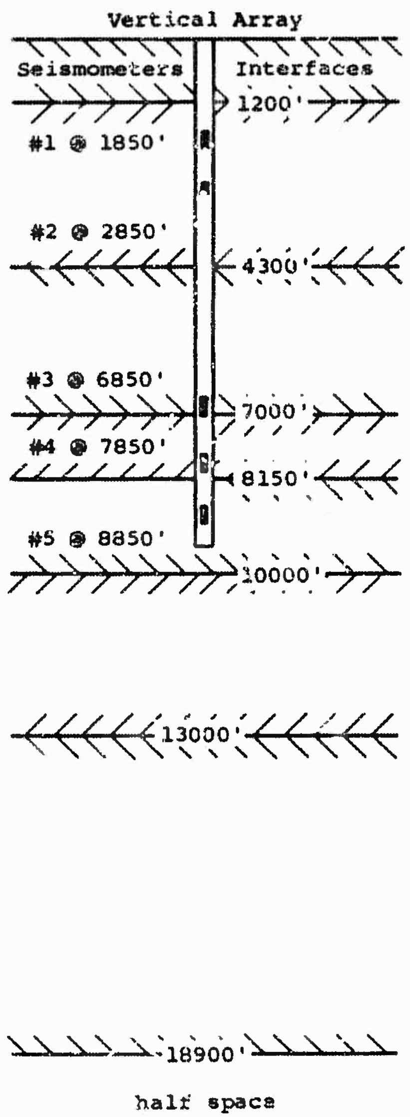
II. SYNTHETIC EXAMPLE

A vertical array of five vertical component seismometers existed in a well at the Uinta Basin Seismological Observatory (UBSO). Figure 1 shows a schematic diagram of the seismometer placement in the vertical array and the log of the surrounding lithology. The Rayleigh dispersion curves, also shown on Figure 1, indicate that the fundamental, first, and second higher Rayleigh modes will all be supported over the signal frequency range of 0.5 to 2.0 cps. Since we want more recording levels than modes, these three Rayleigh modes plus a signal mode will be the only ones considered to exist in our synthetic modeling of this well.

The Rayleigh wave dispersion analysis of this well log leads to the mode-depth frequency responses, $H_{km}(\omega)$, defined by equation (1).

Figure 2 shows plots of these filter responses for the first three Rayleigh modes relative to the responses at the surface of the ground.

The optimum filter, G, solutions are the least squares inverse to the Rayleigh signal filter matrix H. Thus the matrix products of G and H gives the identity matrix as shown in equations (6) and (8) GH = I. In our test model we have assumed the signal exists with the same size and amplitude on all traces. In other words, we are neglecting ghosting. We have derived optimum filter solutions only over the signal range of 0.5 to 2.0 cps. For the frequencies below 0.5, we have smoothed the frequency responses to zero according to a sinusoidal gain function for both the H and G frequency responses. We have smoothed these responses to zero in a similar way over the range from 2 to 5 cps.



UBO Well
Well Log

Velocities P	km/sec. S	density
2.951	1.652	2.3
3.387	1.897	2.3
4.621	2.591	2.4
4.161	2.338	2.4
4.721	2.643	2.5
4.720	2.643	2.5
5.486	3.072	2.55
6.300	3.530	2.700

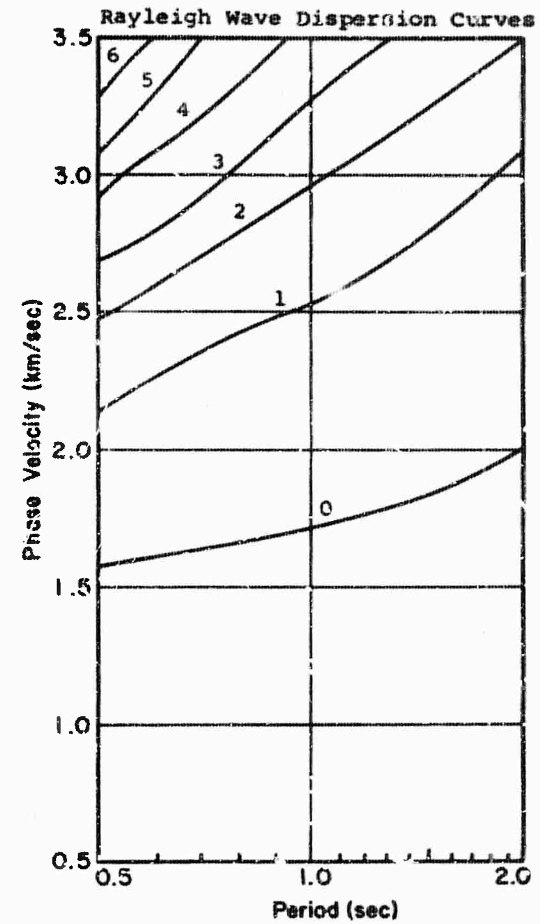


Figure 1. UBO Well Log, Schematic and Dispersion Curves

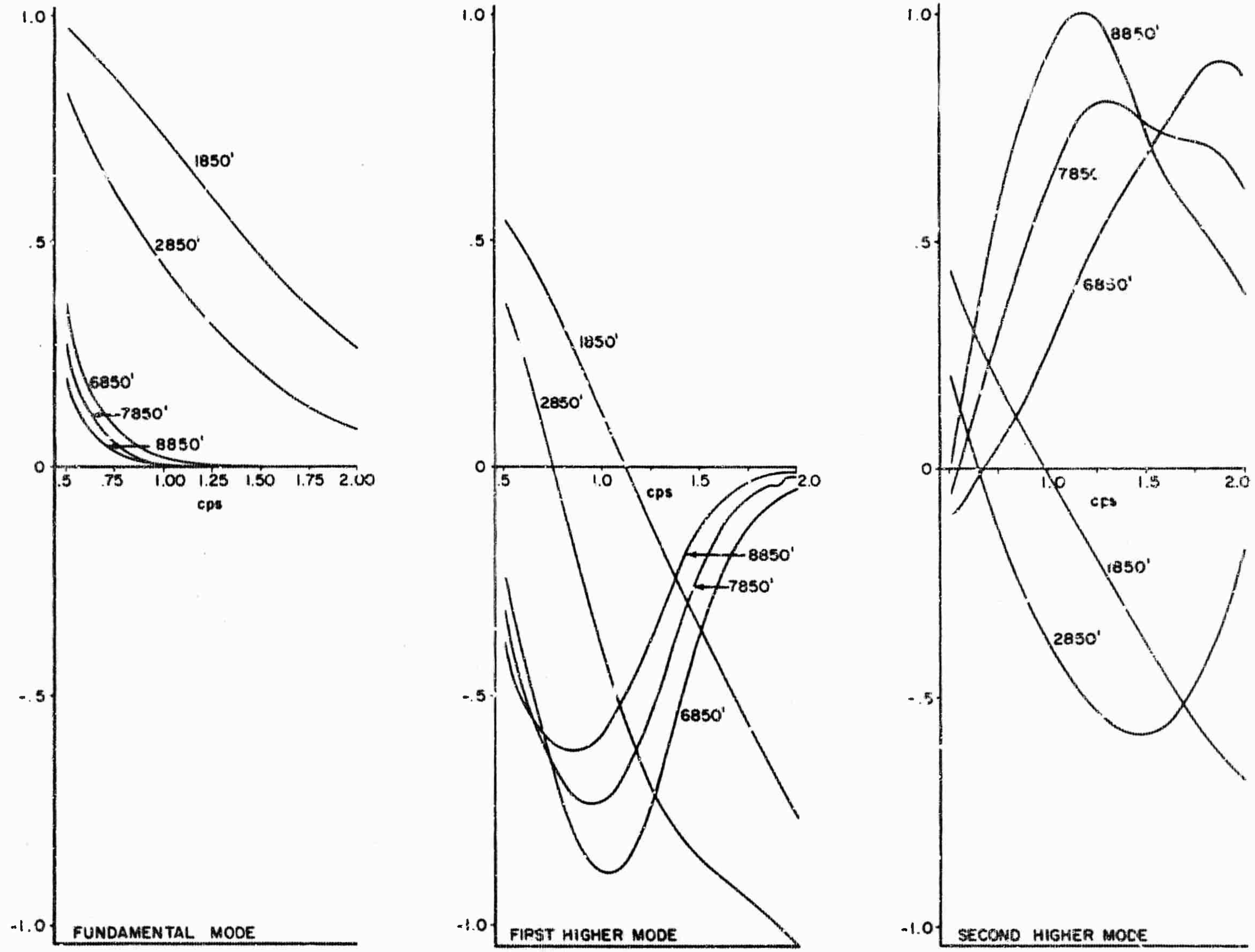


Figure 2. $H_{jk}(\omega)$ Frequency Responses of Rayleigh Modes for the Five Seismometers in the UBO Array. (Responses are relative to a surface seismometer)

In our computations the zeros in the identity matrix are less than 1×10^{-6}. Below 0.5 and above 2.0 cps the GH product still gives zeros in the off diagonal elements. The H matrix assumed below 0.5 and above 2.0 cps is (aH) where the scalar, a, is the cosine function of frequency. In the same way the solution assumed for the optimum filters in this range is (aG). Consequently, the matrix product of these frequencies is given by

$$aG\ aH = a^2 I \tag{9}$$

Consequently, the orthogonality of our optimum filter solutions is maintained over the entire frequency range.

In order to demonstrate that our optimum filter solutions are indeed correct, we created some synthetic data which does conform to the well log analysis we have assumed for the UBO well. We chose four independent seismograms from our digital data files. We bandpass filtered each so that the main energy content was between 0.5 and 2.0 cps. The first of these traces was identified as the fundamental mode on the surface of the ground and filtered according to the H matrix to produce the equivalent fundamental mode at the various instrument depths in the UBO well. The second trace was identified as the first higher mode and similarly filtered according to its depth behavior determined by the H matrix. The third was identified as the second higher mode, and so on. These Rayleigh mode traces we combine with an artificial signal to produce a mixture of signal and Rayleigh modes expected from this well.

Figure 3 shows the data from the five levels of the vertical array if the signal only were present. The companion traces on Figure 3 show the optimum filter output (estimate) for the signal, the fundamental, the first higher, and second higher modes.

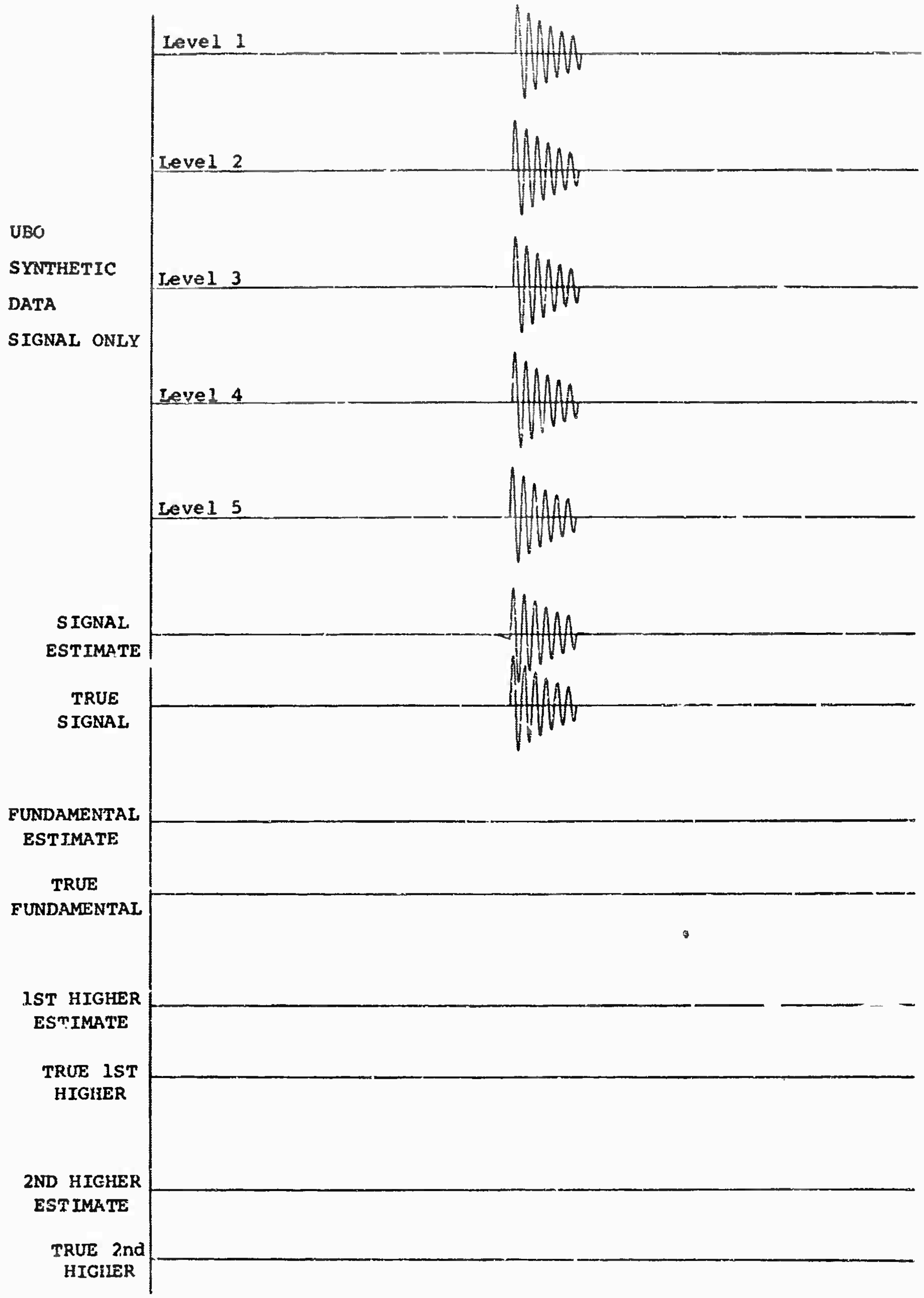


Figure 3. Optimum Filters Estimating Four Modes (the Signal and Three Rayleigh Modes) from Synthetic Data with the Signal Only Present.

Immediately below each optimum filter estimate is the true noise or signal mode that a seismometer would see on the surface if the other modes were not present. The distortion of the signal is slight and can be attributed to the bandpass properties of our optimum filter solutions. The Rayleigh mode outputs should be zero and, in fact, are less than 7×10^{-5} everywhere.

Figure 4 is similar to Figure 3 except that the data contains the signal plus the fundamental mode. As can be seen, the optimum filter outputs agree in size and waveform with the true surface responses of the signal and the fundamental Rayleigh mode.

Figure 5 is similar to Figures 3 and 4 except that the data contains the signal plus the fundamental and first higher Rayleigh modes. Again, all three modes present are reproduced in size and wave shape. The output trying to produce the second higher mode, which is absent, has no value greater than 1×10^{-4}.

Figure 6 is similar to the previous three except that the second higher mode has been added into the vertical array data. Again, the outputs for the signal and the three Rayleigh modes are reproduced in size and waveform within a few percent of the expected results. The signal trace shows better than a 20 db improvement over the best signal/noise ratio available in the vertical array.

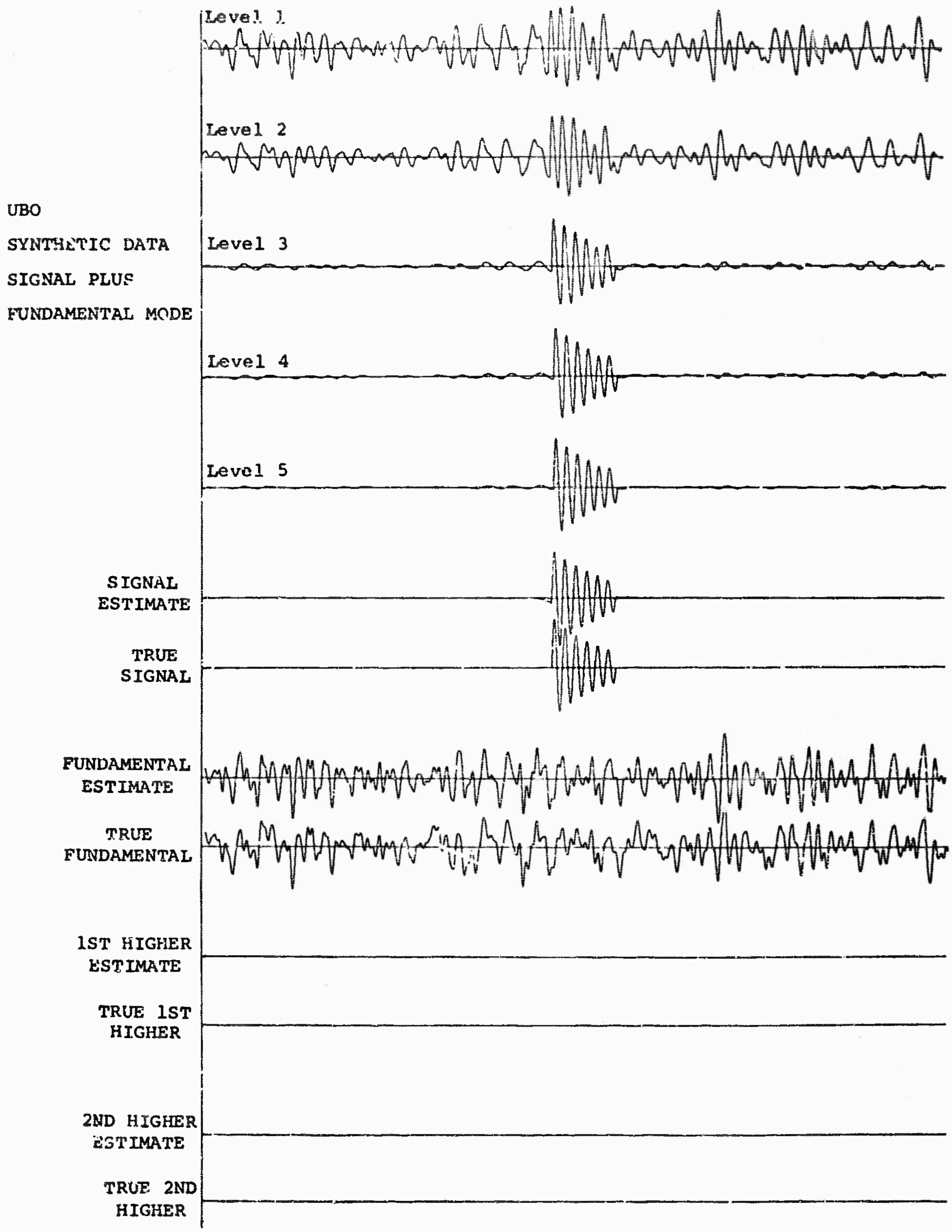


Figure 4. Optimum Filters Estimating Four Modes (The Signal and Three Rayleigh Modes) from Synthetic Data with Only Two Modes Present.

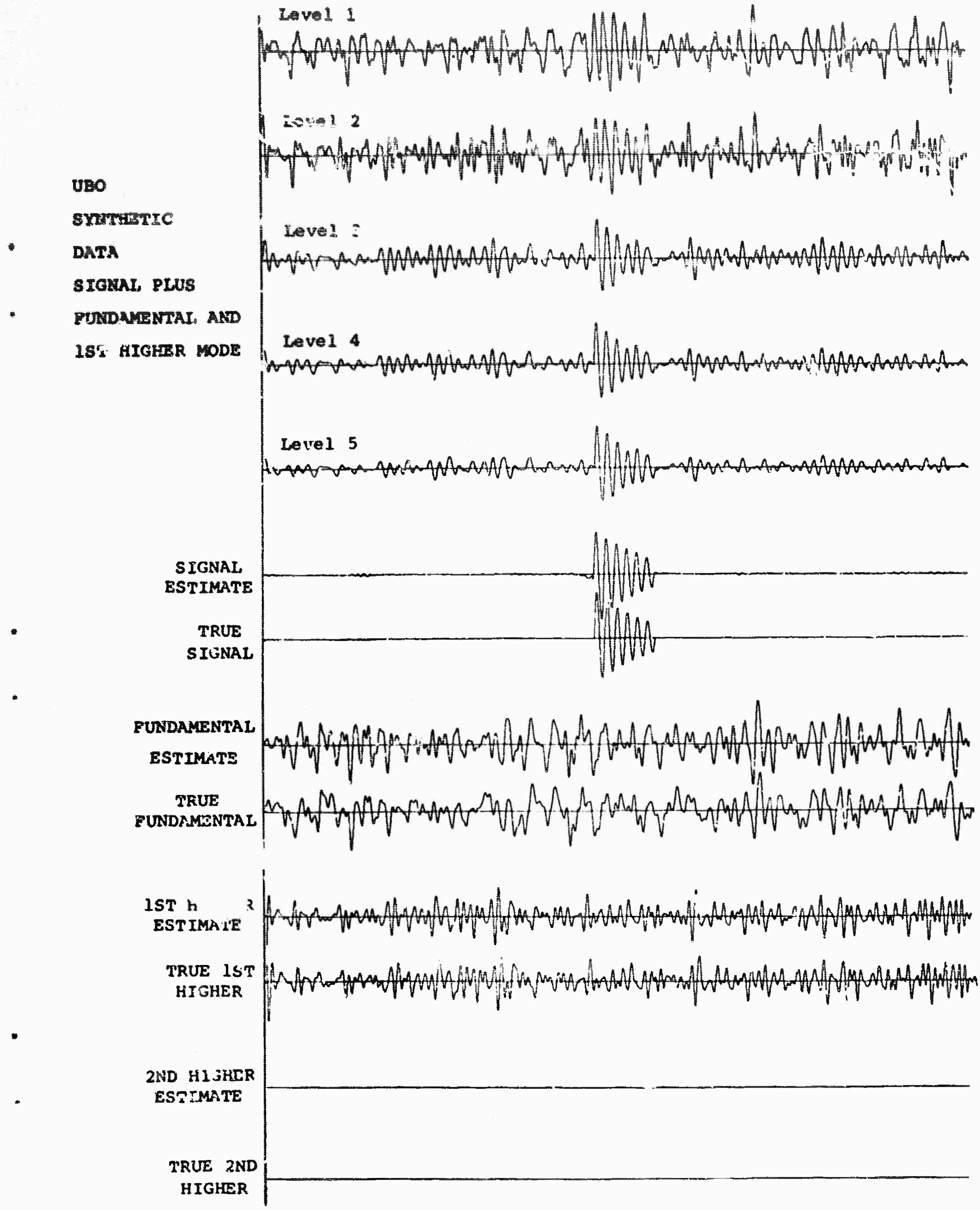


Figure 5. Optimum Filters Estimating Four Modes (the Signal and Three Rayleigh Modes) from Synthetic Data with only Three Modes Present.

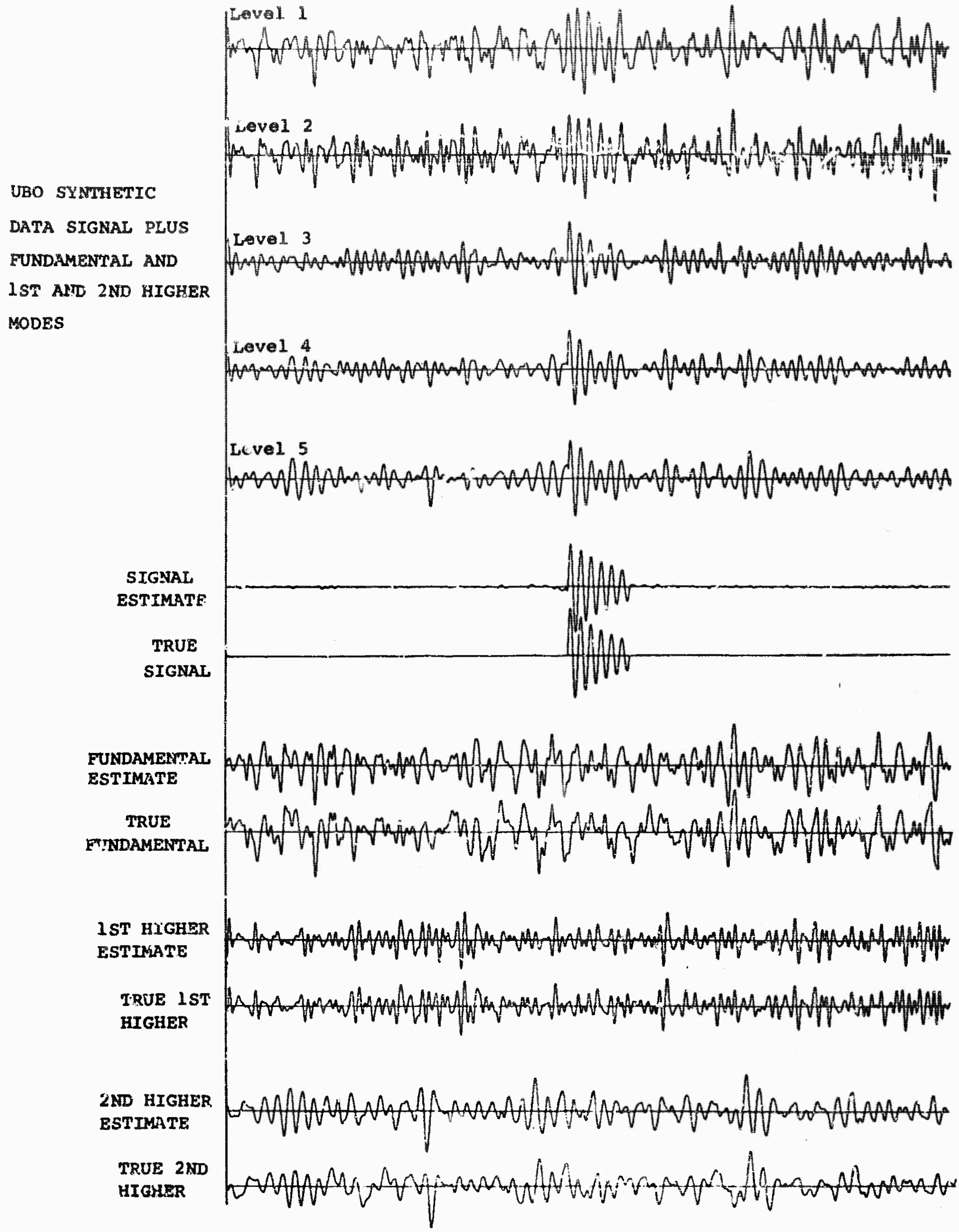


Figure 6. Optimum Filters Estimating Four Modes (The Signal and Three Rayleigh Modes) from Synthetic Data with all Four Modes Present.

III. EXAMPLE WITH UBO NOISE AND A SYNTHETIC SIGNAL

We have seen that the optimum filters perform as expected when the data properties match the dispersion analysis of the well log. We must now apply these solutions to data recorded at the vertical array. To concentrate on Rayleigh mode suppression and reproduction, we have avoided complications which might be introduced by deghosting. Any signals recorded by this array will have ghost reflections. Consequently, we must add a synthetic signal, which satisfies our identical size and waveshape assumption, to the five-level noise output of the array. The first five traces on Figure 7 show the noise background and synthetic signal used in this test.

There are several sets of signal and noise mode estimates shown on Figure 7. All of the optimum filters used require inputs from all five levels. However, we can ask for estimates of only a single mode or for estimates of several modes in the filter outputs. We designate a five level input, two mode output set of filters as a 5 x 2 set. The more modes a set of filters estimate, the larger the filter gains will be. It follows that any errors resulting from incorrect dispersion analysis, instrument calibrations, or non-parallel layering will be amplified much more in these filters with fewer degrees of freedom.

The outputs on Figure 7 are from a 5 x 1, 5 x 2, 5 x 3, and a 5 x 4 set of filters. The 5 x 1 set estimates the signal merely by averaging the inputs from all five levels. These outputs show progressively increasing low frequency errors on the estimates of all modes as the degrees of freedom decrease (i.e., as the number of outputs increase).

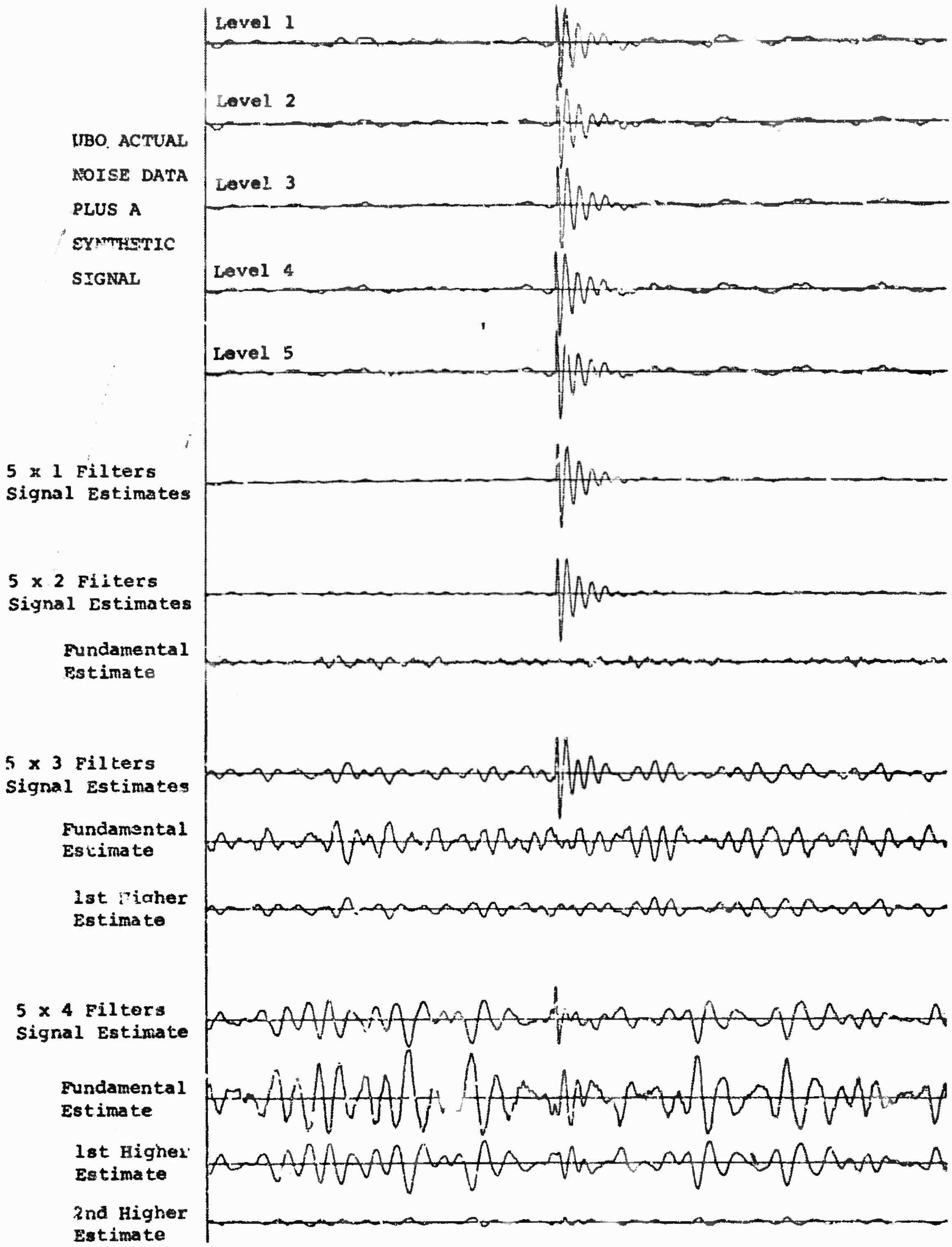


Figure 7. Several sets of optimum filters are applied to UBO noise data with a synthetic signal. The more modes a set of optimum filters estimates, the larger the filter gains, and the more errors are amplified. These data contain considerable energy below 0.5 cps for which the filters are not designed. As a result low frequency errors are large.

We know that the optimum filter solutions do not agree with the well analysis for frequencies below 0.5 cps. The well was not analyzed below this frequency. Rather the optimum filters were interpolated between 0 and 0.5 cps from the solution at 0.5 cps. Yet we expect the correct solutions to become more erratic as the array aperature measured in wavelengths becomes smaller. If the optimum filters were correct at all frequencies, and if the second higher mode were absent, as seems likely from the bottom trace on Figure 7; then the outputs from the 5 x 3 and the 5 x 4 filters would match.

IV. CONCLUSIONS

Qualitative experience has disclosed the following features of our optimum filter solutions:

1. These filters are indeed orthogonal and separate the noise and signal modes as planned.

2. These optimum filters extend for 400 points in time since the frequency interval chosen was .05 cps.

3. The gain on the synthetic examples was greater than 20 db with solutions restricted to 0.5 to 2.0 frequency range. More resolution in frequency could increase this figure.

4. The optimum filters are zero phase shift filters. Therefore, they are algebraically additive.

5. The optimum filters become larger in gains (both positive and negative) as degrees of freedom decrease.

6. The optimum filters become larger in gains (both positive and negative) as the aperature of array goes down. Thus, for low frequencies the solutions tend to become unstable.

7. Extra modes not considered and errors in assumptions cause errors in the output. Errors in assumptions can include an incorrect well log, non-parallel layering in surrounding medium, and incorrect calibrations of seismometers.

8. Extra degrees of freedom are needed to cut gains of optimum filters and make optimum solutions more tolerant of errors.

9. Extra degrees of freedom are best obtained by increasing the number of seismometers in the vertical array.

10. More stable solutions (i.e., optimum filters with lower gain) will be obtained from the deeper vertical arrays which have the seismometers distributed rather uniformly throughout the array.

We will evaluate these properties of vertical arrays quantitatively as the study progresses. We will also add deghosting to the optimum filter programs.

The next vertical array of interest is the one in the Grapevine well, GVTX. This array has six seismometers down-hole plus a surface instrument all recorded on the same tape. In addition it is located in a sedimentary basin rather than the Rocky Mountains so the assumption of plane, horizontal layering may be better satisfied.

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14. KEY WORDS	LINK A		LINK B		LINK C	
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