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A STUDY OF ADAPTIVE BEAMFORMING DETECTION PERFORMANCE ON ALPA (ALASKAN LONG-PERIOD ARRAY) INTERFERING EVENTS

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Texas Instruments, Incorporated

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A STUOY OF AOAPTIVE BEAMFORMING OETECTIUN PERFORMANCE ON ALPA INTERFERING EVENTS

TECHNICAL REPORT NO. 6

VELA NETWORK EVALUATION ANO AUTOMATIC PROCESSING RESEARCH

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This report presents the results obtained from applying a time-domain maximum likelihood adaptive-beamforming processor to simulated mixed-event data from the Alaskan Long-Period Array. Adaptive-beamforming detection threshold reduction with respect to the beamsteer threshold is investigated as two parameters are varied: the time separation between Rayleigh-wave arrivals, and the azimuthal separation between the events. In the simulation performed for this report, the arrival time of a signal buried in a stronger

20 Continued.

off-azimuth interfering event has little effect on the 11 dB ABF threshold reduction (Figure III-1) obtained, but the threshold reduction is strongly dependent on the azimuthal separation between the events (Figure III-10).

ABSTRACT

This report presents the results obtained from applying a time-domain maximum likelihood adaptive-beamforming processor to simulated mixed-event data from the Alaskan Long-Period Array. Adaptive-beamforming detection threshold reduction with respect to the beamsteer threshold is investigated as two parameters are varied: the time separation between Rayleigh-wave arrivals, and the azimuthal separation between the events. In the simulation performed for this report, the arrival time of a signal buried in a stronger off-azimuth interfering event has little effect on the 11 dB ABF threshold reduction (Figure III-1) obtained, but the threshold reduction is strongly dependent on the azimuthal separation between the events (Figure III-10).

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SECTION I
INTRODUCTION

A. PURPOSE OF THIS STUDY

One of the objectives for the signal estimation task in the VELA Network Evaluation and Automatic Processing Research Program (Project VT/5705) is to investigate and report on new techniques for optimally detecting the arrival of a second seismic event buried in the coda of a first-arriving event.

This report deals with results obtained by applying a maximum likelihood adaptive-beamforming filter to events simulated from Alaskan Long Period Array (ALPA) long-period data. The effects of varying two parameters were studied: the time separation intervals between the Rayleigh-wave arrivals at fixed azimuths and the azimuthal separations between two signals at a constant arrival time separation.

A description of the maximum likelihood adaptive filter algorithm and the ALPA array is given in a report by Barnard and O'Brien (1974).

B. ORGANIZATION OF THE REPORT

Section II describes the experimental approach used here and in the study by Barnard and O'Brien, and summarizes the results obtained there. Section III presents the results of the two studies described above. Section IV presents the conclusions of the study, and references are listed in Section V.

SECTION II
EXPERIMENTAL APPROACH AND PREVIOUS RESULTS

A. EXPERIMENTAL APPROACH

Let $B(f, k_o, k)$ be the time-shift-and-sum filter response at a look wavenumber $\vec{k}_o = f\vec{V}_o/V_o^2$ to a wave of frequency f and wavenumber k. The beamsteer response is given by (Barnard and O'Brien, 1974):

$$B(f, \vec{k}_o, \vec{k}) = \frac{1}{M} \sum_{n=1}^{M} \exp\left[i2\pi (f\tau_n - \vec{k} \cdot \vec{x}_n)\right] \tag{II-1}$$

where $\tau_n = \vec{V}_o \cdot \vec{x}_n / V_o^2$ is the time-lag for the n-th site with steering velocity $\vec{V}_o$, $\vec{x}_n$ is the n-th site position vector, M is the number of sites used, and $i = \sqrt{-1}$. The adaptive beamforming filter response, $A(f, k_o, k)$ can be written as

$$A(f, \vec{k}_o, \vec{k}) = \sum_{n=1}^{M} A_n(f) \exp\left[i2\pi (f\tau_n - \vec{k} \cdot \vec{x}_n)\right] \tag{II-2}$$

where $A_n(f)$ is the Fourier transform of the adaptive convolution filter applied to the n-th channel at a given time. The transform $A_n(f)$ depends on the data and consequently varies with time. Expressing the plane-wave propagation vectors $\vec{k}_o$ or $\vec{k}$ in terms of azimuthal angles, we have

$$\vec{k} = (-\frac{f}{V} \sin \theta, -\frac{f}{V} \cos \theta) \tag{II-3}$$

for a two-dimensional array, where the source azimuth θ is measured clockwise relative to north. Then the beamsteer and the adaptive filter power responses in dB are, respectively,

$$P_B(f, \theta_o, \theta) = 10 \log_{10} \left| B(f, \vec{k}_o, \vec{k}) \right|^2 \quad \text{(II-4)}$$

and

$$P_A(f, \theta_o, \theta) = 10 \log_{10} \left| A(f, \vec{k}_o, \vec{k}) \right|^2 . \quad \text{(II-5)}$$

For actual time-overlapped data traces, there is no reliable method to isolate the energy contribution from each separate event. In order to evaluate adaptive-beamforming filter performance in suppressing the interfering event in mixed-event situations, the most realistic approach is to rely on a simulation of mixed signals. This simulation is done in the following manner. Each channel of two data samples, one containing an on-azimuth signal and the other an off-azimuth event, are separately passed through a zero-phase bandpass prefilter. The off-azimuth interfering event can be shifted from its original azimuth to any desired azimuth. The samples are then added point-by-point and channel-by-channel to produce a composite sample, and then the composite sample is shifted to align the target event. Through this procedure, the azimuthal and time separation between the mixed events can be controlled.

From the composite sample, adaptive filter sets are designed and applied to the data samples individually to create separate beams for the on-azimuth signal and the interfering event. These separate beam outputs are subsequently added together to form a composite-trace beam, which is intended to represent a processed 'real-world' beam. The corresponding time-shift-and-sum beams are also created simultaneously. The evaluation of adaptive filter performance is based on the composite beam.

In this study the ratio of the peak-to-peak amplitude measured after the on-azimuth signal's arrival to the corresponding amplitude measured before its arrival, but after the interfering event arrival, was computed as a measure of detection. When this 'amplitude rise' amounts to 6 dB a detection was claimed. The single-sensor maximum peak-to-peak amplitude was measured and averaged individually for each of the mixed events. Then the event separation was computed by taking the ratio of these averages.

At each time separation, measurements of the amplitude rise defined above were made over a wide range of event separations and at as many as 20 ABF convergence rates ranging from 0.001 to 0.5. The largest event separation at which a 6 dB amplitude rise was achieved, independent of the convergence rate, was called the ABF threshold for that time separation. The same procedure was followed for the beamsteer detector to find its threshold. The ratio of these values is the threshold reduction achieved by using the ABF.

In each simulation the beamsteer detector outputs were examined at the event separation at which the 6 dB amplitude rise was achieved by the ABF processor. In no case was there any evidence of an on-azimuth signal. In addition, the ABF outputs at the event separation where the beamsteer gave a 6 dB rise were calculated, and it was always found that the on-azimuth event was the dominating feature.

In many marginal detection situations, such as those studied here, short-period detection information is available which informs the analyst that two events are mixed in his data sample. This information makes the 6 dB criterion used here sufficient for long-period detection of the on-azimuth event.

Once a detection is declared a secondary but still important objective is to determine the event magnitude for the detected signal. In order to evaluate the accuracy on the magnitude estimates by the detectors, the separate on-azimuth signal beam amplitudes for both beamsteering and adaptive beamforming are divided into the peak amplitudes on the composite-trace beams, to find the signal degradation. Further details of the mixed-event simulation procedure can be found in Barnard and O'Brien (1974).

B. PREVIOUS RESULTS

In the previous report, the results of three long-period mixed-event simulations for a 180° azimuthal separation at various event-separation levels were presented, each using a 15-point adaptive filter. In the first simulation, adaptive beamforming produced a 6 dB composite-trace amplitude rise for an 18 dB event separation at the single-sensor level. The beamsteer processor yielded the same 6 dB composite-trace amplitude rise at a 6.4 dB event separation. As a result, the adaptive processor achieved a detection threshold reduction of about 12 dB, or 0.6 M_s units, relative to beamsteering. The second mixed-event simulation in the previous report used the same events for both the on-azimuth signal and the off-azimuth interfering event for illustrative purposes only.

Some previously unreported results of the third mixed-event simulation are presented here. That simulation was performed at 12, 18, 24, 30, and 36 dB event separations. Figure II-1 shows the observed amplitude rise versus event separation for the ABF and beamsteer outputs. The adaptive convergence rate for the best output is indicated in each case.

Inspection of the ABF curve in Figure II-1 indicates that the slope changes significantly at 24 dB event separation, where the adaptive convergence rate changes from $\mu = 0.2$ to 0.5. Near a 30 dB event separation, where a 6 dB amplitude rise is achieved by the ABF processor, the dashed curve suggests a 2 dB decrease in the amplitude rise per 6 dB increase in event separation.

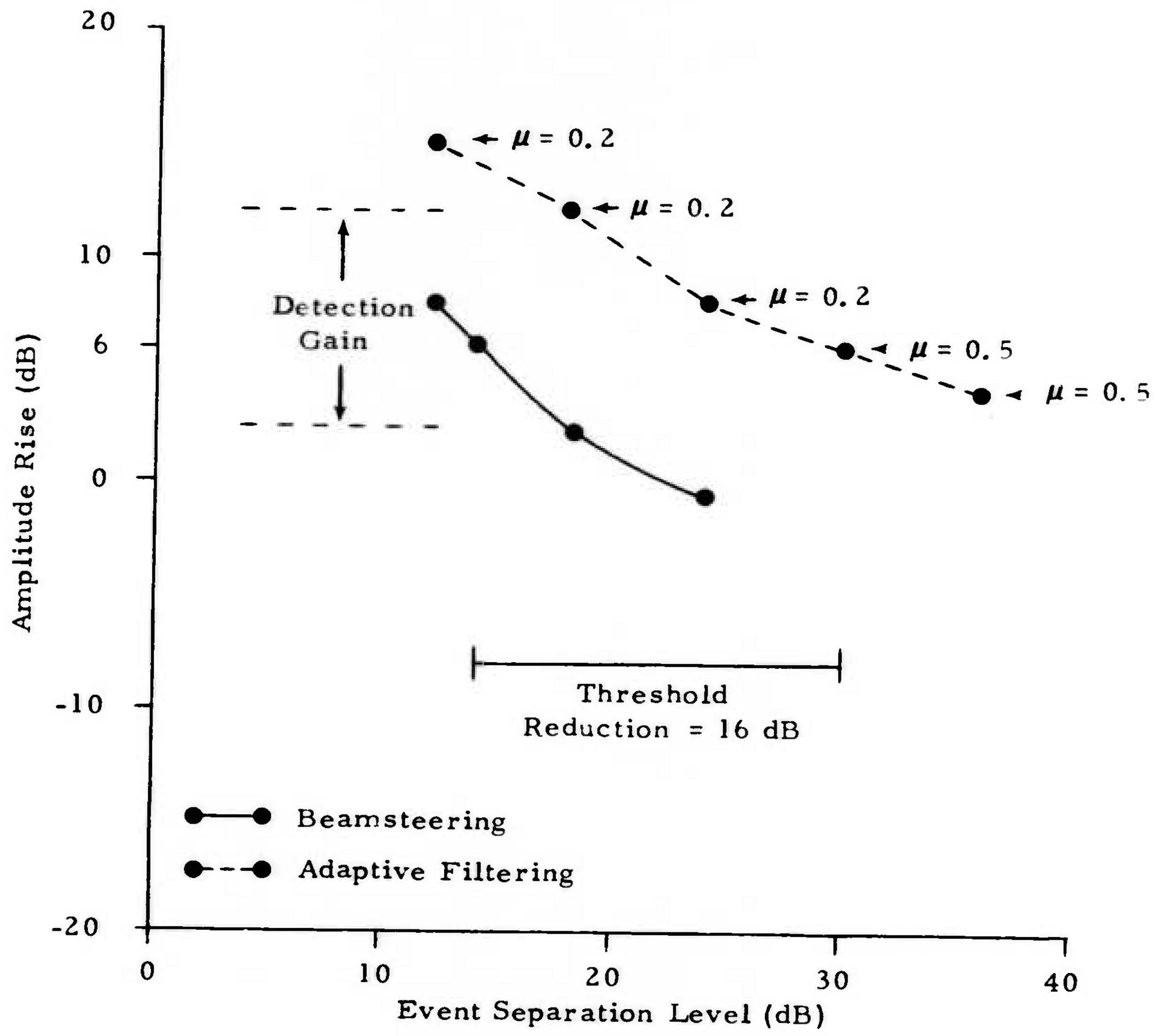

FIGURE II-1

AMPLITUDE RISE VERSUS EVENT-SEPARATION LEVEL FOR 180° AZIMUTHAL SEPARATION

SECTION III

RESULTS

A. ABF THRESHOLD REDUCTION AT VARIOUS ARRIVAL TIME SEPARATIONS

Events on days 296 and 335 of 1972 from the Tonga Islands, arriving at ALPA at 6 hours 46 minutes 40 seconds and 3 hours 24 minutes 40 seconds, respectively, were used in the time-separation simulation. The time intervals between the event arrivals were varied in one-minute steps between zero and seven minutes. In all cases in this subsection, the processing was conducted with a 31-point adaptive filter. Fourteen-site data at ALPA (sites 6, 16, 17, 18, and 19 had unuseable data) were used. The day 296 on-azimuth signal arrived from 205° while the day 335 interfering event azimuth was shifted from 206° to 25°, producing a 180° azimuthal separation between the events. The thresholds, threshold reductions, the ABF convergence rates at which they were found, and the observed signal degradation are presented in Table III-1.

The striking feature of Table III-1 is the nearly constant threshold reduction. This is further brought out in Figure III-1, where the threshold for each detector is plotted against time separation, and it is seen that the curves are roughly parallel, although each has variations of as much as 5 dB. In order to examine this effect, we present the outputs of both detectors for the two and four minute time separation cases in Figures III-2 through III-5. Examination of Figures III-2 and III-3 for the two-minute case shows that the large threshold anomaly there is due to a relatively large composite trace amplitude on both the ABF and beamsteer traces at about 335/03.25.00.

TABLE III-1

TIME SEPARATION STUDY RESULTS

Time Separation (min)	Threshold (dB)		Convergence Rate	Threshold Reduction(dB)	Signal Degradation (dB)	
	Beamsteer	ABF			Beamsteer	ABF
1	11.0	22.0	0.15	11.0	-1.8	2.8
2	6.4	17.4	0.30	11.0	-0.6	3.6
3	10.4	20.0	0.40	9.6	0.0	2.5
4	10.4	21.0	0.30	10.6	-1.4	5.4
5	9.0	20.0	0.10	11.0	-0.7	1.4
6	9.0	20.0	0.10	11.0	-0.4	2.2
7	9.0	18.0	0.10	9.0	0.1	2.4

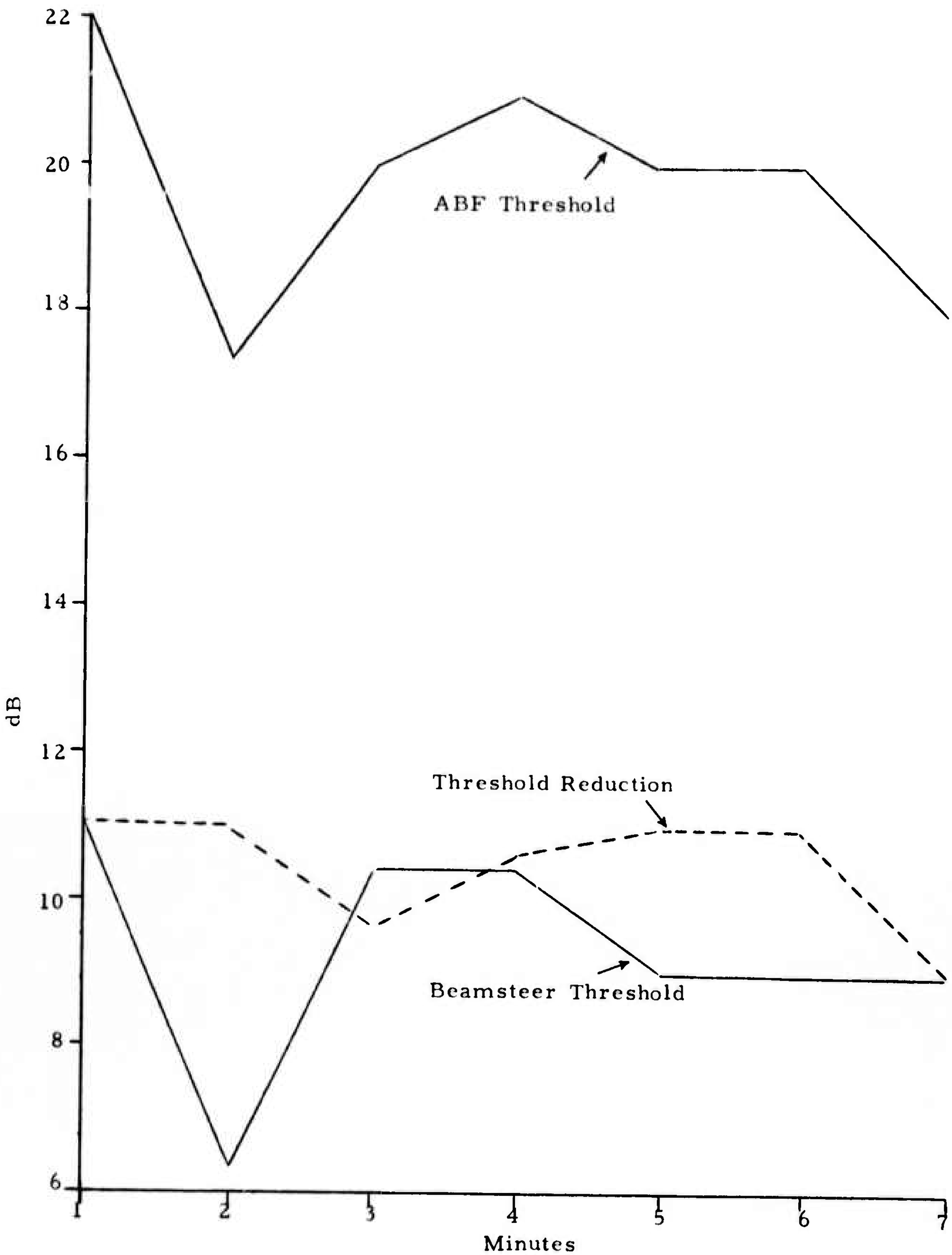

FIGURE III-1

THRESHOLD AND THRESHOLD REDUCTION VERSUS TIME SEPARATION

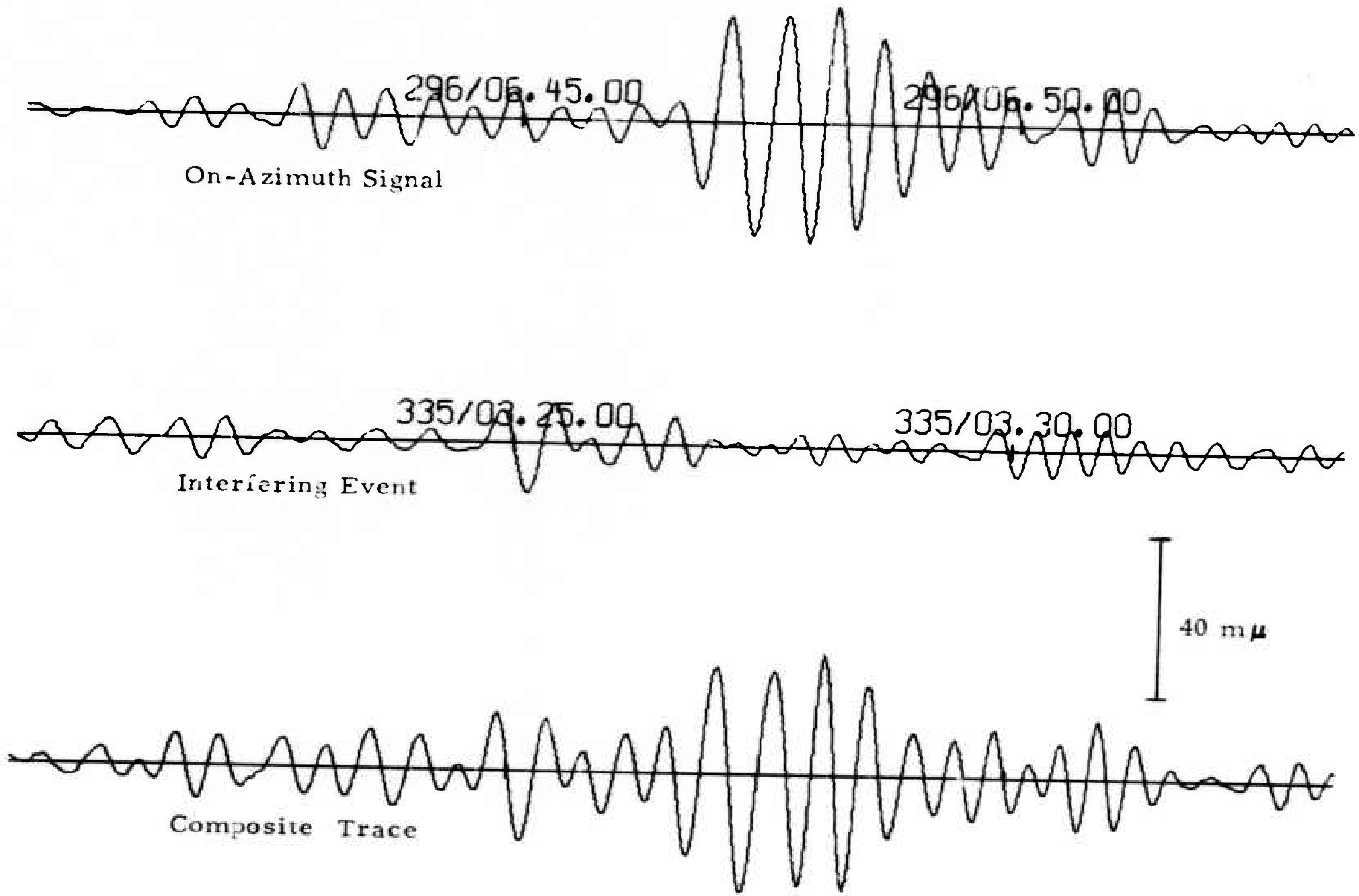

FIGURE III-2

BEAMSTEER OUTPUT FOR 2 MINUTE SEPARATION AND INTERFERING EVENT 6.4 dB ABOVE THE ON-AZIMUTH SIGNAL

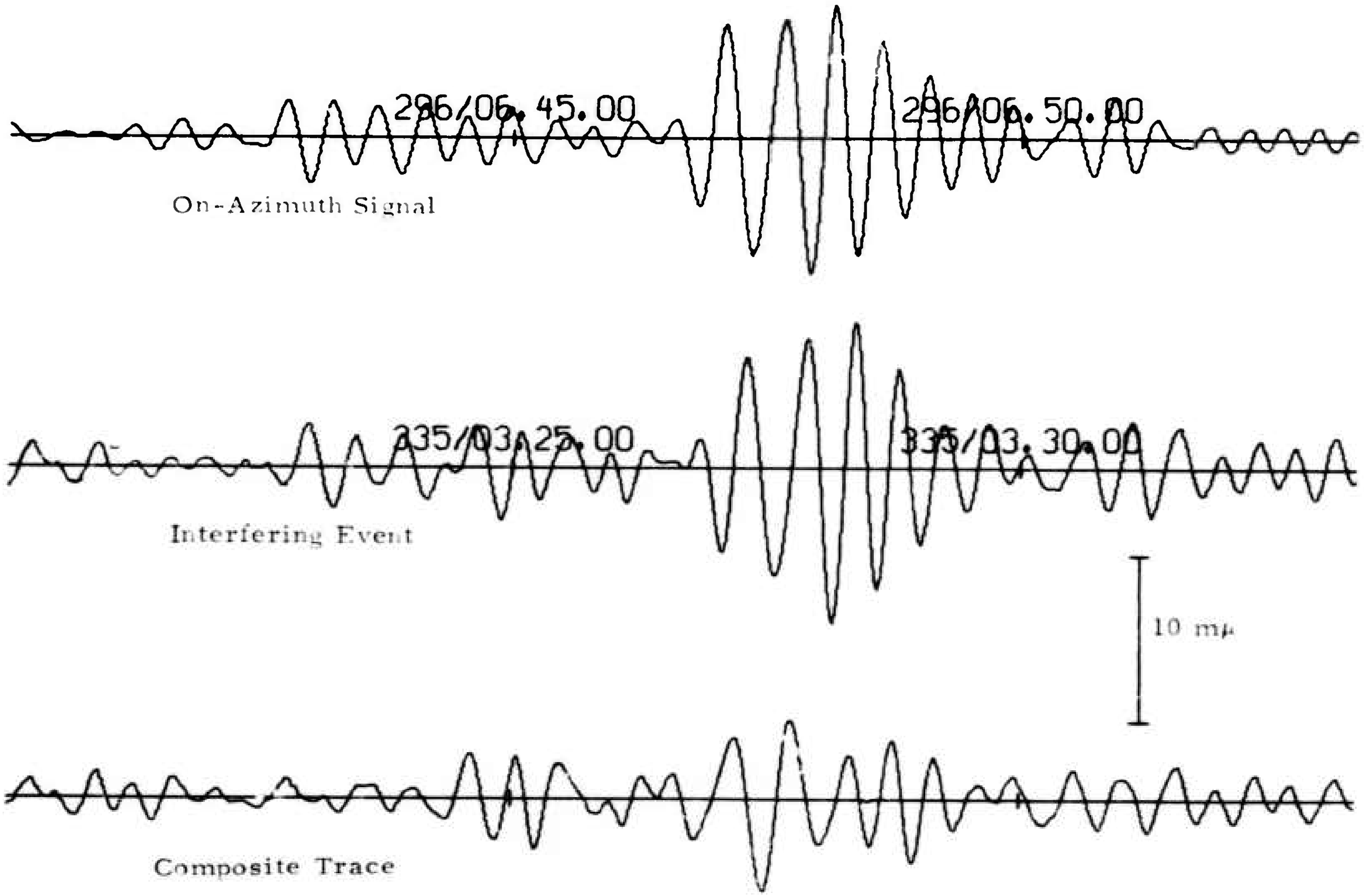

FIGURE III-3

ABF OUTPUT FOR 2 MINUTE SEPARATION, INTERFERING EVENT 17.4 dB ABOVE THE ON-AZIMUTH SIGNAL, AND $\mu = 0.3$

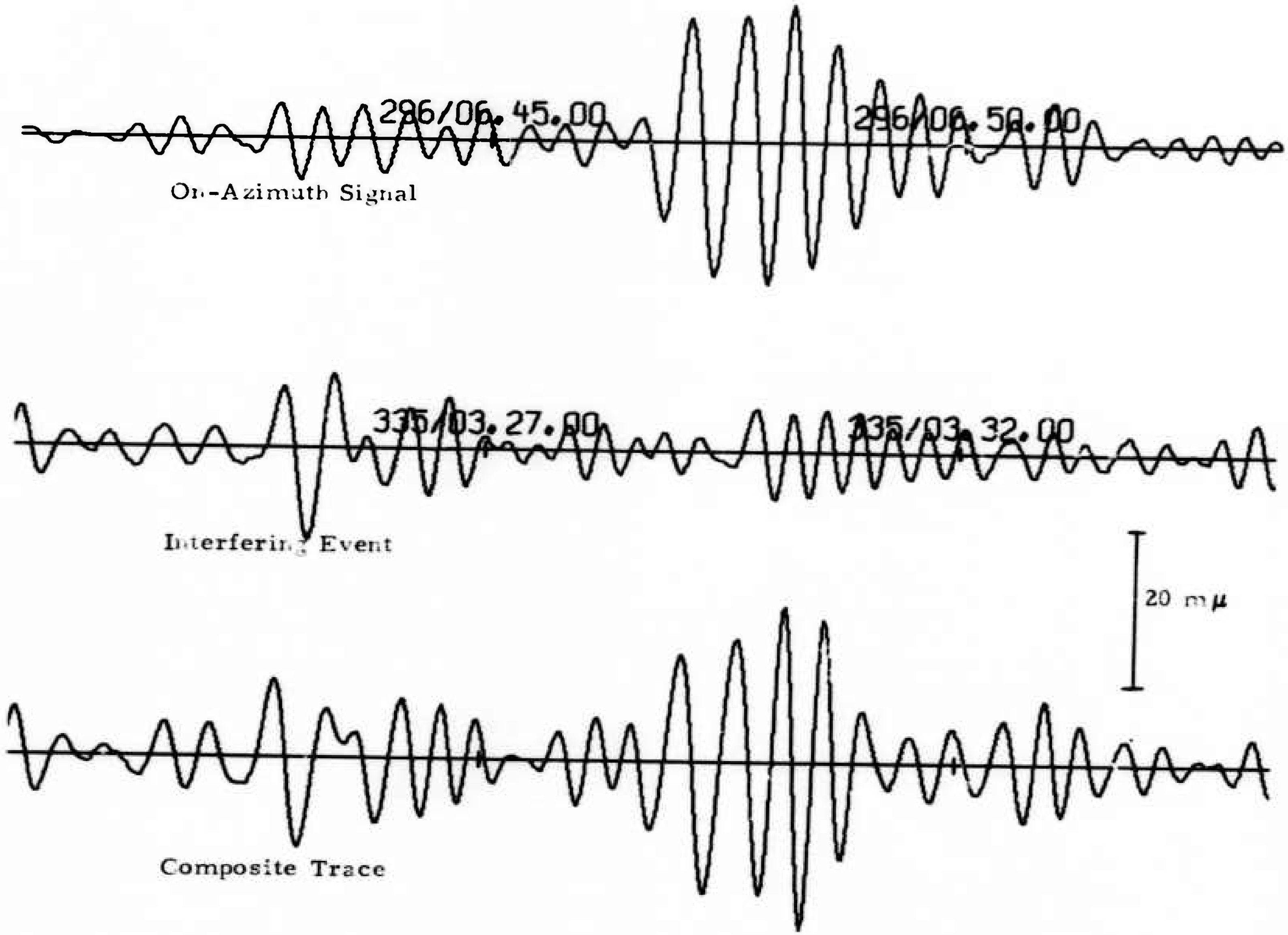

FIGURE III-4

BEAMSTEER OUTPUT FOR 4 MINUTE SEPARATION AND INTERFERING EVENT 10.4 dB ABOVE THE ON-AZIMUTH SIGNAL

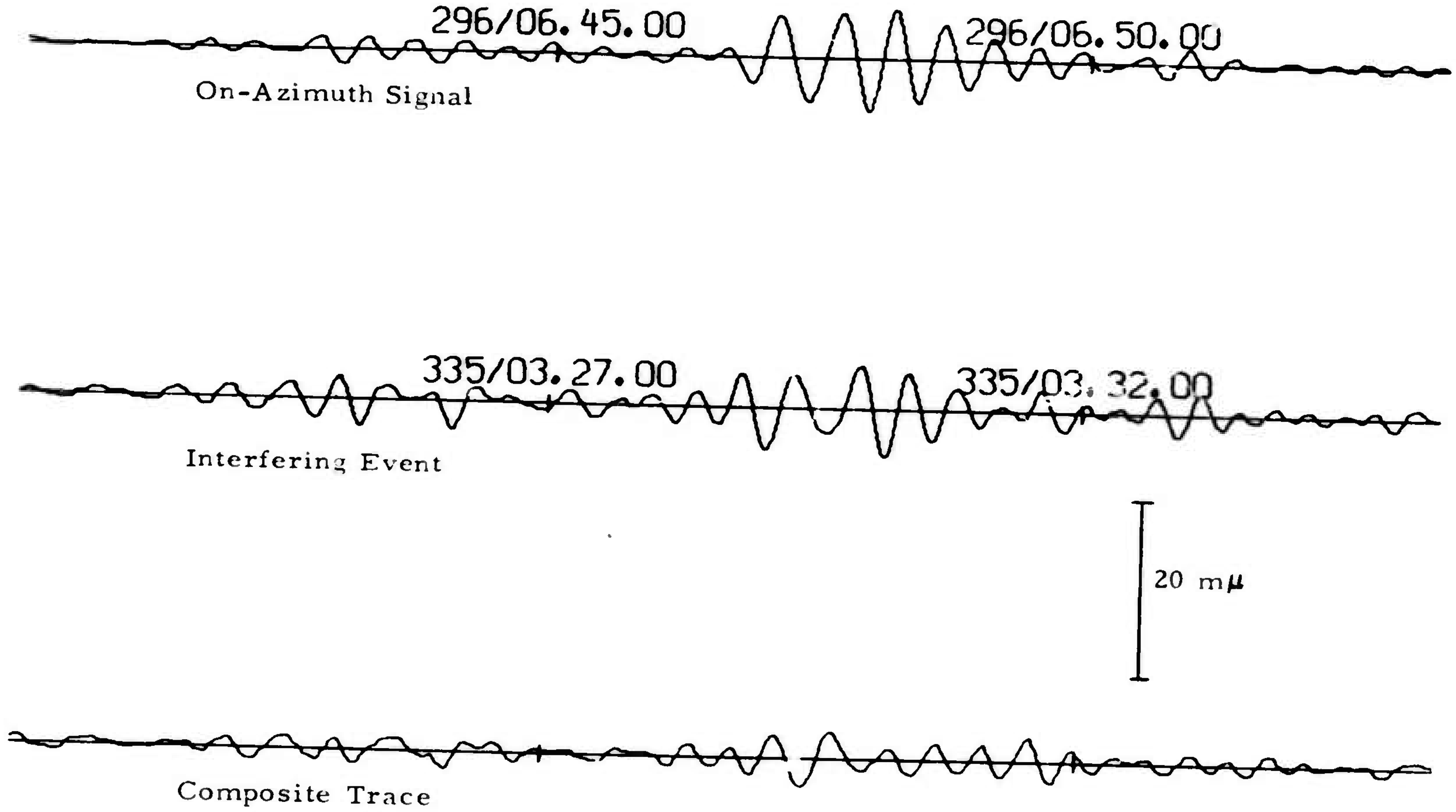

FIGURE III-5

ABF OUTPUT FOR 4 MINUTE SEPARATION, INTERFERING EVENT 21 dB ABOVE THE ON-AZIMUTH SIGNAL, and $\mu = 0.3$

This same group of cycles of interfering event motion is responsible for the peak composite trace motion at every time separation for both detectors. These cycles have exactly the same amplitude from one time separation to another on the beamsteer output because it is a fixed filter. The differences in the ABF interfering event amplitudes from time to time are due to the influence of the on-azimuth event on the filter weights. Since the on-azimuth event is roughly 20 dB below the off-azimuth event, these effects are small. We may also assume that these amplitudes are also nearly constant for the ABF, if it is performing directional filtering, because in that case the ABF weights stay near those for a fixed multichannel filter designed to reject the off-azimuth energy. This question may be resolved with the aid of Figures III-6 and III-7, which are ABF response patterns at the arrival time of the peak of the beamsteer off-azimuth signal taken at twenty and twenty-five second periods respectively and calculated according to Equation(II-5) .

In the 20 second period pattern, a minimum of -26 dB was observed at about an 8° azimuth, while in the 25 second period pattern the -25 dB minimum fell at 26°. Frequency-wavenumber spectra confirmed that at 20 second period, before time shifting, the off-azimuth signal energy was multipathed to 188°, while at 25 second period it was on-azimuth at 205°. Shifting these signals by 179° in azimuth places their new azimuths just at the nulls in the ABF pattern. Consequently, adaptive beamforming here is performing directional filtering at least in part, although it may be also taking advantage of short-term correlations in the data. This result leads us to believe that the off-azimuth amplitudes generating the peak are constant at time separations where no measurements were made.

The on-azimuth event motion is the same, at every time separation, for both adaptive processing and beamsteering, because of the unity-response constraint in the look direction imposed on each. Since both on- and off-azimuth motion is roughly independent of time separation, fortuitous

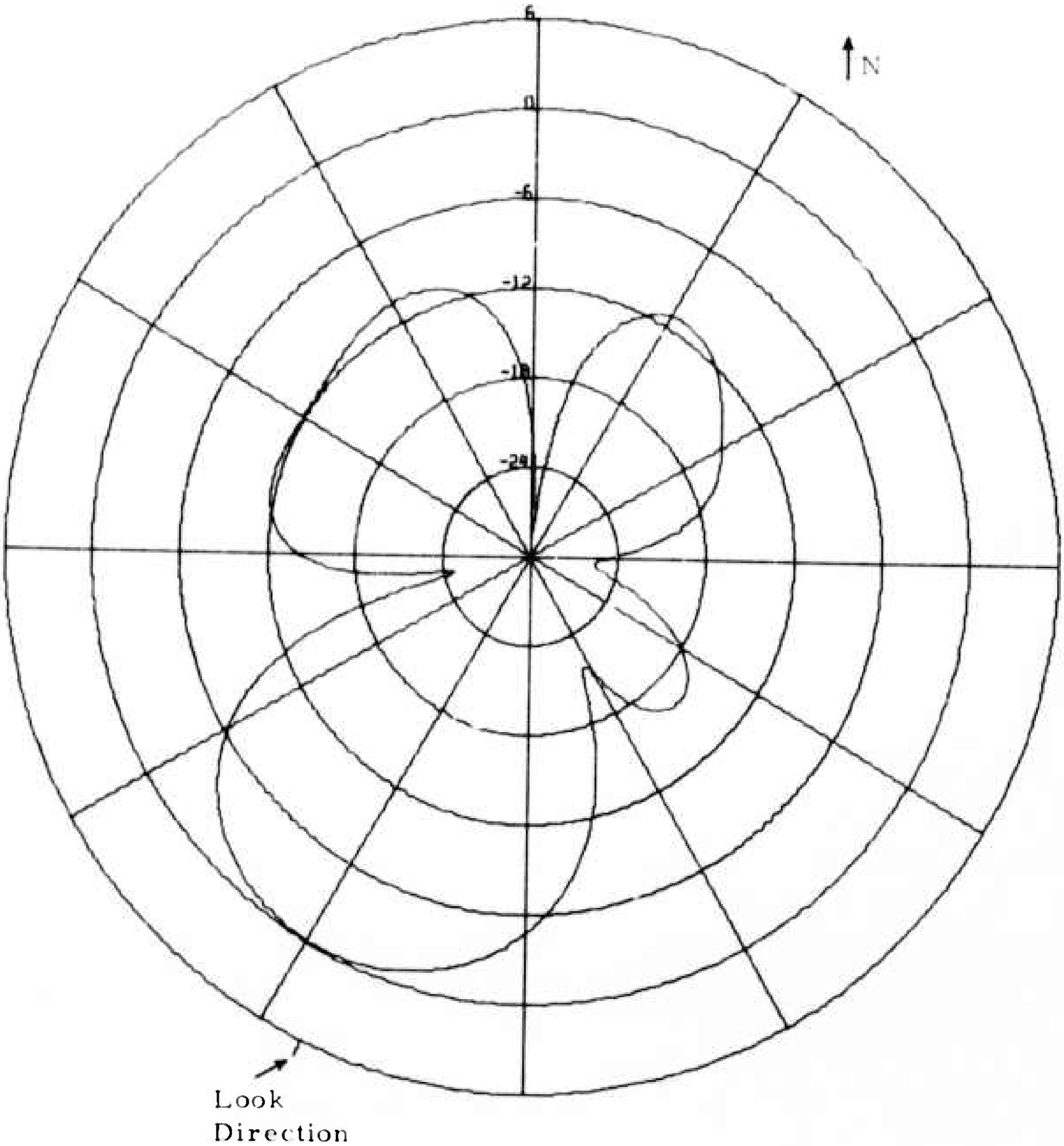

FIGURE III-6

ABF BEAM PATTERN AT 296/06.45.00
20 SECOND PERIOD

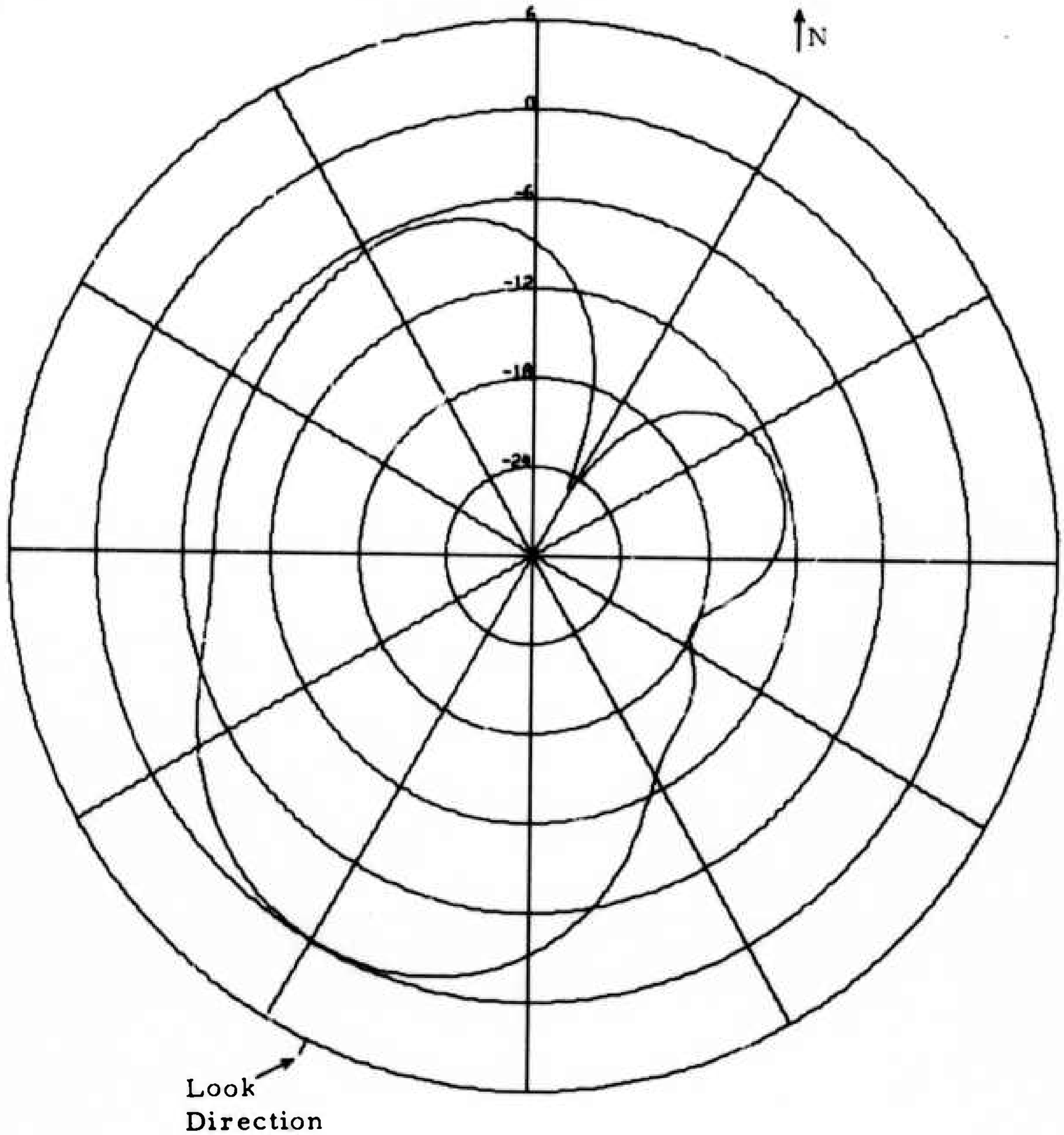

FIGURE III-7

ABF BEAM PATTERN AT 296/06.45.00
25 SECOND PERIOD

additions and cancellations of peaks occurred simultaneously for both processors, lowering their thresholds by the same amount, to yield the constant 11 dB reduction observed here.

The above discussion depends on the fact that the peak of the off-azimuth motion occurred shortly after the signal arrival. This means that the off-azimuth peak always occurred before the on-azimuth peak in this study, and the results would probably be different if this were not the case, since then the same group of cycles would not contribute the peak motion. Subject to this rather weak restriction, however, we might expect that any pair of signals behave in this way. That is, these results suggest that the ABF threshold reduction is a function of azimuthal separation, array geometry, filter length, signal waveform similarities, and amplitude variations across the channels. This conclusion is of course tentative, and must be checked out by further experimental work.

Another feature of interest in Table III-1 is the considerably larger degradation introduced by the ABF than by the beamsteer into the composite trace amplitude. This is no defect in the ABF processor, since its signal degradation measurements were made at signal levels where the beamsteer cannot provide even distorted amplitude estimates of the on-azimuth signal. The presence of an interfering event had little effect on the change of wave period. Maximum change from the on-azimuth traces was about 20% and consequently its effect on the magnitude estimate was less than 0.08 units.

Another conclusion tentatively drawn from this work is that differences in frequency content between interfering events have little, if any, effect on threshold reduction. The signals mixed in this simulation have dominant periods of 30 and 20 seconds, a wider separation than often found in practice. Consequently any effects due to different frequency content should be observable here, if at all. The fact that they were not suggests that this factor is not important. This result, too, must be checked by further investigation.

Two special cases should also be considered. These are the case of no time separation, and the last entry in Table III-1, that of 7-minute separation. A 6 dB amplitude rise cannot be found in the case of no time separation, because there is no time gate containing only the interfering signal in the composite trace. However, a comparison of the off-azimuth traces for the beamsteer and ABF simulations allows this calculation. For the same 11 dB event separation, it was found that the off-azimuth beamsteer amplitude was 1.4 dB below the off-azimuth ABF amplitude. This insignificant difference is consistent with the results of Barnard and O'Brien (1974).

At seven minute time separation the ABF threshold fell to 18 dB, although the beamsteer threshold was the same as for 6 minute separation. At this time separation the events were no longer significantly interfering, and the ABF weights were changing toward the values they take in the presence of background noise, where the ABF processor provides little advantage over the beamsteer processor at the low convergence rate of 0.1 used here. Therefore, we would expect the ABF threshold reduction to decrease as the influence of the interfering event on its filter weights becomes less, as observed.

B. ABF THRESHOLD REDUCTION AT VARIOUS AZIMUTHAL SEPARATIONS

In this subsection, events on day 276 of 1971 from Kamchatka and day 7 of 1972 from New Guinea were employed, respectively, as the on-azimuth signal and the off-azimuth interfering event. Their arrival times at ALPA were 22 hours 07 minutes 0 seconds and 7 hours 01 minutes 0 seconds. Data at all sites but 3, 4, 5, 6, 7, 11, and 18 were used. In view of the independence of the results on the time separation found in the last subsection, this parameter was fixed at 11 minutes, where the events were still well overlapped. The on-azimuth event remained at 273° throughout the study, while the interfering event was shifted to various azimuths between 273° and 93°. A fifteen-point adaptive filter was applied in all cases, and the remainder of the experimental procedure was the same as in the time separation study. Table III-2 presents the results in a format similar to that of Table III-1. Time traces were qualitatively very similar to Figures III-2 through III-5. Typical examples for an azimuthal separation of 60° are shown in Figures III-8 and III-9.

Examination of Table III-2 shows that the ABF provides little threshold reduction at 0° separation, as expected. A peak in the reduction is achieved at about 150°, and thereafter the reduction is somewhat less. This behavior can be understood by reference to Figure III-10 where the ABF and beamsteer thresholds and their differences are plotted.

In this figure it can be seen that the ABF threshold increases smoothly to a maximum of 30 dB at 120° azimuthal separation and remains at that value at all larger separations. The beamsteer threshold, by contrast, has two extrema and is increasing at 180°. Consequently, all the structure at azimuthal separations greater than 120° in the threshold reduction curve is attributable to variations in the beamsteer threshold, which depends on the spectral content and azimuth of the off-azimuth signal.

Figure III-10 also demonstrates that the ABF's superiority extends down to small azimuthal separations between the interfering events. The beamwidth, as measured by the angular separation where the threshold is 6 dB is about 35° for the ABF and 55° for the beamsteer, an important reduction.

The results of the study of these events at an azimuthal separation of 180° are comparable to those found in the previous subsection. Here an ABF threshold reduction of 16 dB was found, rather than the 11 dB reduction found for the first event pair. Both the ABF and beamsteer thresholds are higher in this simulation than the previous example, and this effect is presumably due to a number of factors whose separate importance cannot be estimated.

TABLE III-2

ABF THRESHOLD REDUCTION VERSUS AZIMUTHAL SEPARATION

Azimuthal Separation (Degrees)	Threshold(dB)		Convergence Rate	Threshold Reduction(dB)	Signal Degradation (dB)	
	Beamsteer	ABF			Beamsteer	ABF
0	0.0	1.6	0.50	1.6	-4.6	-4.0
30	1.0	3.2	0.50	2.2	-3.1	-4.0
45	3.4	14.0	0.40	10.6	-2.3	0.7
60	7.0	20.0	0.30	13.0	-1.8	0.2
90	9.0	26.0	0.15	17.0	-2.2	-3.8
120	7.0	30.5	0.10	23.5	-0.8	-5.4
150	6.0	30.0	0.30	24.0	0.6	0.6
180	14.0	30.0	0.50	16.0	-1.8	1.8

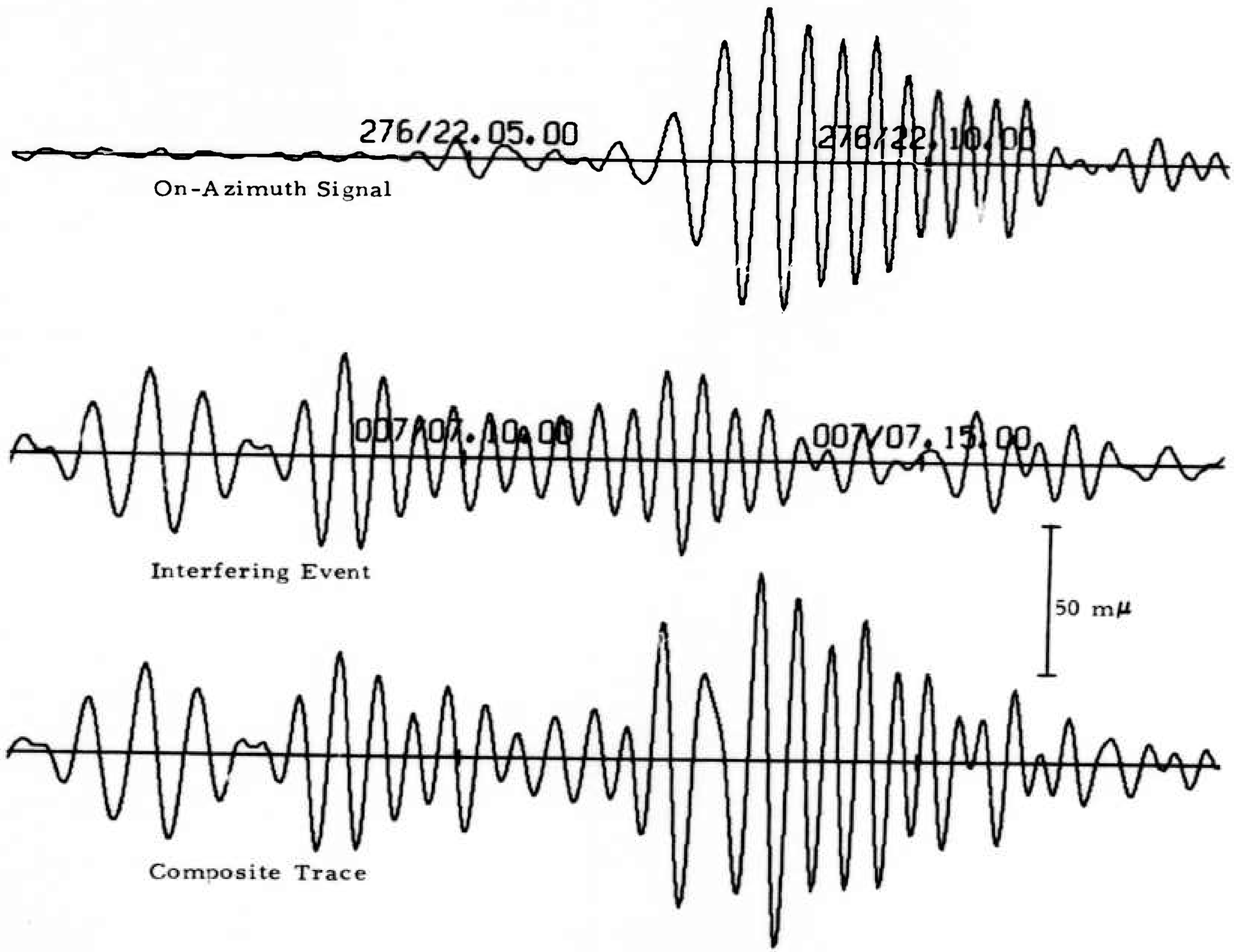

FIGURE III-8

BEAMSTEER OUTPUT FOR 60° AZIMUTHAL SEPARATION AND INTERFERING EVENT 7.0 dB ABOVE THE ON-AZIMUTH SIGNAL

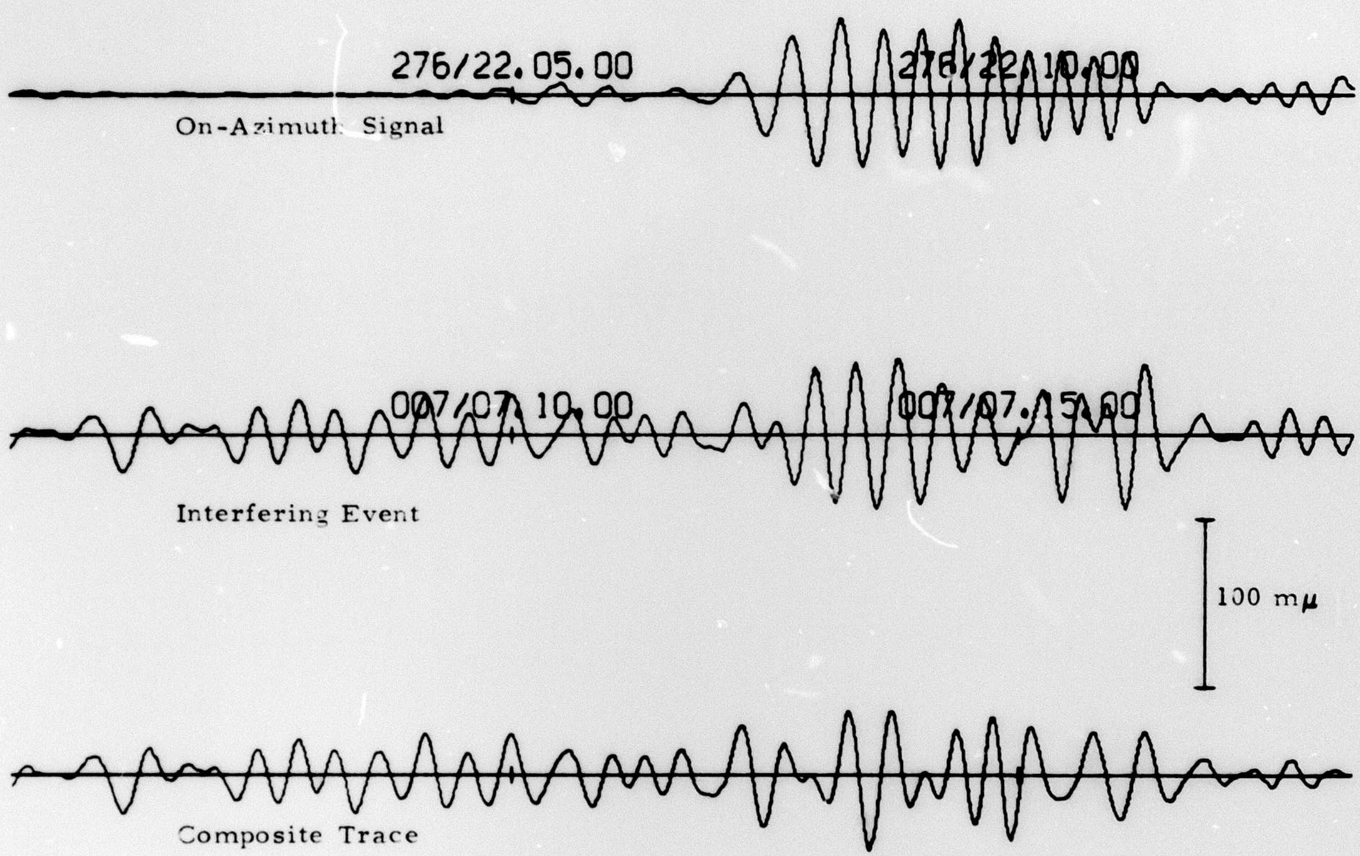

FIGURE III-9

ABF OUTPUT FOR 60° AZIMUTHAL SEPARATION, INTERFERING EVENT 20 dB ABOVE THE ON-AZIMUTH SIGNAL, AND $\mu = 0.3$

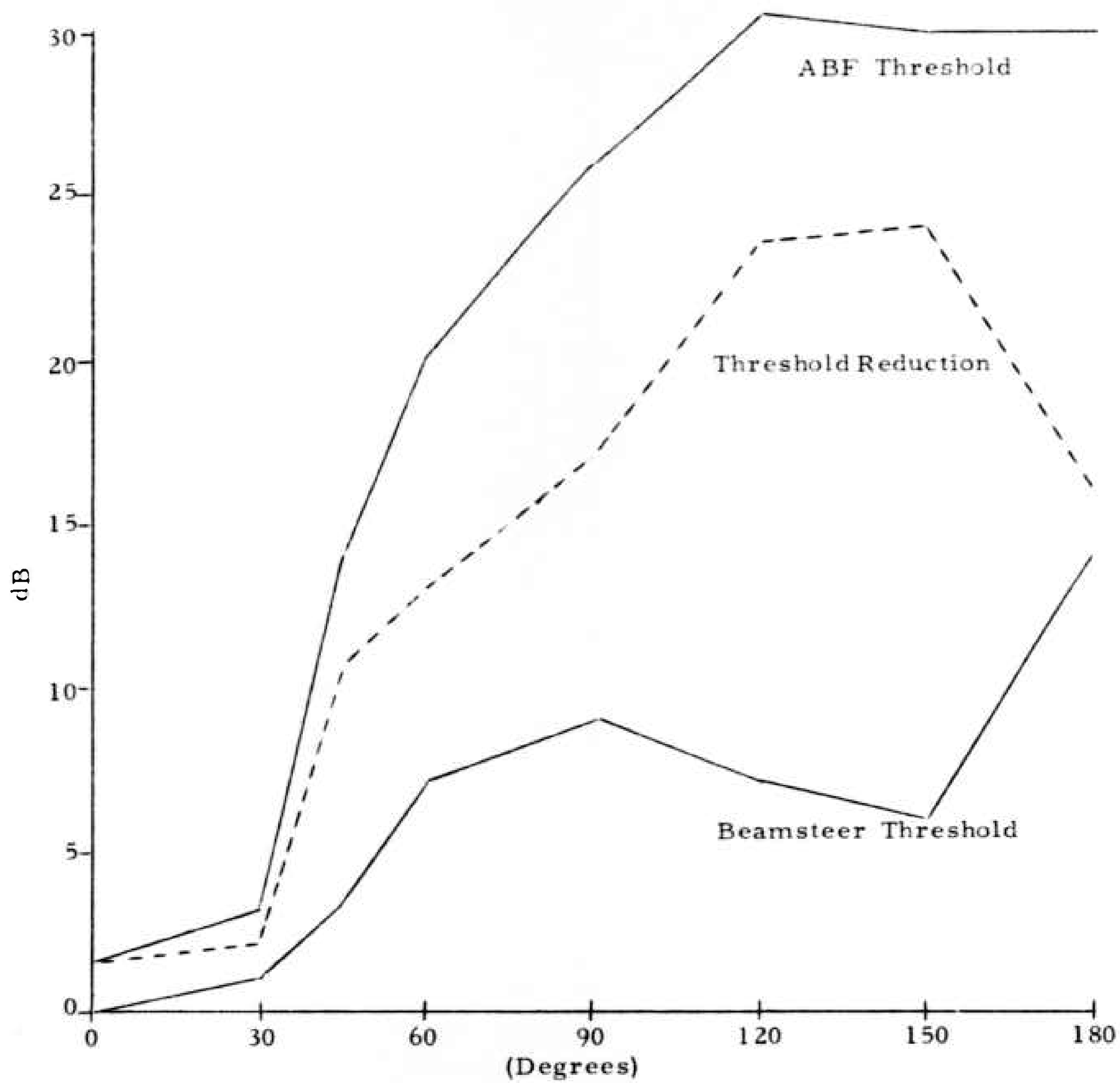

FIGURE III-10

THRESHOLD AND THRESHOLD REDUCTION VERSUS AZIMUTHAL SEPARATION

In this study a number of values of signal degradation found to be negative, indicating that constructive interference between on- and off-azimuth events contributed the composite trace peak. The variability exhibited by this parameter prevents any conclusions from being drawn concerning relative signal degradation.

The only feature requiring further comment is the 1.6 dB ABF rejection of 0^{o} separation. This value should be zero if both signals were exactly described by plane wave models and if the constraint of unit response in the look direction was exactly preserved. Neither of these conditions were met, and their relative importance cannot be readily estimated. In any case this effect is a small one.

SECTION IV
CONCLUSIONS

The experimental work presented in this study is limited, but nevertheless supports a consistent picture of the ABF's performance relative to the beamsteer. The ABF is indeed performing directional filtering, at least in part, as shown by the correspondence of its response pattern nulls with peaks in the f-k spectra at various times and frequencies. The ABF's superiority, at any azimuthal or time separation, is due to two factors. First, its response pattern nulls are deeper than the beamsteer's deepest nulls in most cases, especially for energy at periods greater than 25 seconds. Second, it is able to place these nulls at the interfering event azimuth, rather than in a direction determined by the array geometry as in the case of beamsteering. The first of these advantages is due to the ABF's large number of degrees of freedom, and the second is due to its adaptive nature.

Quantitatively, the conclusions are on a less firm footing. The arguments above and the results of subsection III-A suggest that the ABF threshold suppression is not a function of time separation for a wide class of event pairs, but the numerical value of that reduction depends on several factors and consequently is not predictable in general. The azimuthal dependence of the reduction is neither constant nor predictable, for the same reason. However, the reduction was as high as 20 dB (one magnitude unit) and was at least 9 dB (0.45 magnitude units) better for the ABF than for the beamsteer at all time separations and at all azimuthal separations greater than 45°.

Finally, it is important to reiterate that the ABF processor has shown the capability to recover on-azimuth signals up to 30 dB <u>below</u> the interfering signal (1.5 magnitude units) for some cases; this capability is 12 dB better (0.6 magnitude units) than any other technique that has been tested. Thus, the ABF has the potential to significantly reduce the interfering event problem provided that a surveillance network includes long-period arrays.

SECTION V
REFERENCES

Barnard, T. E., and L. J. O'Brien, 1974, An Evaluation of Adaptive-Beamforming Techniques Applied to Recorded Seismic Data, Technical Report No. 8, Texas Instruments Report No. ALEX(01)-TR-74-08, Contract Number F08606-74-C-0033, Texas Instruments Incorporated, Dallas, Texas.