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Vertical Array Receptions of the Heard Island Transmissions

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1 Introduction

The Heard Island Feasibility Test (HIFT) demonstrated that coded acoustic signals could be detected at ranges up to 18,000 km with currently available source technology. This paper describes one component of the HIFT where a large aperture vertical line array was deployed to record the signals transmitted from Heard Island.

One may pose the question: why use a vertical line array (VLA)? There are several responses to this. The first simply involves the signal to noise ratios (SNR). The transmissions to both coasts of the United States were nearly antipodal. While explosive signals have been detected at these ranges, transmission loss measurements did not exist.[10] In fact, one of the major challenges prior to HIFT was predicting the received signal amplitudes; estimates differed by more than $\pm 30\ dB$ depending upon the assumptions made about the propagation! This scale of prediction error is indicative of our uncertainty about transglobal acoustic propagation. In its simplest use the VLA provides some array gain to improve SNR's.

A second response concerns long range acoustic propagation. Signals must propagate axially in the SOFAR duct to be detected at these long ranges. At the 57 Hz center frequency of the HIFT these axial, or ducted, paths are efficiently described using a modal representation. The modal distribution is critical to understanding the acoustic propagation. The spatial distribution of the signals across the VLA provides information which is not available from a time series.

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Finally, the motivation for the HIFT was to test the feasibility of using global acoustics for monitoring basin scale ocean climate. The modes or raypaths sample the vertical structure of the ocean. Since they span different vertical sections, they provide additional information about the ocean. At relatively short ranges, but still many hundreds of kilometers, raypaths are well resolved and they have been exploited in ocean acoustic tomography to infer vertical structure for mesoscale ocean climate. At long ranges the axial modes are probably the most energetic due to various loss mechanism of the higher angle signals; however, they have been difficult to identify since they have arrival time separations which are too small to be resolved temporally with the available bandwidth. VLA's can separate these modes spatially providing a means of modal tomography for basin scale ocean climate.

It was late in the planning of the HIFT when the importance of vertical line arrays was recognized, so an intense effort was made to include two in the HIFT. With the support of the Department of Energy, Science Applications International Corporation, and the Monterey Bay Aquarium Research Institute, two arrays, one off Monterey, CA and the other off Bermuda, were deployed for the HIFT.

The VLA's did provide valuable information about the HIFT signals. Probably the most important observation was that the modal structure is a lot richer than expected. Our expectation was that only the very lowest modes would be detected at global ranges due to loss mechanisms such as boundary interactions and internal waves. The VLA data demonstrated the presence of higher modes and have stimulated a lot of research to explain this. Hypotheses include nonadiabatic propagation through the Antarctic Circumpolar Current and bottom interactions at the Campbell Plateau. The VLA identified the presence of the higher order modes unambiguously and aided the interpretation of the data significantly.

The low SNR's observed off Monterey were the major disappointment. This required large integration times and consequently smeared the information about arrival times. Both of these observations have been very important to the thinking for future experiments using acoustics to monitor ocean climate.

2 Background: Normal mode representation of acoustic propagation

Normal mode representations for acoustic signals are well established in the literature.[2] Since they are important in interpreting the data, we include a very brief description of them. Normal modes are especially useful at low frequencies, *e.g.* 57 *Hz*, where a few modes often provide an efficient representation of ducted signals. The phase speed of each mode determines the section of the water columns which it spans and the modes travel with different group velocities. As a result the modes "sample" different sections of the water column and they can be separated both spatially by their shape and temporally by their group delays.

Normal modes are derived using a horizontally stratified environmental model. Since the propagation paths from Heard Island to the location of the vertical array were range dependent, one must apply some approximations to use a normal mode representation. The adiabatic approximation is the simplest approximation invoked. It assumes that the range dependence is gradual enough that there is no transfer of energy among the modes and the modes change "adiabatically" with the range dependent environmental model. It models the propagation to the vertical array as[1]

$$\mathrm{p}(\mathbf{r}_R) = W(\mathbf{r}_R)T(\mathbf{r}_R, \mathbf{r}_S)\mathrm{x}(\mathbf{r}_S). \tag{1}$$

where $\mathbf{r}_S$ is the source location, $\mathbf{r}_R$ is the vertical receiver array location, $\mathrm{x}(\mathbf{r}_S)$ represents the mode excitation at the source, $T(f, \mathbf{r}_R, \mathbf{r}_S)$ is a diagonal matrix which describes the adiabatic propagation from source to receiver and the observation matrix $W(f, \mathbf{r}_R)$ projects the modes on the elements of the receiver array. We denote the modes and horizontal wavenumbers in the Helmholtz equation at location $\mathbf{r}$ to be $\phi_i(z, \mathbf{r})$ and $\mathrm{k}_i(\mathbf{r})$ respectively. The mode excitation is given by

$$\mathrm{x}(\mathbf{r}_S) = \begin{bmatrix} \phi_1(z_S, \mathbf{r}_S) \\ \phi_2(z_S, \mathbf{r}_S) \\ \vdots \\ \phi_M(z_S, \mathbf{r}_S) \end{bmatrix}. \tag{2}$$

The diagonal elements of the propagation matrix are given by

$$T_{i,i}(\mathbf{r}_R, \mathbf{r}_S) = \sqrt{\frac{2}{\pi}} \frac{e^{-j\pi/4}}{\sqrt{\mathrm{k}_i(\mathbf{r}_R)|\mathbf{r}_R - \mathbf{r}_S|}} e^{j\int_{\mathbf{r}_S}^{\mathbf{r}_R} \mathrm{k}_i(\mathbf{r})dr}. \tag{3}$$

The adiabatic assumption leads to the diagonal structure of the matrix. With nonadiabatic propagation there is coupling into the off diagonal terms. Note that the wavenumbers $\mathrm{k}_i(\mathbf{r})$ may include a complex term which incorporates the modal attenuation from volume absorption and boundary losses. The observation matrix is given by

$$W(\mathbf{r}_R) = \begin{bmatrix} \phi_1(z_1, \mathbf{r}_R) & \phi_2(z_1, \mathbf{r}_R) & \cdots & \phi_M(z_1, \mathbf{r}_R) \\ \phi_1(z_2, \mathbf{r}_R) & \phi_2(z_2, \mathbf{r}_R) & \cdots & \phi_M(z_2, \mathbf{r}_R) \\ \vdots & \vdots & \ddots & \vdots \\ \vdots & \vdots & \phi_m(z_n, \mathbf{r}_R) & \vdots \\ \phi_1(z_N, \mathbf{r}_R) & \vdots & \vdots & \phi_M(z_N, \mathbf{r}_R) \end{bmatrix}, \tag{4}$$

Equations 1-4 are used in interpreting the VLA data in terms of their modal content. Note that to be observed the mode must have significant expression at the depths of the array elements. In particular, a low order mode trapped near the SOFAR axis cannot be observed at a deep sensor where it has no expression.

3 Experiment

3.1 Vertical array receiver

The vertical array had 32 hydrophones spaced at 45 *m*. The shallowest hydrophone was nominally at 345 *m* in the water column and the deepest at 1745 *m*. The array was connected to a data acquisition system aboard the *R/V Point Sur* by a floating tether

[1]We have suppressed the notation indicating the frequency dependence. All quantities were computed for 57 *Hz*.

approximately 1 *km* away. The deployment configuration is illustrated in Fig. 1. The array had four subsystems: (i) the vertical line array; (ii) the surface wave isolation subsystem; (iii) the tracking and monitoring equipment and (iv) the data acquisition system.

3.1.1 Vertical line array

The array was fabricated using 2900 *m* of SAIC Quiet Cable [2]. The cable consisted of electrical conductors with an antistrumming external jacket on the vertical section and the hydrophones. The electrical cable contained 50 twisted pairs of # 28 gauge solid conductors. The data from the hydrophones used 32 of these pairs and each power bus was a group of three pairs. Thes conductors were covered by a Kevlar strength member and a waterproof jacket. This jacket had a triangular cross section wound in a helix to reduce strumming induced by vortex shedding on the cable. The hydrophones had a sensitivity of $-170\ dB\ re\ 1v/\mu Pa$ over the range of 10 - 2000 *Hz*. The hydrophones were connected to the cable through waterproof, reinforced "breakouts" through the Kevlar jacket. Roughly 1800 *m* of the cable was on the vertical section; the remaining 1100 *m* was a tether to the recording ship. This was done to provide a separation from the ship to reduce ambient noise and to isolate the ship motion caused by the wind. The array was deployed using a TSE Model SDP-70 winch through a 6 in ID, 15 in bellmouth on the afterdeck of the *R/V Point Sur.*

3.1.2 Surface isolation subsystem

The sensitivity of the hydrophones to swell induced motion required a suspension system with a spring/mass/damper design which had a natural frequency far lower than the expected swell period. (A 3 *cm* displacement leads to a 1 *v* output for a hydrophone with a $-170\ dB\ re\ 1v/\mu Pa.$) The suspension system performed several functions: i) positioning of the hydrophones in the SOFAR channel, ii) isolating the vertical motion of the array in response to wave forces, and iii) floating the tether section on the surface such that it could be tracked and not damaged by the ship. The vertical suspension consisted of a damper/ballast assembly at the bottom of the array, a flotation sphere at the top of the array and an isolation section connecting to the surface. A perforated steel drum supplemented by 40 *lbs* of lead weights for an overall weight in air of approximately 260 lbs were used for the damper/ballast assembly. The flotation was a 1 *m* spherical syntatic foam float which provided 400 *lbs* of buoyancy. The surface isolation had 25 syntatic foam football floats each providing 6.25 *lbs* of buoyancy.

3.1.3 Tracking and monitoring section

The trickiest part of deploying such a long array connected to a ship was to isolate the ship from the array with a very "loose" tether. The ship was driven downwind which pulled on the array and resulted in very high noise levels on the hydrophones. If we put slack in the tether by backing down on it, there was the very real danger of wrapping the cable around the propellers and this did happen once. Operation at night and during high sea states was especially risky. The tracking and monitoring section consisted of lobster pot

[2]Trademark SAIC

floats distributed along the tether to keep it on the surface and a set of strobe lights for night operation. The *modus operandi* involved positioning the ship before the data reception such that there was a lot of slack in the tether; during reception the ship was allowed to drift down wind with minimum power applied until the vertical section of the array started to ascend; then the ship would attempt to backdown carefully on the array to relieve the tension.

The deployment and/or current shear at the site led to the array acquiring a tilt. The magnitude of this was monitored and it nominally was around 2.5°. For an aperture of $1380m$ this leads to a horizontal displacement of $60m$ which is significant compared to the $26m$ wavelength at 57 Hz. Unfortunately, the azimuth sensor failed, so direction had to be inferred from the local currents. The surface current heading was generally to the southeast (approximately 150°T) and this was consistent with the results deduced from the data.

3.1.4 Data acquisition

The data was recorded using a multichannel autoranging acquisition system developed at Woods Hole Oceanographic Institution for its Arctic field programs. [7]. Each channel was bandpass filtered between 10 and 80 Hz and sampled at 228 Hz, or four times the carrier of the HIFT signals. The acquisition had a dynamic range in excess of 130 dB and a precision of 72 dB. [3] MBARI and the NPS also had data acquisition systems, but the results reported here are from the WHOI system.

3.2 Bermuda array

The depth and spacings of the hydrophones in the Bermuda array were identical to those on the Monterey array; however, it was moored from the bottom and included internal A/D and recording units which were in a cannister contained in a subsurface float. This design represented an attempt to decouple the array from surface waves and to isolate it from nearby ship noise. The array was deployed without difficulty approximately due east of Bermuda in 4500 m of water on January 28, 1991. Upon completion of the transmissions from Heard Island the recovery team attempted to retrieve the array. The acoustic releases responded appropriately, but the array failed to surface. An attempt to recover the array by dragging was made the following month; however, it was abandoned after four days because of high sea states. A second and successful recovery attempt was made in November. The entire array was retrieved using an integrated GPS navigation system and a Benthos transceiver for accurate positioning of the drag equipment.[14] Remarkably, the data cannister which included the data acquisition computer, the A/D circuitry and three EXABYTE tape recorders was intact and had not leaked. Unfortunately, there were no data on the tapes.

The mooring failure appears to have been caused by insufficient reserve buoyancy for the Bermuda location. The cause of the computer failure is still unknown since the system cycled as designed when powered upon recovery. Given the signal strength observed on the Bermuda NAVFAC, the data loss was a bitter disappointment.

[3] We specify dynamic range to be the ratio of the largest to the smallest signal which can be recorded and precision to be the number of significant bits in a recorded signal.

4 Site selection, ship tracks and environmental data

The siting of the vertical array was based upon the acoustic modeling of the propagation from Heard Island to the coast of California by Chiu *et al.* [3] An upgraded version of the Hamiltonian Acoustic Ray tracing Program for the Ocean (HARPO) [6] and gridded temperature and salinity data simulated by the Semtner-Chervin Eddy Resolving Global Ocean General Circulation Model [15] were used for the propagation and environmental models.

In the analysis raypaths were computed using 11 consecutive, instantaneous fields extracted from the ocean model data set at 30 day intervals in the simulation. These 11 fields contained both meso- and gyre scale variability. A reliable ray envelope criterion was established to be those paths not impeded by land masses and with less than five bottom interactions. The rays within the envelope and insonifying the west coast of California were determined. This is illustrated in Fig. 2. This envelope was a rather thin beam. It is bounded between azimuthal launch angles of 133° and 136° (measured clockwise from North) and in the vertical by launch angles between 0° and 2°. The horizontal envelope dimension of the ray bundle was nearly constant in time near the source but becomes quite variable near at the receiver site off the California coast. The variability is introduced mainly in the southern Ocean as the ray bundle traverses the Antarctic Circumpolar Current. The reception envelope has a mean direction of 32° (from 212°) and mean width of $150km$ and it encounters the coast in a region generally confined between Point Arguello and San Francisco Bay. The mean width can vary as much as half the mean over the 11 extracted fields. Areas common to all fields were mapped to estimate the best receiving locations. No other reliable ray envelopes from Heard Island to California were found using this modeling approach. This analysis led to selecting a location roughly 200 km offshore at a site west of any major local bathymetry which would shadow the signals. This is labeled "01261525Z" in Figure 2. This is closest to site where the data subsequently discussed was acquired.

Since the *R/V Point Sur* was not moored, it drifted on average towards SE to SSE. The winds were relatively calm and the sea state was low so the *R/V Point Sur* was able to maintain excellent station keeping during the array deployment and during the reception of January 26th and 27th. On January 28th the winds and sea state increased to the point where is was considered very risky to maintain the tether to the array because of the danger of backing down on it. As it turned out the *R/V Cory Chouest* transmitting the signals had to suspend operations at roughly the same time so few recording opportunities were lost. When the seas abated the array was reattached; however, there was a maneuvering error and the *R/V Point Sur* backed down on the array and wrapped the cable around the port screw. This occurred at the location labelled "01292115Z". After recovering the array we returned to port to cut the damaged section away and repair the array cable; we then returned to sea to occupy site labelled "013112108Z" which was somewhat south of the original location. [4]

CTD profiles were taken before and after both deployments from which local sound

[4] We chose the more southerly location because we heard that there were strong receptions at the location of the Canadian ship *CFAV Endeavor*; as it turned out the SNR on an individual phone was roughly the same.

speed profiles were calculated. [5] These were very typical of the region with a shallow (100 m) mixed layer and an axis depth roughly at 600 m with a fairly broad minimum. Figure 3 illustrates the sound speed profile taken closest to the time of data receptions subsequently discussed.

The first 10 normal modes were calculated from the sound speed profile in Figure 3. These are illustrated in Figure 4. We have superimposed a set of horizontal lines indicating the nominal depths of hydrophones on which we have good quality data. Note that modes 1 and 2 are close to zero for hyrdrophones 18 and below and modes 3 - 6 are close to zero for the hydrophones 29 - 31 at the deepest part of the array. These observations become important in interpreting sonograms on the individual phones.

A normal mode can be interpreted as a coherent superposition of up and down going rays with ray parameter given by the phase speed of the modes. For each mode these rays cross the sound channel axis at an angles given by

$$\Delta\Theta_n = \pm \arccos(c_{\text{axis}}/c_{p_n}) \tag{5}$$

where c_{axis} is the sound speed at the axis and c_{p_n} is the phase speed of mode n. The phase speeds and axis crossing angles are tabulated in Table 1; we refer to this when interpreting the $\omega - k$ frequency wavenumber spectral analysis of the data.

The vertical extent of the modes can be determined by using the phase speed of of the modes as well. The upper and lower extents Z_u, Z_l are given by the depths where the sound speed equals the phase speed. These are also tabulated in Table 1. In addition, the channels which are included within this span are noted; we refer to this when interpreting the sonogram analysis of the data.

Mode	c_{p_n} (m/s)	$\Delta\Theta_n$ (deg)	Z_u (m)	Z_l (m)	Channels
1	1480.885	1.466	425.	700.	3 - 8
2	1481.787	2.479	375.	925.	2 - 13
3	1482.635	3.146	350.	1100.	2 - 18
4	1483.431	3.663	300.	1225.	1 - 20
5	1484.240	4.122	250.	1325.	1 - 23
6	1485.003	4.512	225.	1425.	1 - 25
7	1485.759	4.867	200.	1500.	1 - 26
8	1486.492	5.189	150.	1575.	1 - 28
9	1487.259	5.504	125.	1650.	1 - 30
10	1488.021	5.801	100.	1725.	1 - 31

Table 1: Phase speeds, c_{p_n}, axis crossing angles, $\Delta\Theta_n$, upper and lower modal extents, Z_u, Z_l, and channels coverage for modes $1 - 10$

[5] Simultaneously CTD's were considered too risky while the array was deployed.

5 Experimental results

The analysis of the data concentrates on three reception periods in the first part of the experiment when CW signals were transmitted. There are several reasons which led to this. The primary reason was the low SNR of the signals detected at the site off Monterey. The CW signals concentrated all the power in the carrier so very narrowband filtering and long integration times could be done to improve SNR. The processing for M sequences led to marginal detections which was probably the result of the drifting of the VLA. We use just the first three reception periods because both the transmitted signal levels from the *R/V Cory Chouest* near Heard Island were highest and the largest number of hydrophones of the VLA tethed to the *R/V Point Sur* were functioning.

There were three analyses of the data

- Sonograms of each sensor *versus* depth;
- Frequency-vertical wavenumber ($\omega - k$) spectra;
- Modal decompositions by beamforming and least mean square fitting.

5.1 VLA data quality

Low SNR's at the receiver were the major problem for the VLA data analysis. The average signal level at a near axis hydrophone was estimated to be approximately -75 dB re $1\mu Pa$ by factoring in the gain due to narrow band filtering of the data. This level implies a transmission loss of $145dB$. (Note that this is the narrowband transmission loss and not the loss per identifiable path.) The ambient noise level was measured several times in the course of the experiment and it was typically 89 dB re $1\mu Pa/\sqrt{Hz}$. This was done using a real time spectrum analyzer and averaging the levels in bands where there was little evidence of ship tonals from the *Point Sur*. The self noise was monitored continuously during the experiment using a sonogram; it was most noticeable as tonals in spectra. The measured ambient noise level was 3 - 6 dB higher than the predictions from the US Navy DANES model [12] and the ANDES (Ver 2.2) model [13] prior to the experiment and this may be attributable to the self noise of the *RV Point Sur*. The 89 dB level is also consistent with a set of measurements made by Miller during tests for self noise made prior to the experiment. [11] The single channel SNR was typically -15 dB. The signal and noise levels are consistent with the measurements made by Heard,[5], using a towed array from *CFAV Endeavor* operating west of San Diego but in the same ray bundle from Heard Island.

There were three other problems with the VLA which influenced the data quality. Several hydrophones in the lower section of the array did not operate reliably. One known cause of this was the failure of a line powering some of the phones. We believe other phones failed because the continuous surface wave action caused the thin (# 28) wires for the twisted pairs to anneal and break.

Tilt, depth and heading sensors were used to monitor motion at the top of the array (345 m) and below sensor 21 (1245 m). (See Figure 1.) The deep sensor produced unreliable results and the compass in the shallow sensor did not operate reliably. As a result we have only the depth and tilt magnitude of the shallow sensor for inferring array geometry. The depth and tilt magnitudes for the three CW intervals are indicated in Figure 5. We also had acoustic current meters on the cable (see Figure 1). One can make inferences about array tilt from the direction of the current; however, this is complicated by the station keeping of the *Point Sur* as it attempted to keep slack on the tether.

The array tilt and depth are important in any signal processing because of the differential phase shift it induces down the VLA. This is given by

$$\Delta\phi_i = \frac{2\pi}{\lambda}(z_i - z_0)\sin(\theta_{\text{tilt}})\cos(\phi_{\text{HI}} - \phi_{\text{tilt}}) \tag{6}$$

where z_0 is a reference depths (the top hydrophone of the VLA), ϕ_{HI} is the bearing on the geodesic away from Heard Island and $\theta_{\text{tilt}}, \phi_{\text{tilt}}$ are the array tilt and azimuth. We know ϕ_{HI} to be 214° and we estimate ϕ_{tilt} to be 150° which leads to a difference of approximately 64°. For example, tilt magnitudes of 2.5 ° were typical and would have led to a phase difference of 178°. If uncompensated, this leads to a significant degradation in array performance.

The array depth becomes an important issue when the spatial structure of the modes are included in the signal processing. Fortunately, the low order modes are smooth functions, so minor changes are not consequential. The difficulties with inferring the VLA geometry on the HIFT suggest that reliable monitoring of array shape and heading is imperative for any signal processing of VLA data.

The final VLA data quality issue concerns the very high amplitude, random spikes which are present in the data. A broadband playback of the data indicated that there were infrequent, but strong, broadband transients propagating across the array. We believe the that one of the hydrophone "breakouts" became loose and induced vibrations on the cable. and is the source of these transients. We have suppressed this by a combination of broadband filtering and clipping in the signal processing. This has been very effective in mitigating these transients.

5.2 Signal conditioning

Three groups - MIT/Woods Hole, SAIC and NPS/MBARI - did the VLA data analysis; as a result, there are some light differences in the signal conditioning done before the respective analyses. All involved some form of clipping to suppress the transients and some bandpass filtering to reject out of band noise. The signal flow for the three analyses are illustrated in Figure 6. The results concerning the modal content, nevertheless, are very consistent.

The MIT/WHOI is indicated on the left side of Fig. 6. The transients were suppressed by a short duration, broadband FIR filter with a passband from 48 - 66 *Hz* and then clipped at level of 1 standard deviation. The complex envelope of the data about 57 *Hz* was formed where the passband of the quadrature demodulator was 1 *Hz*. This was followed by downsampling by 50 for a sampling rate of 4.56 *Hz* an FIR (finite impulse response) filter with a passband of ± 135 mHz. The data were demodulation for the doppler shift resulting from the ship motion and final narrowband FIR filter with a passband of ± 6 mHz. The doppler shifts were checked to insure that the measured and estimated shifts were consistent. Table 2 compares the predicted and measured doppler shifts.

Data set	Bearing (deg)	Speed (kts)	Launch Angle	Predicted Doppler (mHz)	Measured Doppler (mHz)
01261525	254.5	2.99	133	-31.5	-30.5
01270222	252.0	2.51	133	-24.5	-24.0
01271505	234.5	3.21	133	-12.6	-12.5

Table 2: Comparison of predicted and measured Doppler shift for the CW signals received on the VLA

This resulted in a complex, low pass signal which was the input to the several analyses. Figure 7 illustrates the magnitude and phase time series of the top 14 channels for transmission on January 27, 1991 transmitted at 0000Z and received at 0322Z. Note that the magnitude shows a fair amount of variability among the channels while the phase is much more consistent. The fluctuating magnitude makes assigning an output SNR difficult, but a reasonable estimate is around 5-10 *dB*. The 6 *mHz* filter provides approximately 22 *dB* of processing gain, so the input SNR fluctuated between -15 to -10 *dB* on a single channel on a per Hertz basis.

The conditioning for the SAIC frequency wavenumber analysis is similar to for MIT/WHOI and is indicated in the center of Figure 6. There is ± 1 standard deviation clipping, quadrature demodulation with a $\pm.5$ Hz band and downsampling by 100. The NPS/MBARI conditioning is on the right side of Figure 6 and consisted soley of clipping before the modal beamformer and spectral analysis.

5.3 Sonograms versus depth

The simplest type of processing was to form sonograms of the data for each hydrophone on all three data sets. This was done using the MIT/WHOI signal conditioning illustrated on left of Figure 6. This gives an indication of the power distribution and the its variability *versus* time and depth. These are illustrated in Figures 8 a,b,c,d. The sonograms for each event form a column. The time axis is positioned to the start of the data acquisition and not referenced to specific time. There is also a constant time delay for each event because of signal processing. We were confident of good quality data on 21 of the 32 channels; their depths are noted on left of the figures.

Several observations can be made directly from these sonograms. First, there is significant variability in both time and depth. The signals seem to fade in and out one a time scale consistent with the observations at some of the other sites. More surprisingly, the magnitude does not track consistently *versus* depth which seems to suggest some type of time varying interference among several modes. Next, one can observe that power can be detected at even the deepest hydrophones. If one relates this to the depth dependence of the modal amplitudes in Figure 4, this implies modes 6 or higher were present since lower order modes do not have significant expression at these deepest hydrophones.

5.4 Frequency wave number distribution

A frequency vertical wavenumber spectrum provides a measure of the vertical distribution of power. It also incorporates the phase information which is not a factor in the sonogram analysis. While the array spanned an extent such that the inhomogeneity of the sound channel was significant and a plane wave analysis implicit in using wavenumbers does not strictly apply, the spectra do suggest the vertical angular distribution of the power. These plots evoke modal description as the interference of a pair of upward and downward going planewaves. For comparison Table 1 indicates the vertical crossing angle of each mode at the sound channel axis.

Frequency-vertical wavenumber analysis was performed on the data to determine the distribution of acoustic energy in vertical angle with respect to the array. The data processing flow is shown in the center of Figure 6. A total of 57 *min* of data, 19 *min* from each of three different time periods, was processed. The results are shown in Figures 9 a,b,c for each of the CW events. The intensity is displayed in 1 dB increments. The tilt of the array shifts the center of wavenumber distribution, but it is the difference in angles that determines modal correspondence.

The difference in arrival angles between upward and downward going angles is 6° for the data from 1527Z Jan 26 (event 01261527) and 0322Z Jan 27 (event 01270322). For the data from 1539Z Jan 27 (event 01271539) there are two pairs with differences of 7° and 10° . Note that the energy is not uniformly distributed over these spreads but is clumped towards the extremes. This would indicate that energy is more concentrated in discrete rays at the higher angles, or higher modes. We can attempt to develop a more consistent interpretation of these data by including an assumption about the tilt of the array. As explained in Section 3 the array was instrumented for tilt measurement, however, the compass failed for the direction of tilt so only the maximum apparent tilt is known. In the insets shown in Figures 9 a,b,c an array tilt is assumed that is consistent with measured tilts. Nominal tilt magnitude were 2.5°, so a relative angle of 60° between the average drift direction and the signal direction from Heard Island yields an effective tilt of approximately 1.2°. These assumed tilts are away from the direction of propagation that is the bottom of the array being further from Heard Island which is also consistent with the drift track of the *R/V Point Sur* with respect to the line of sound from Heard Island.

These tilt assumptions yield consistent pairs of upward and downward going arrivals at ±3° which correspond to modes 3-4 for the data from 1527Z Jan 26 and 0322Z Jan 27. For the data from 1539Z Jan 27 the yield an upward and downward going pair at ±3.5° with another pair at ±6.5°. These correspond to modes 4 and 12; however, the arrival at down 8.5° is 3 dB lower than the other peak arrivals. If we ignore this arrival, a tilt of .5° towards Heard Island would give an upward an downward pair at ±5° which corresponds to mode 7. The sonograms in Figure 8 for this last event suggest higher signal levels on the deeper hydrophones implying the presence of higher order modes.

The lack of definitive tilt information is unfortunate, so one wants to careful not to extract too much detail from these figures. Nevertheless, independent of the tilt assumptions, the fact remains that the data do show discrete ray arrivals at high angles that correspond to maximum modal levels at mode 3-4 and the suggestion of up to mode 7 in the energy arriving at the VLA off Monterey from Heard Island.

5.5 Modal beamforming

Modal beamforming is another array processing method for estimating the modal distribution at a VLA. In this technique one simply forms a linear combination of the data from each channel where the weighting is proportional to the modeshapes. Since the modeshapes are frequency dependent, it is easiest to use a discrete Fourier transform implementation for the array processing. The output for mode m is given by

$$Y_m(f) = \sum_{n=1}^{N} W_{m,n}(f) X_n(f); \tag{7}$$

the weighting, $W_{m,n}$, is given by

$$W_{m,n} = \frac{\phi_m(Z_n, f)}{\sum_{n=1}^{N} |\phi_m(Z_n, f)|^2} \tag{8}$$

where $\phi_m(Z_n, f)$ is the amplitude of the m th mode at depth Z_n (see Eq. 4). After modal beamforming a spectral analysis of the beamformed signal, $y_m(t)$, can be done to compare the relative amplitude of the modes.

Modal beamforming was applied to the VLA data of January 27, 1539Z (event 01271539).[4] The signal conditioning, which is indicated on the right column of Fig. 6, consisted of clipping to eliminate the effects of the wideband noise transients previously described. A very careful compensation for array depth was done and only the a 15 hydrophones were used to reduce the effects of array tilt. Fig. 10 illustrates a spectral analysis of the data which indicates the Heard Island CW signal near 57 Hz using both a single channel and modal beamforming. The upper left panel Fig. 10 indicates the power spectral density of a single phone positioned near the SOFAR axis while the remaining panels are spectral density estimates of beamformer outputs for modes 1-5. They array gain is clearly evident. More importantly, the spectra for mode 3 has a peak level almost 3 dB higher than all the others. This is remarkably consistent with the sonogram and frequency-vertical wavenumber analyses.

The aperture of the array was constrained so modal beamforming leads to crosstalk in the estimates for higher order modes; consequently, beamforming above mode 5 was not attempted.

5.6 Modal fitting

Modal beamforming is equivalent to matched mode methods in matched field processing. [1] If the array spanned the entire column with a dense sensor spacing, the orthogonality of the modes leads to an ideal separation of the modes. In practice it does not, so there is cross talk among the modes by what can be considered the modal equivalent of sidelobes.

One way of reducing this is to perform a least mean fit to the data using the mode shapes as the basis functions. This is done by finding the coefficients $a_i(t)$ which minimize the mean square error over an interval around t, or minimize $\mathcal{E}(t)$ *versus* $a_i(t)$ where

$$\mathcal{E}(t) = \frac{1}{\Delta T} \int_{t-\Delta T/2}^{t+\Delta T/2} \sum_{i=1}^{M} |\tilde{r}_i - \sum_{j=1}^{N} a_j(t) \phi_j(Z_i)|^2 dt \tag{9}$$

where $\tilde{r}_i$ is the doppler shifted and tilt corrected complex envelope of the signal at channel i. (We actually performed search over tilt to minimize an average of $\mathcal{E}$. This is a straightforward problem in least squares and the solution can be found in many references. [8].

The tradeoffs for the VLA data concerned the choice of the averaging interval, ΔT, and the number modes, N, in the fitting. The time varying character of the complex envelope permitted just short averaging time. The mode fitting depends upon both amplitude and phase so the amplitude fluctuation are problematic. We used a 200 sec averaging time which was consistent with the bandwidths of the FIR filters in the signal conditioning. The number of modes is largely determined by the number channels. The number of degrees of freedom in the fitting must be constrained; otherwise any data set can be represented with non physical results. We felt very confident about the top 14 channels and used 7 modes to keep the degrees of freedom inthe fit constrained.

Figures 11 a,b,c illustrate the modal fitting amplitudes as a function of time for the three events. The use of 7 modes led to fitting errors of approximately 25 percent during the early part of the signal reception and before the added noise due to the tension on the array. The conclusion is generally similar to the previous analyses. The peak amplitudes are found for modes 5-6 which suggests the higher angle energy incident at the VLA. This contrast a bit with the modal beamforming which found mode 5 to be very low; the difference can be accounted for by a difference in the tilt modeling, but we are not certain of this conclusion.

6 Data interpretation and summary

We have performed four analysis of the VLA receptions of the Heard Island signals. All four suggest the presence of higher order modes. The frequency- vertical wavenumber analysis and the modal beamforming indicate that mode 3 has the highest amplitude while the modal fitting suggests that made 5-6 are largest. It is difficult to resolve the differences since the SNR at the VLA, nearly 18,000 km with a transmission loss of around 145 dB, is quite low. Individual arrivals could not be distinguished because of the long integration time necessitated by the low SNR.

The results are, nevertheless, consistent with the modeling done by McDonald *et al*,[9] for the propagation from Heard Island to the VLA site. Figure 12 indicates this. The top of Figure 12 is the refracted geodesic for mode 1 from Heard Island to Monterey. (The geodesic for the higher modes do not differ by much.) The middle illustrates the solution of a wide angle parabolic equation (PE) starting the source depth and location near Heard Island. One can see the solution appears to be nearly adiabatic except near the point designated "C". The bottom part of the figure is the result of projecting the PE solution on range dependent modes 1-30 along the geodesic. The projections suggest a large number of modes present up to "C"; then there is significant attenuation by the blockage and nonadiatic conversion of the surface modes to ducted modes. From "C" to "E" the signal propagates adiabatically. While it is difficult to discern, the model suggests that modes 5-6 are most energetic.

The engineering of the VLA was also instructive. The failure of the sensors for monitoring array shape and heading complicated the signal processing a lot. While we knew a tethered deployment would be tricky, it was not as much of problem as anticipated once we developed the procedure for prepositioning the array, carefully backing down on it when it came under tension and monitoring its response via the depth sensor.

The most important conclusion is that the vertical distribution of energy for signals which propagated nearly antipodal distances around the Earth is more complicated than predicted and much needs to be learned for future efforts involving such long range propagation.

7 Acknowledgements

The Vertical Line Array effort for the Heard Island Feasibility Test was supported by the Monterey Bay Aquarium Research Institute (MBARI), the Department of Energy (DOE), the Naval Postgraduate School (NPS) and Science Applications International Corporation (SAIC). The authors wish to thank the officers and crew of the em R/V Point Sur for their help with a complicated deployment of the VLA. We also want to thank B. Sperry (MIT/WHOI), E. Scheer (WHOI), D. Gever (SAIC), L. Ehret (NPS) and S. Crocker (NPS) for their assistance in the data analysis.

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8 Figure captions

Figure 1
Deployment configuration of the HIFT Vertical Array

Figure 2
Horizontal ray tubes for predicting receptions of HIFT transmissions based upon Semtner mesoscale model. (from Chiu, [3]

Figure 3
Sound speed profile derived from CTD taken prior to HIFT data acquisition.

Figure 4
The first ten modes at the receiver site using the sound speed profile of Figure 3

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Tilt and depth of the VLA during the CW receptions

Figure 6
Signal conditioning flow diagram for the MIT/WHOI, SAIC and NPS/MBARI VLA data analysis.

Figure 7
Magnitude (linear) and phase for the 01270322 data set using the MIT/WHOI signal conditioning

Figures 8 a,b,c,d
Sonograms of 21 hydrophones for each of the CW signals on the VLA. Each column is an event, or CW transmission, and each row is a hydrophone. Note the presence of energy on the deeper hydrophones.

Figures 9 a,b,c
Frequency-vertical wavenumber spectra for each of the CW signals on the VLA. The insets hypothesize a consistent array tilt and the differences in angles suggest the concentration of the higher order (3-4) modes.

Figure 10
Comparison of the spectral estimate of a single hydrophone with the spectra of modes 1-5 after modal beamforming.

Figure 11 a,b,c
Modal amplitude coefficients for a time varying least squares fit of the data from the three

CW events.

Figure 12
Parabolic equation solution for the path from Heard Island to the VLA. The geodesic is at the top, the magnitude of the PE solution in the middle and the projection on the local modes at the bottom.

HEARD ISLAND FEASIBILITY TEST
MONTEREY VERTICAL ARRAY

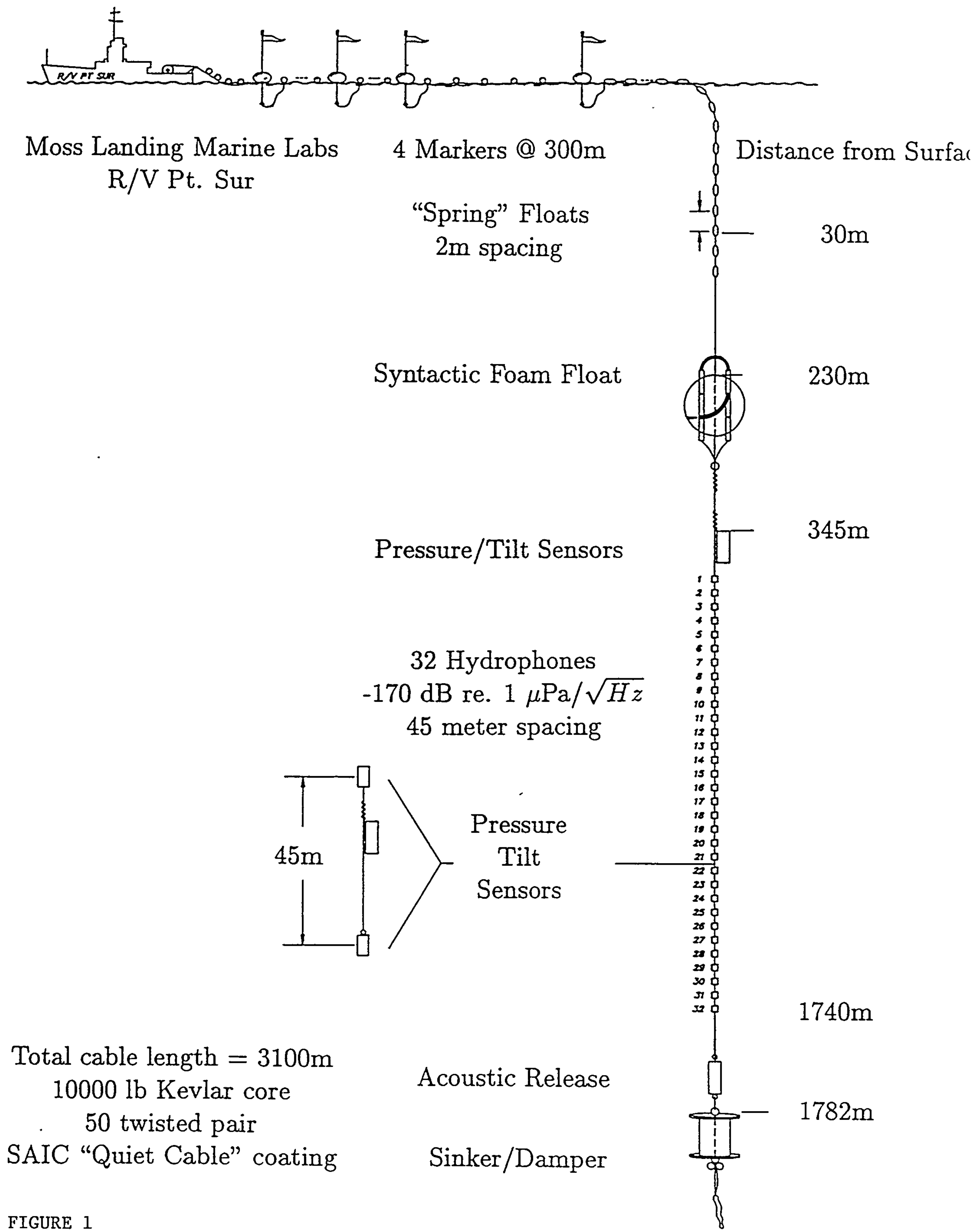


FIGURE 1

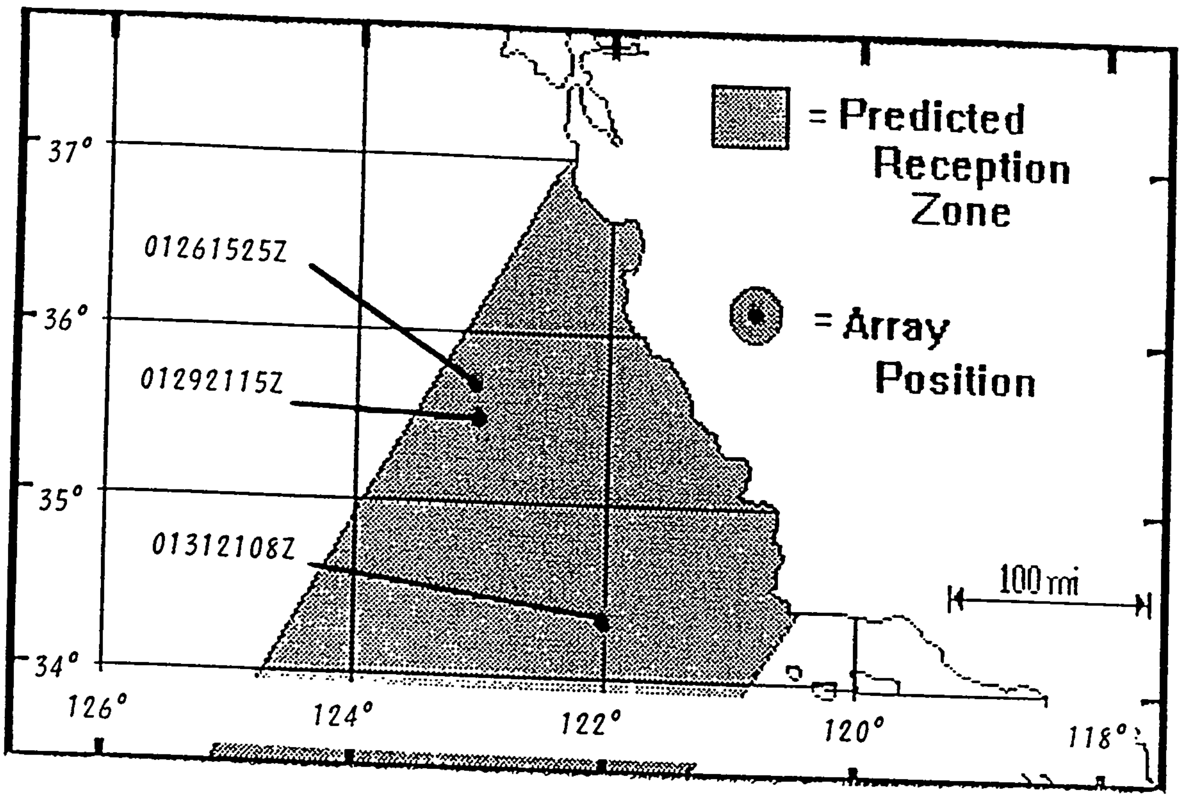
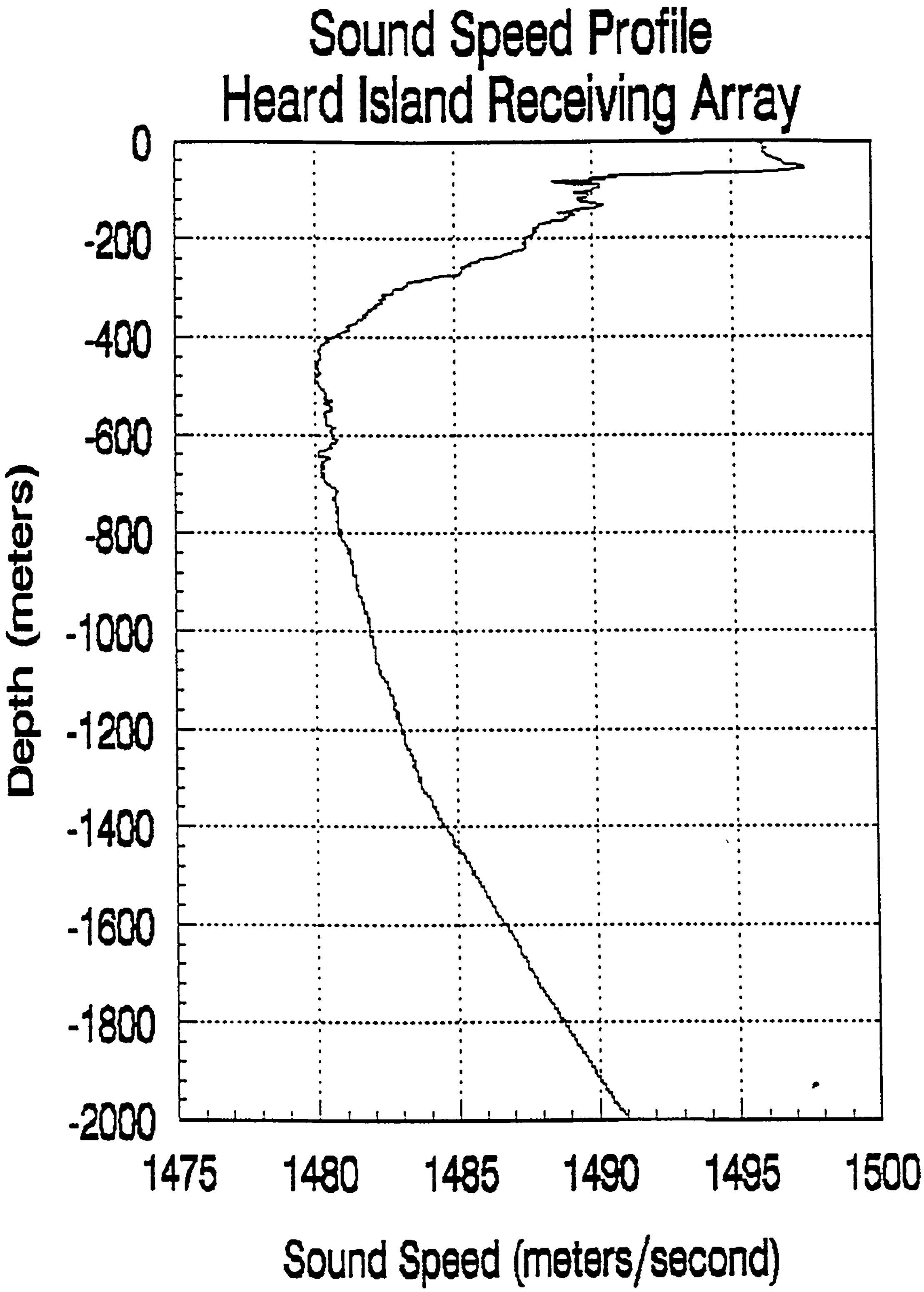

= Predicted Reception Zone
= Array Position
37°
36°
35°
34°
126°
124°
122°
120°
118°
01261525Z
01292115Z
01312108Z
100 mi

FIGURE 2



Sound Speed Profile
Heard Island Receiving Array
Depth (meters)
0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
-1800
-2000
1475
1480
1485
1490
1495
1500
Sound Speed (meters/second)

FIGURE 3

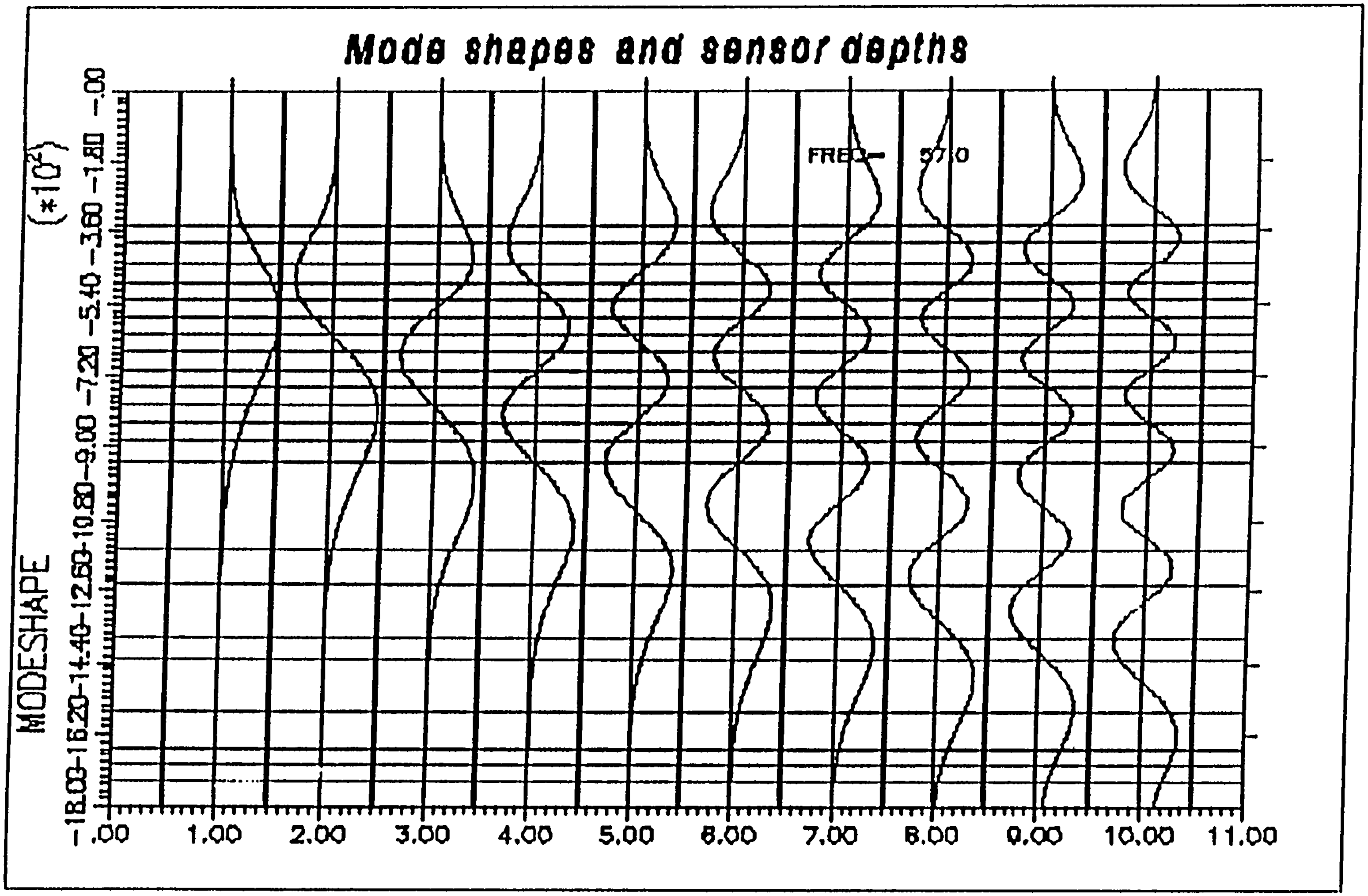
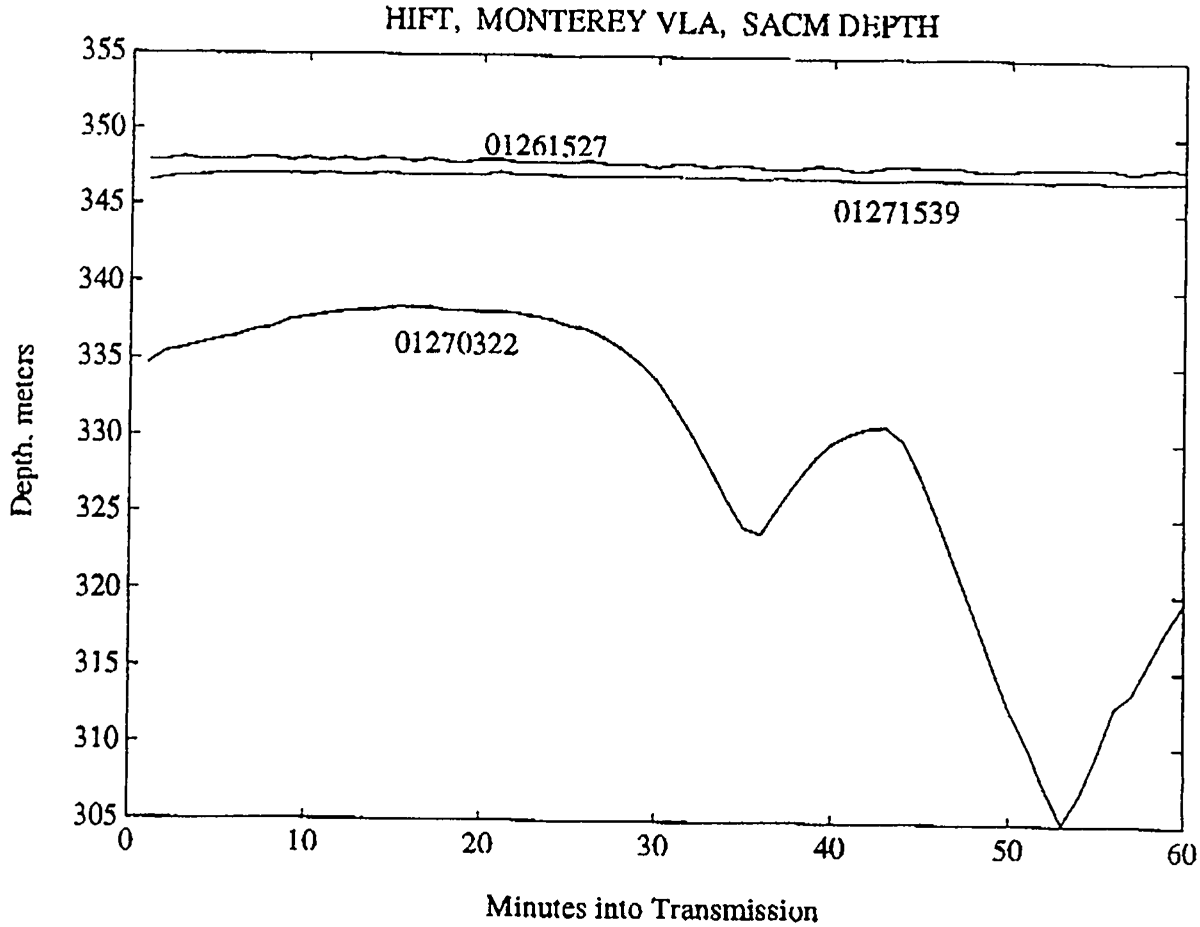

Mode shapes and sensor depths
MODESHAPE
(*10²)
-18.00 -16.20 -14.40 -12.60 -10.80 -9.00 -7.20 -5.40 -3.60 -1.80 -.00
.00 1.00 2.00 3.00 4.00 5.00 6.00 7.00 8.00 9.00 10.00 11.00
FREQ= 57.0

FIGURE 4


HIFT, MONTEREY VLA, SACM DEPTH
Depth, meters
355
350
345
340
335
330
325
320
315
310
305
01261527
01271539
01270322
0
10
20
30
40
50
60
Minutes into Transmission

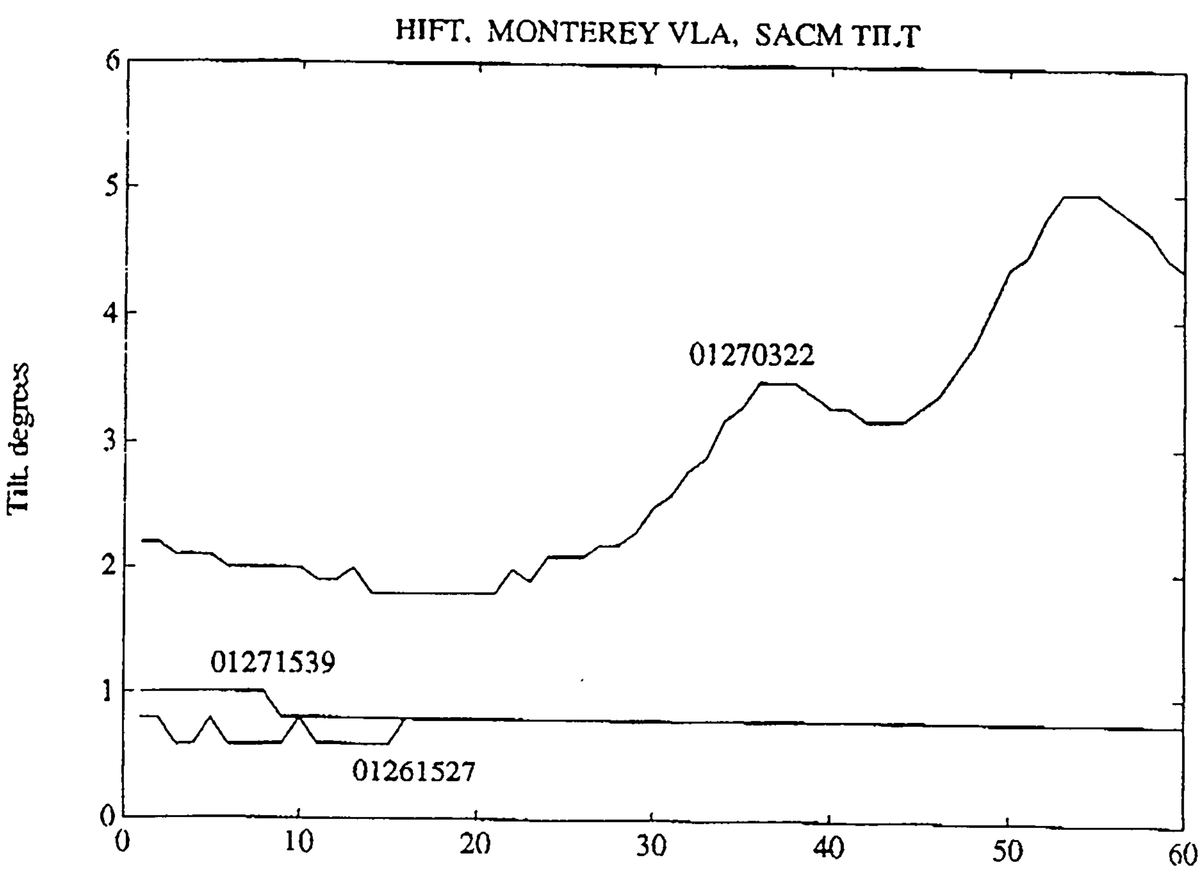

HIFT, MONTEREY VLA, SACM TILT
Tilt, degrees
6
5
4
3
2
1
0
01270322
01271539
01261527
0
10
20
30
40
50
60

FIGURE 5

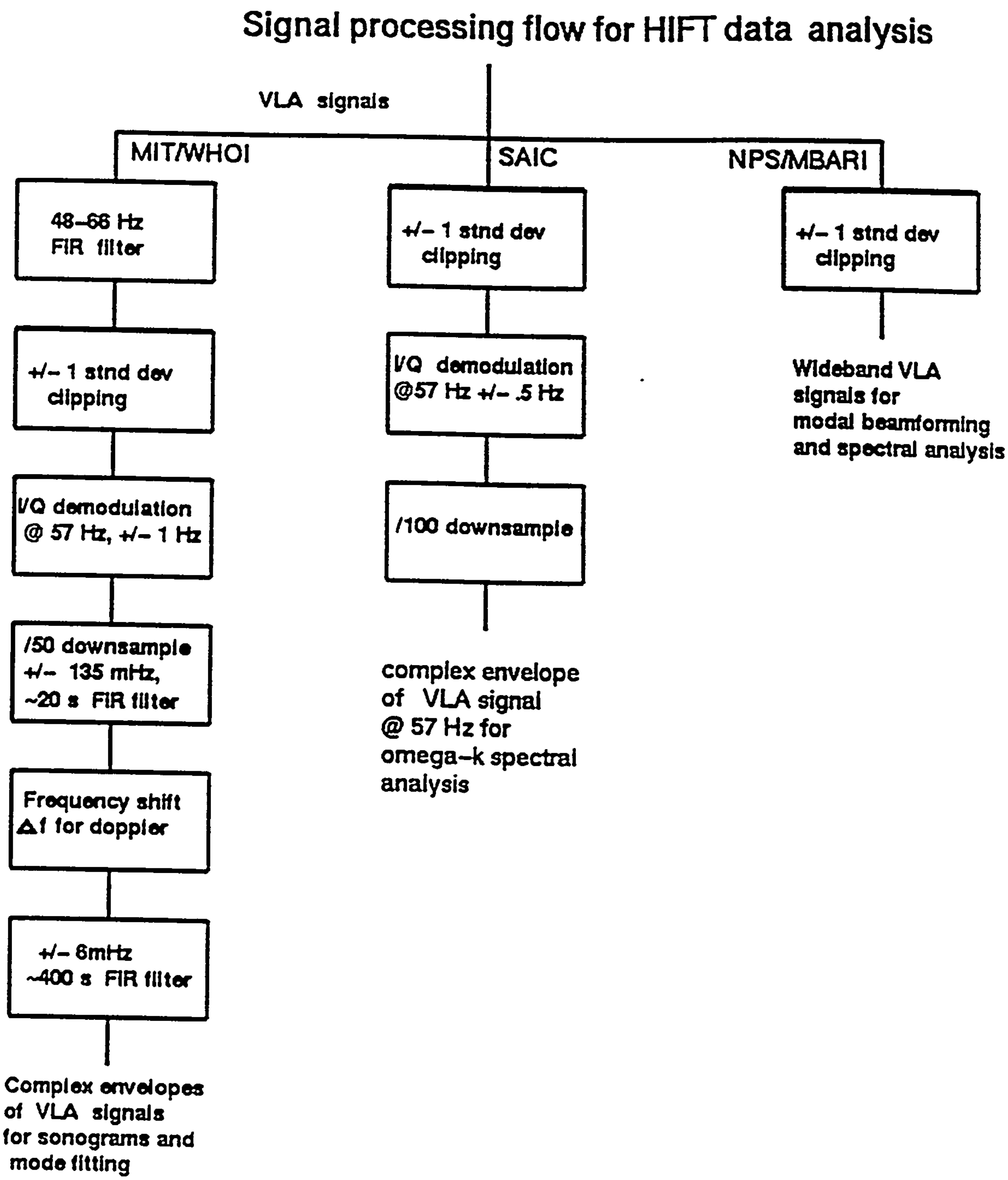
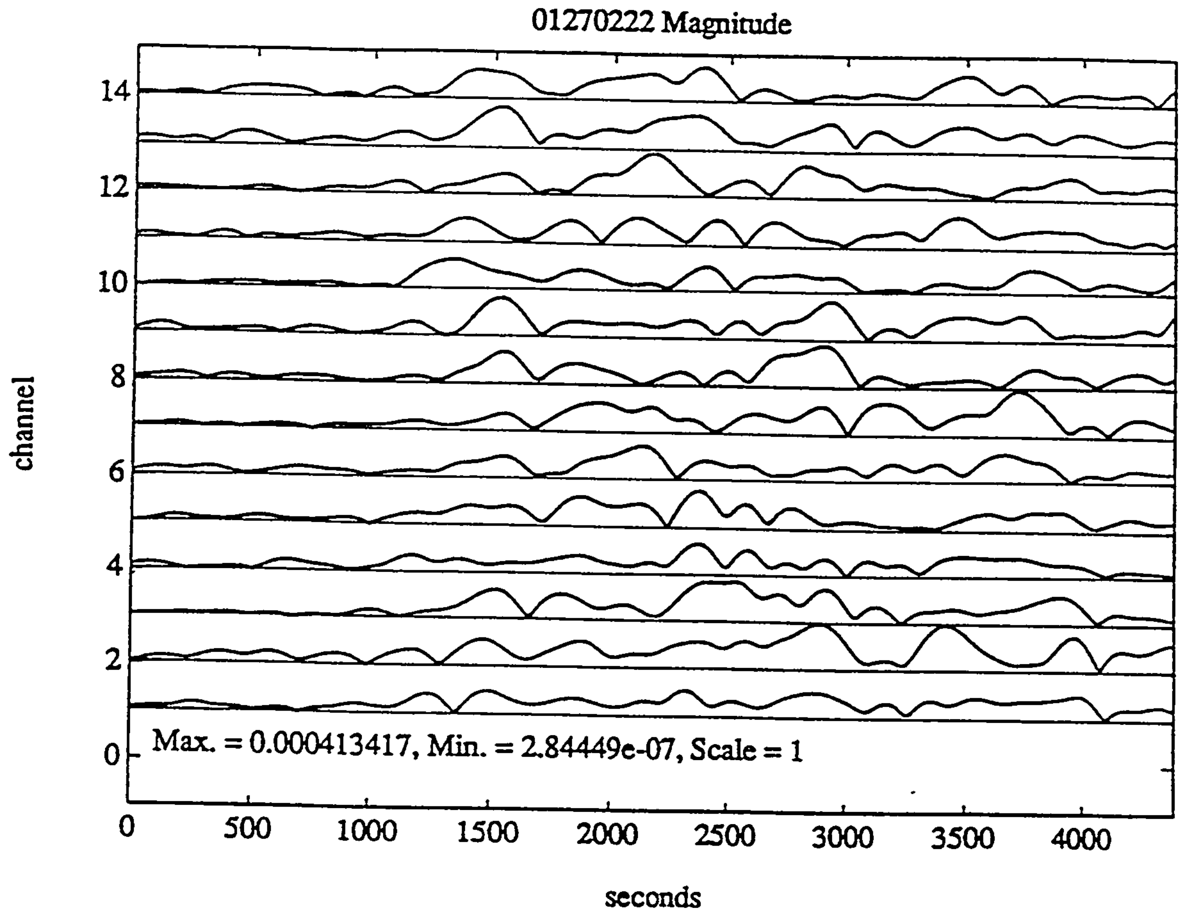

Signal processing flow for HIFT data analysis
VLA signals
MIT/WHOI
SAIC
NPS/MBARI
48–66 Hz FIR filter
+/– 1 stnd dev clipping
I/Q demodulation @ 57 Hz, +/– 1 Hz
/50 downsample +/– 135 mHz, ~20 s FIR filter
Frequency shift Δf for doppler
+/– 6mHz ~400 s FIR filter
Complex envelopes of VLA signals for sonograms and mode fitting
+/– 1 stnd dev clipping
I/Q demodulation @57 Hz +/– .5 Hz
/100 downsample
complex envelope of VLA signal @ 57 Hz for omega–k spectral analysis
+/– 1 stnd dev clipping
Wideband VLA signals for modal beamforming and spectral analysis

FIGURE 6



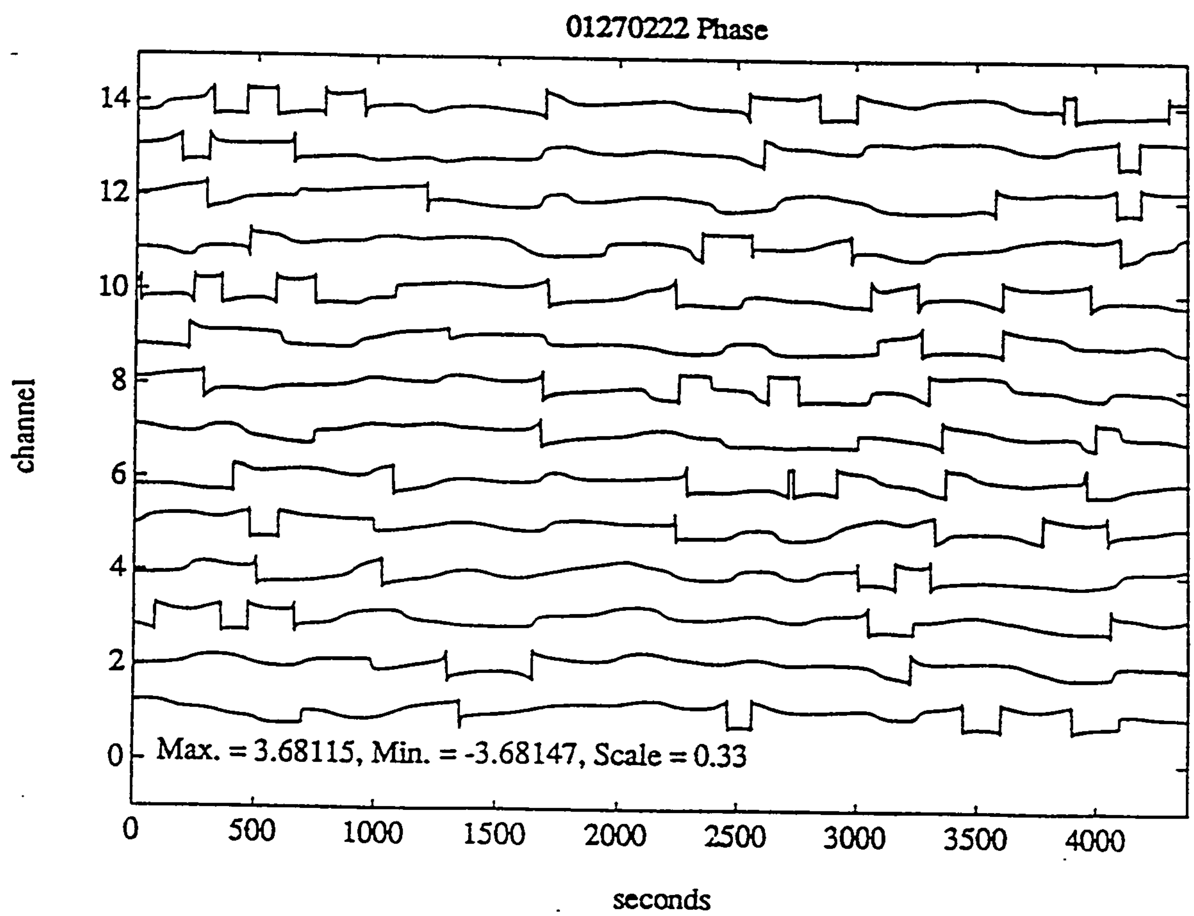


FIGURE 7

Signal transmitted on 1/27 at 00:00:00 GMT
Approximate arrival at 03:15:00 GMT (847 seconds in figure)

Transmission Event

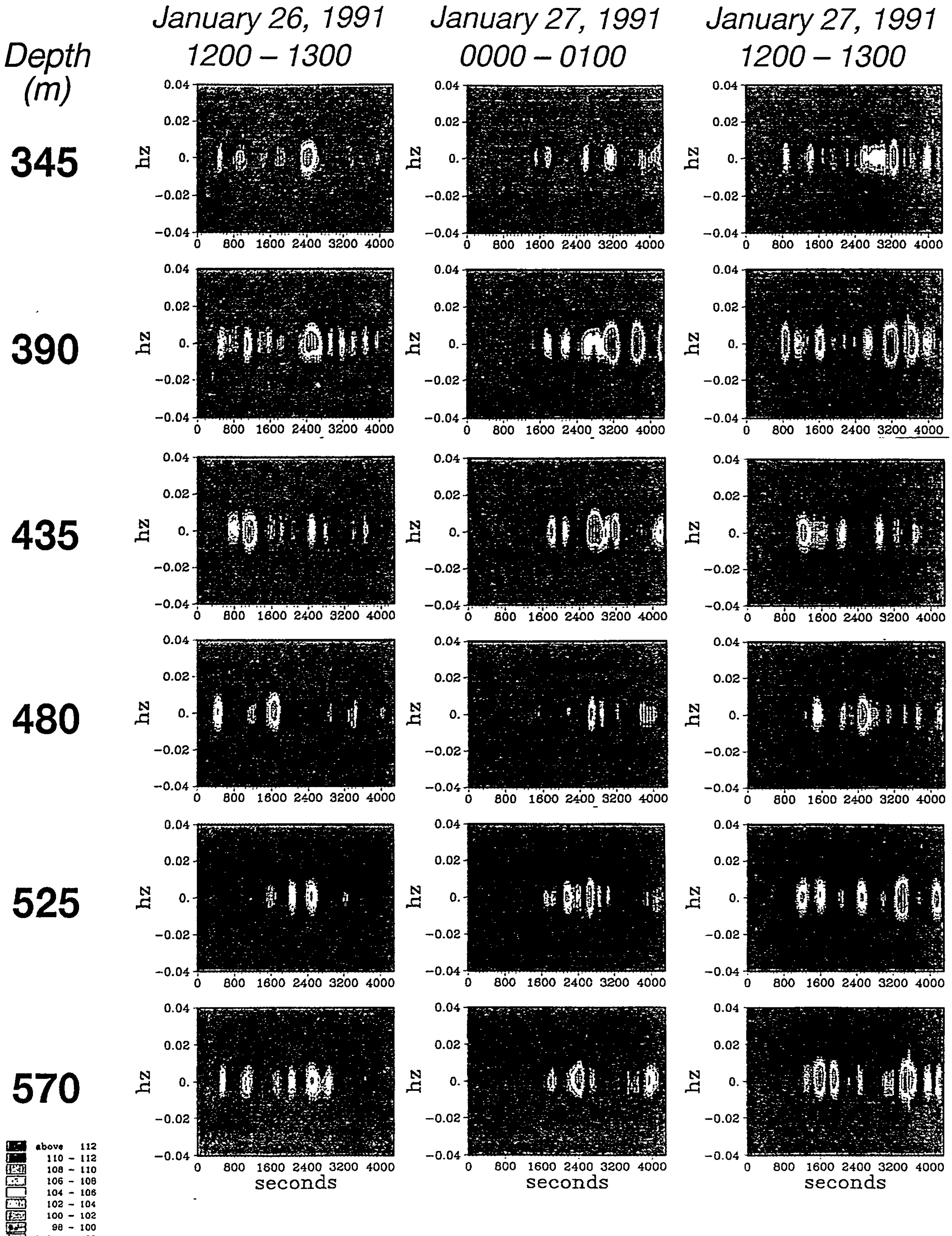


FIGURE 8a

Transmission Event

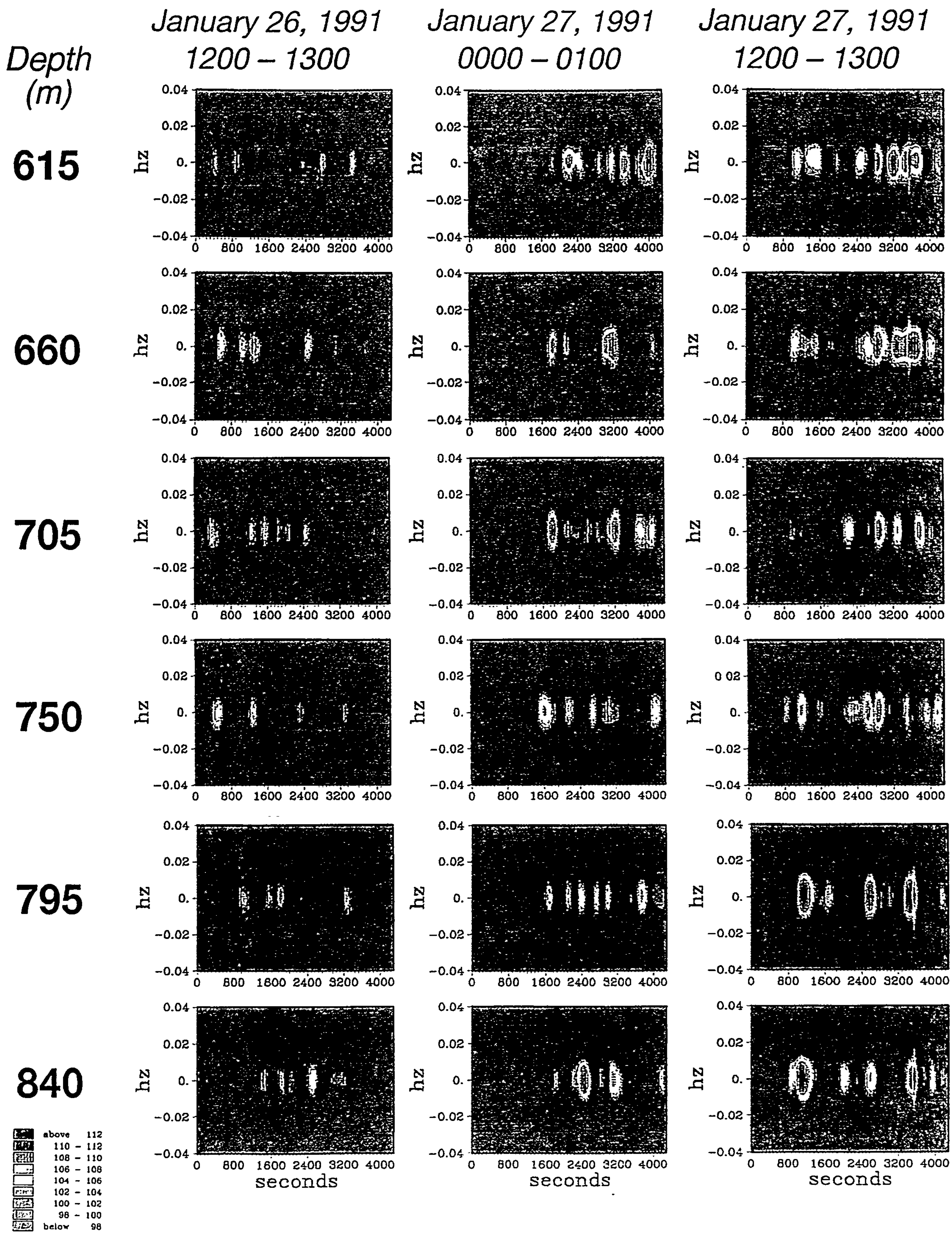


FIGURE 8b

Transmission Event

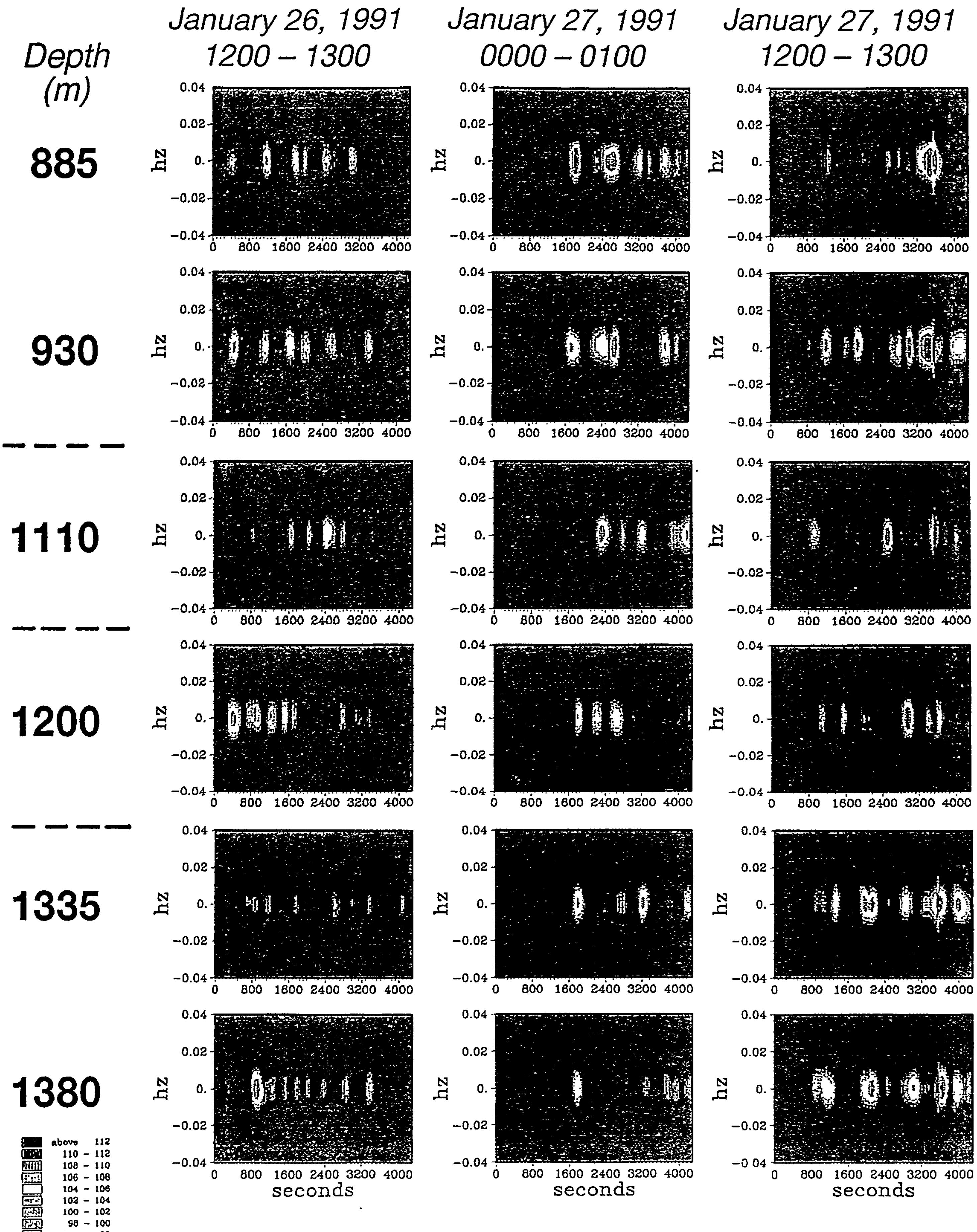


FIGURE 8c

Transmission Event

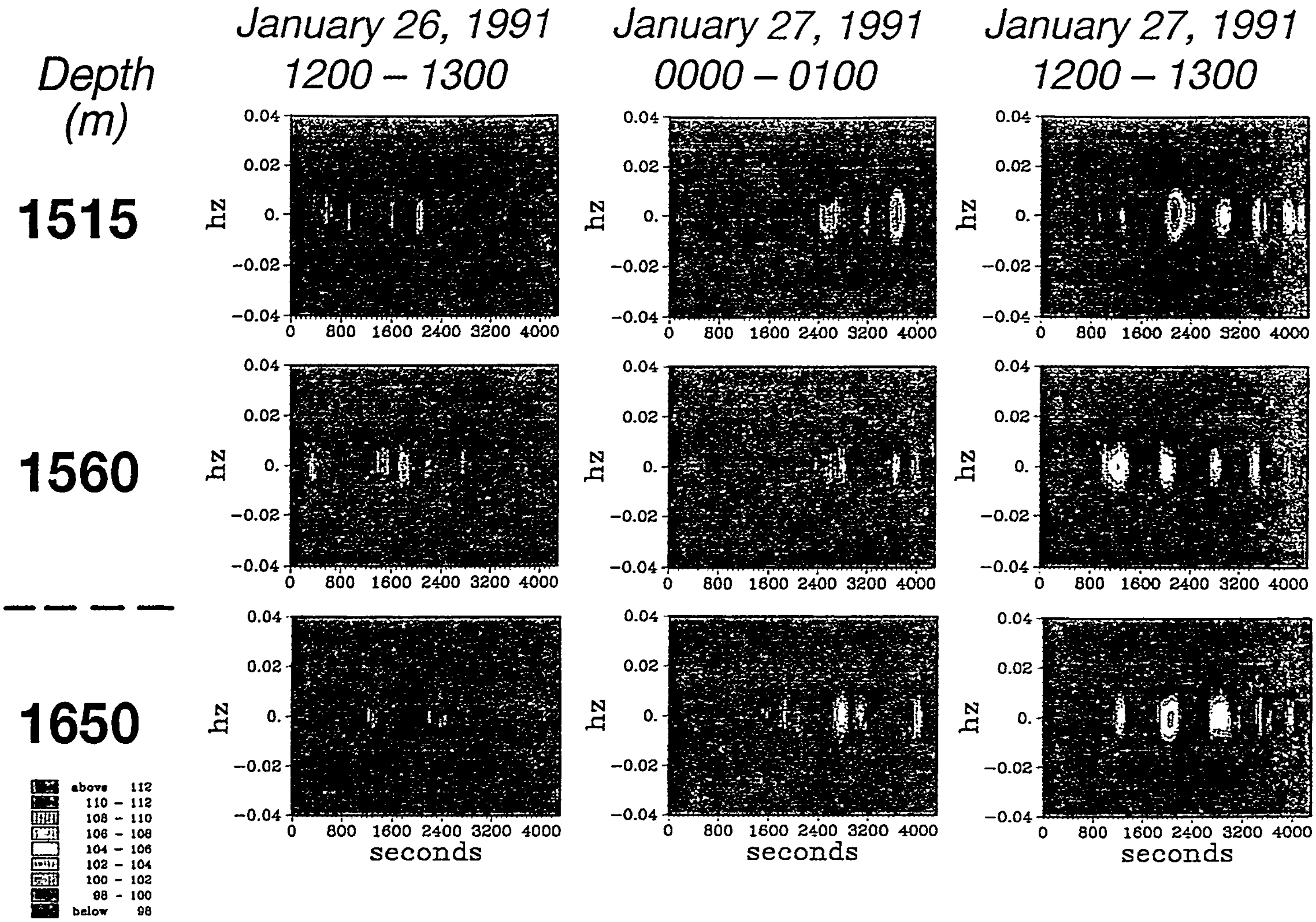


FIGURE 8d

K-F Heard Island 1/26/91 1527Z

Narrowband 21 Channels
Wavenumber vs. Frequency

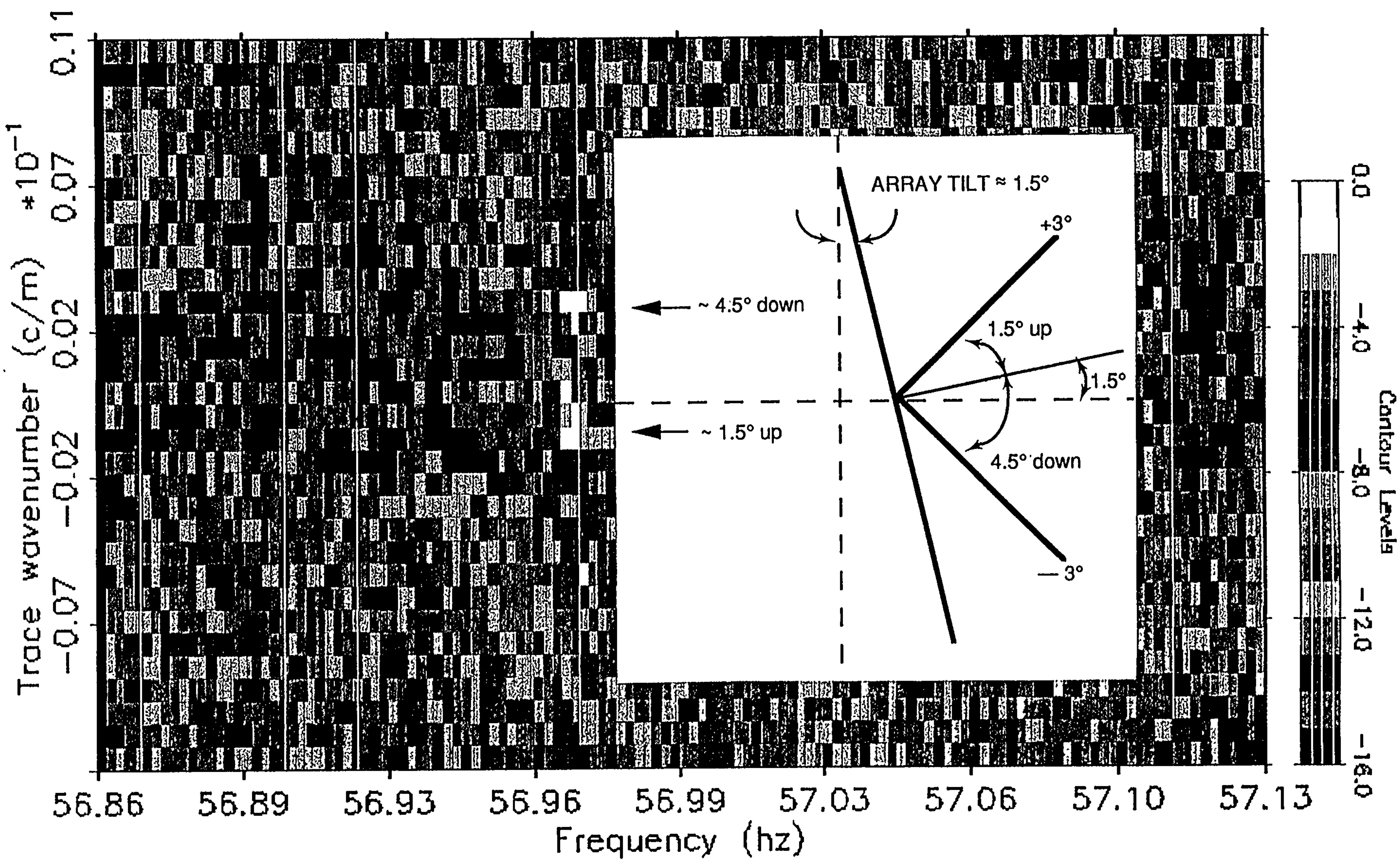


FIGURE 9a

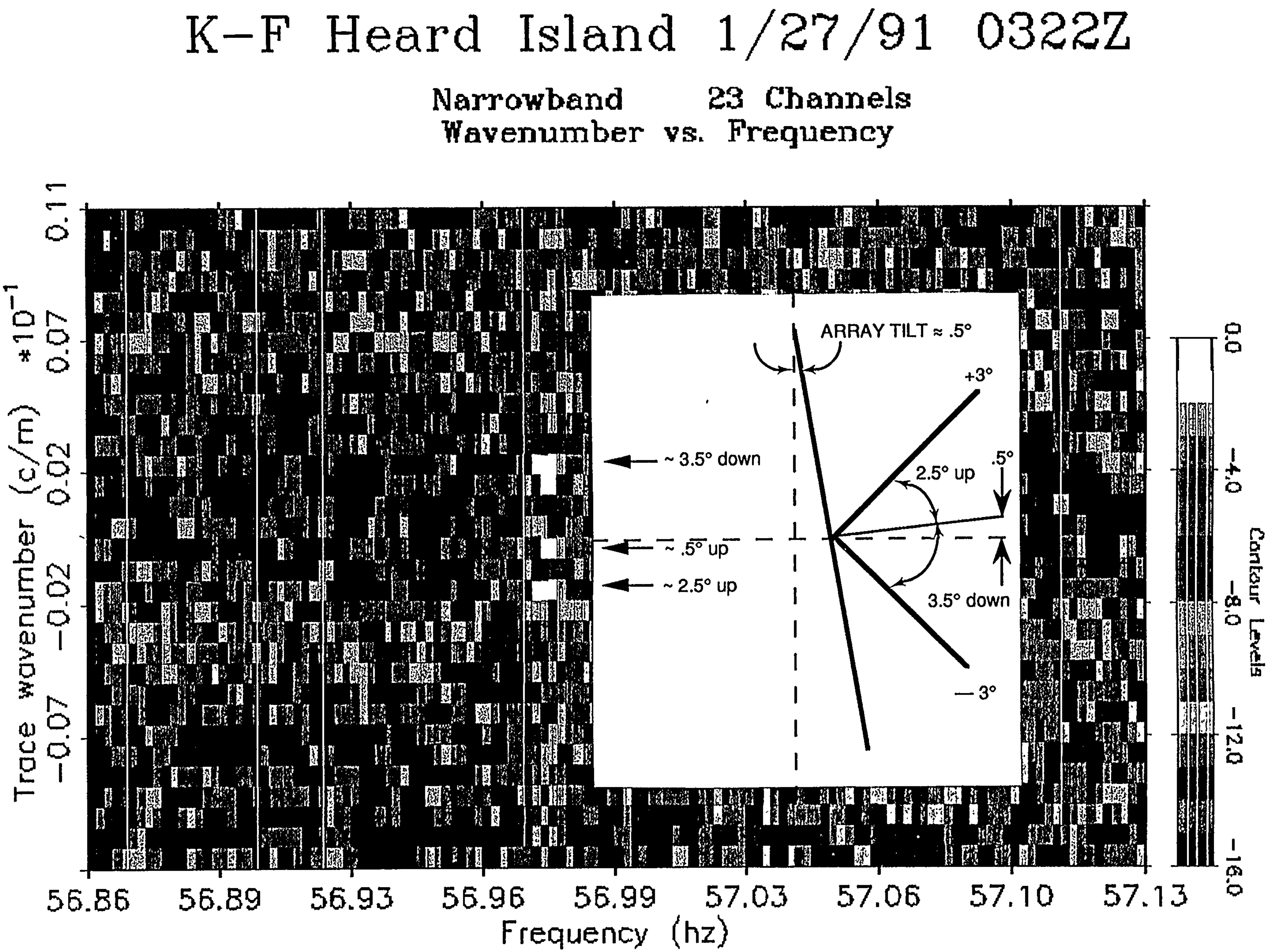

K-F Heard Island 1/27/91 0322Z
Narrowband 23 Channels
Wavenumber vs. Frequency
Trace wavenumber (c/m) *10⁻¹
0.11
0.07
0.02
-0.02
-0.07
Frequency (hz)
56.86
56.89
56.93
56.96
56.99
57.03
57.06
57.10
57.13
Contour Levels
0.0
-4.0
-8.0
-12.0
-16.0
ARRAY TILT ≈ .5°
+3°
.5°
2.5° up
3.5° down
— 3°
~ 3.5° down
~ .5° up
~ 2.5° up

FIGURE 9b

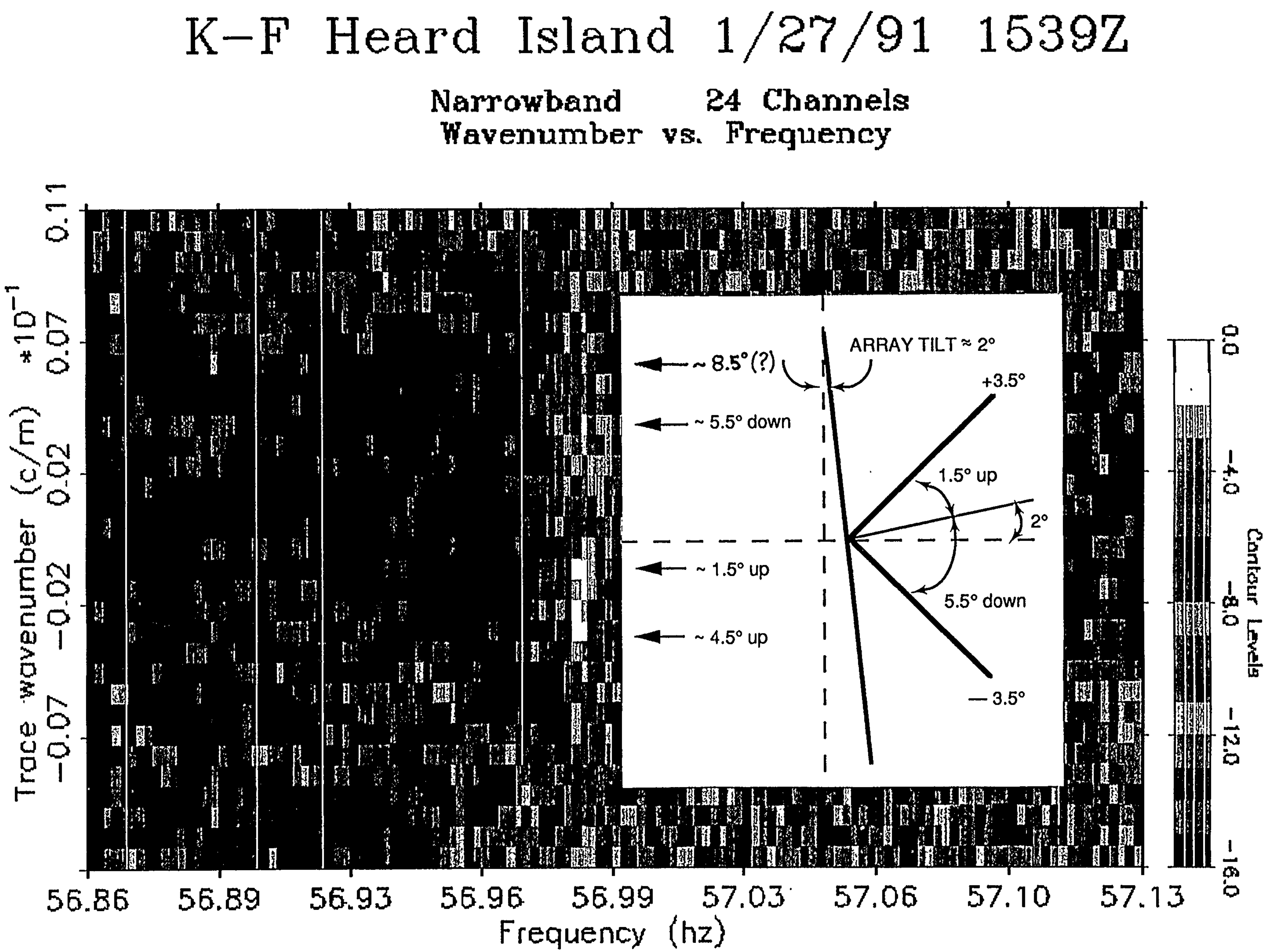
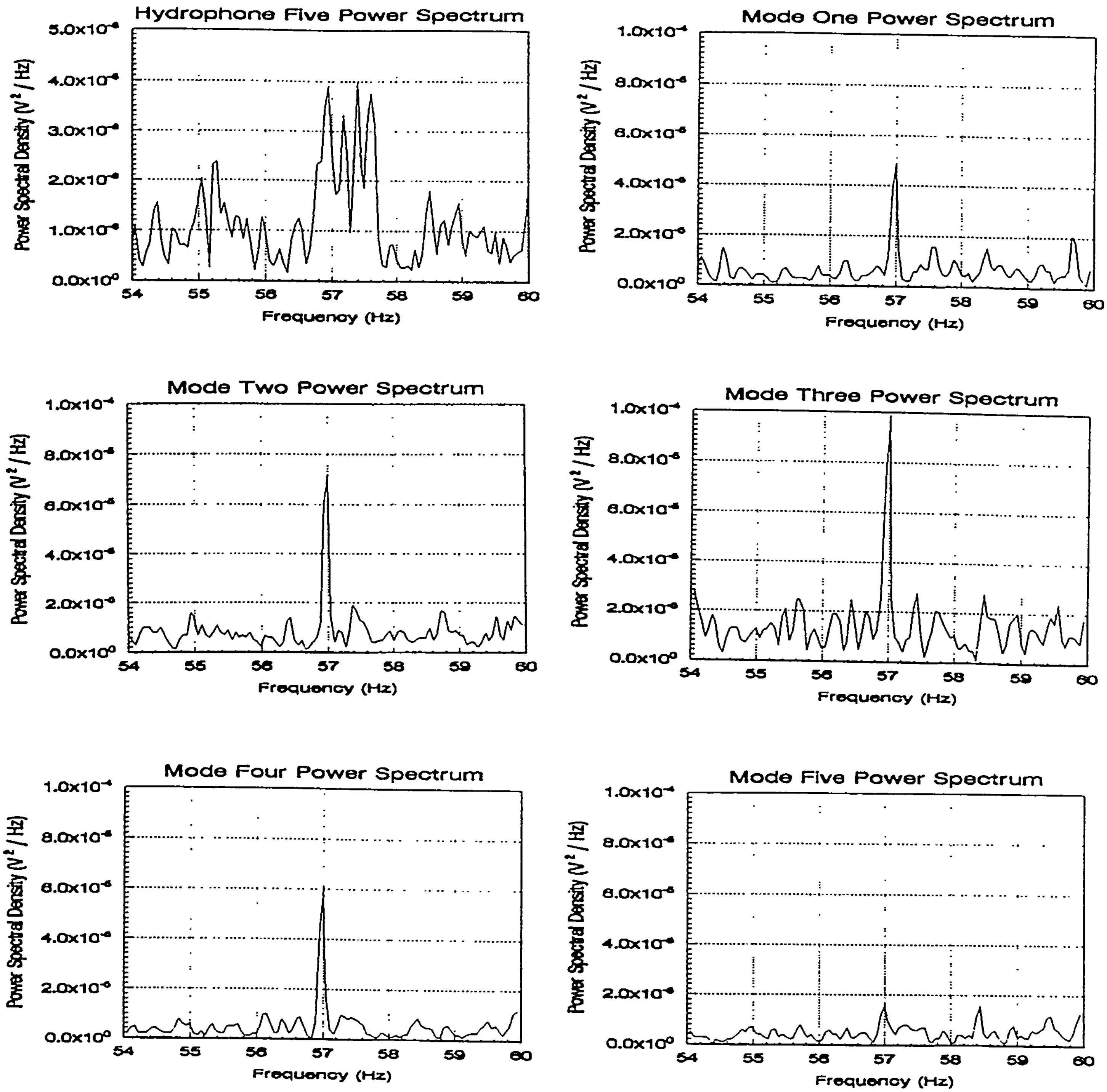

K-F Heard Island 1/27/91 1539Z
Narrowband 24 Channels
Wavenumber vs. Frequency
Trace wavenumber (c/m) *10^-1
0.11
0.07
0.02
-0.02
-0.07
Frequency (hz)
56.86
56.89
56.93
56.96
56.99
57.03
57.06
57.10
57.13
Contour Levels
0.0
-4.0
-8.0
-12.0
-16.0
ARRAY TILT ≈ 2°
~ 8.5°(?)
~ 5.5° down
~ 1.5° up
~ 4.5° up
+3.5°
1.5° up
2°
5.5° down
— 3.5°

FIGURE 9c



Hydrophone Five Power Spectrum
Mode One Power Spectrum
Mode Two Power Spectrum
Mode Three Power Spectrum
Mode Four Power Spectrum
Mode Five Power Spectrum
Power Spectral Density (V² / Hz)
Frequency (Hz)

FIGURE 10

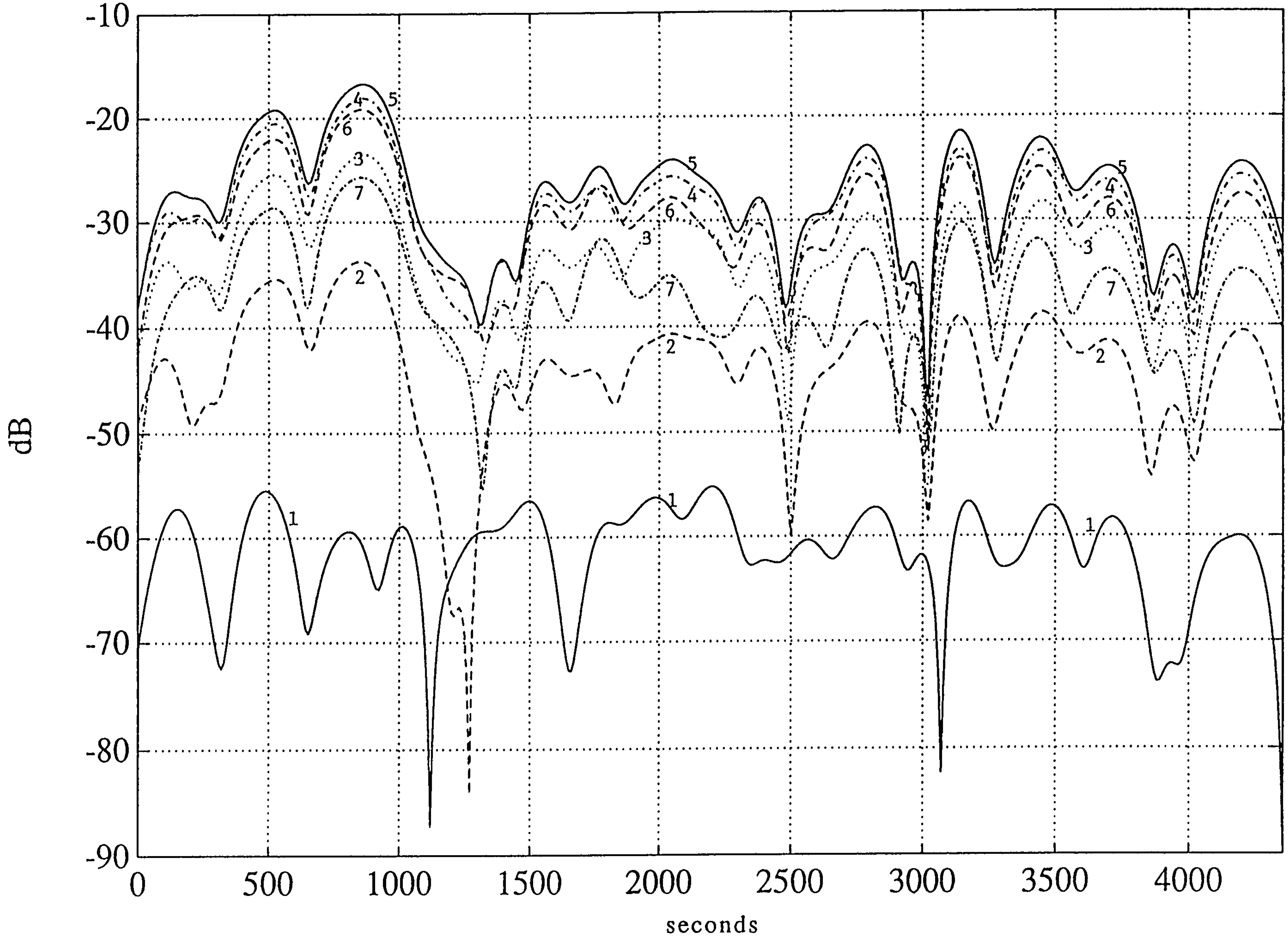


FIGURE 11a

Data set 01261525 (transmitted 1/26 1200)
Signal arrival 770 seconds prior to time 0 in figure.
Mode Coefficients for Modes 1-7

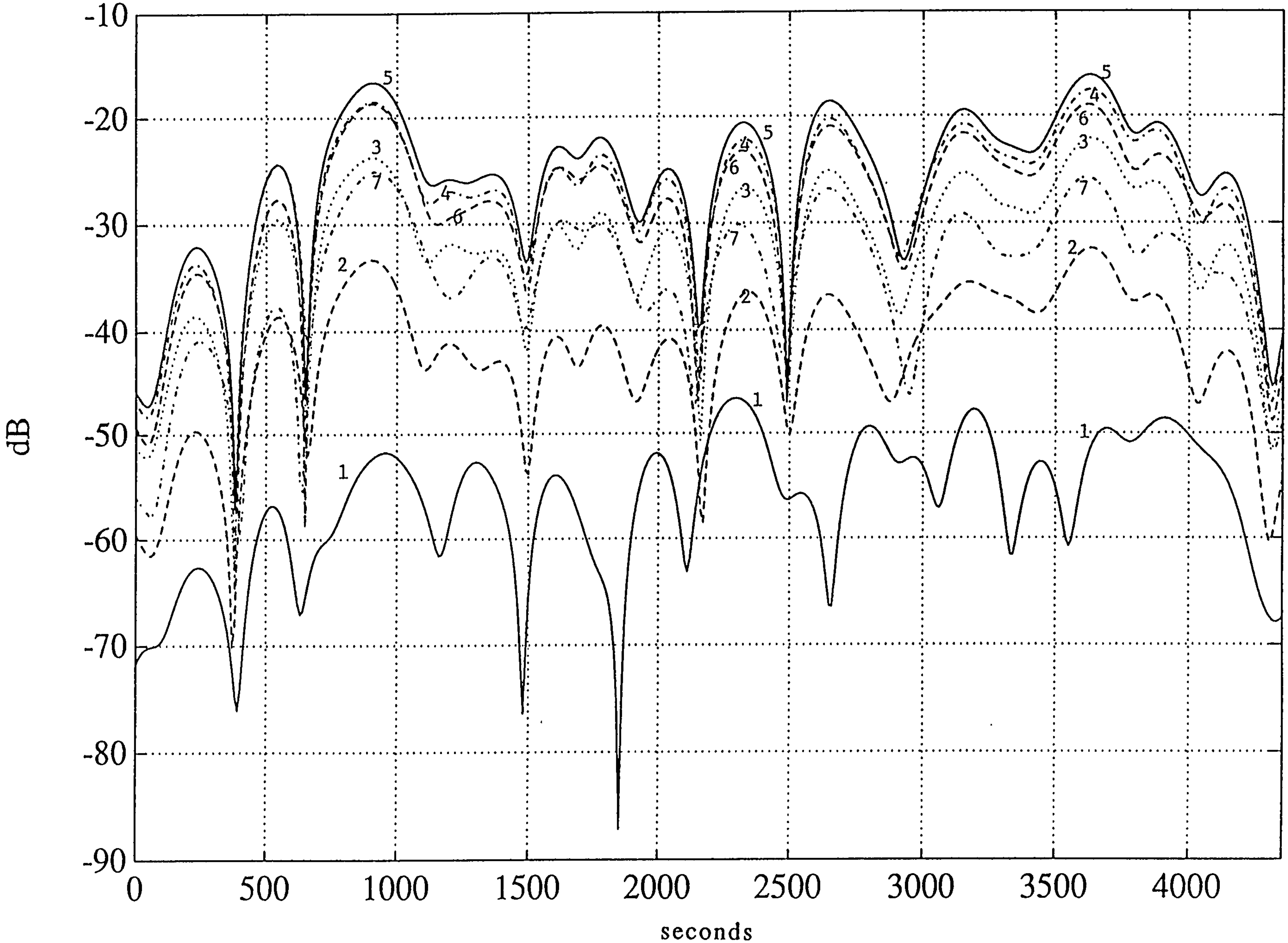


FIGURE 11b

Data set 01271505 (transmitted 1/27 1200)
Signal arrival at 170 seconds.
Mode Coefficients for Modes 1-7

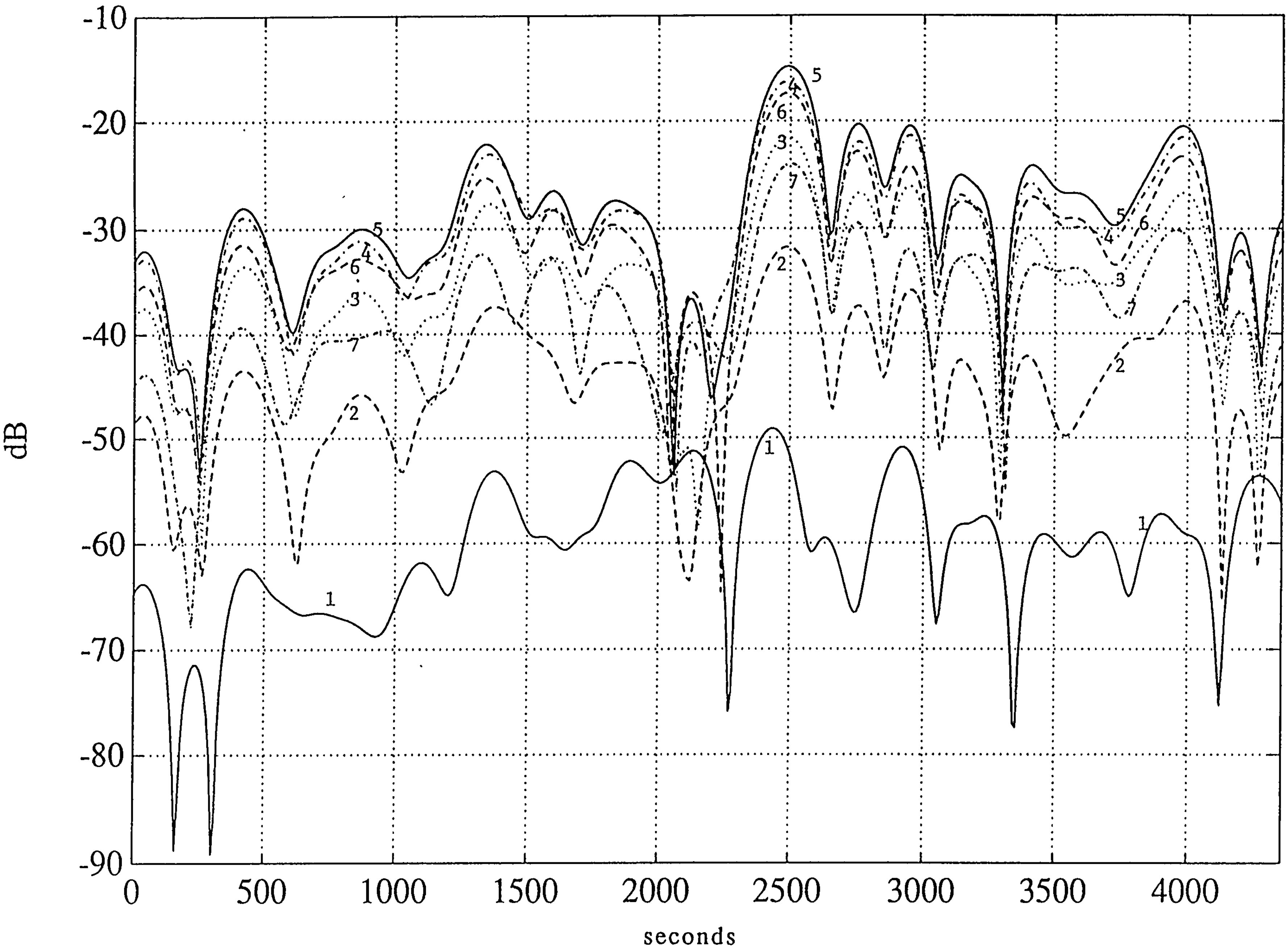
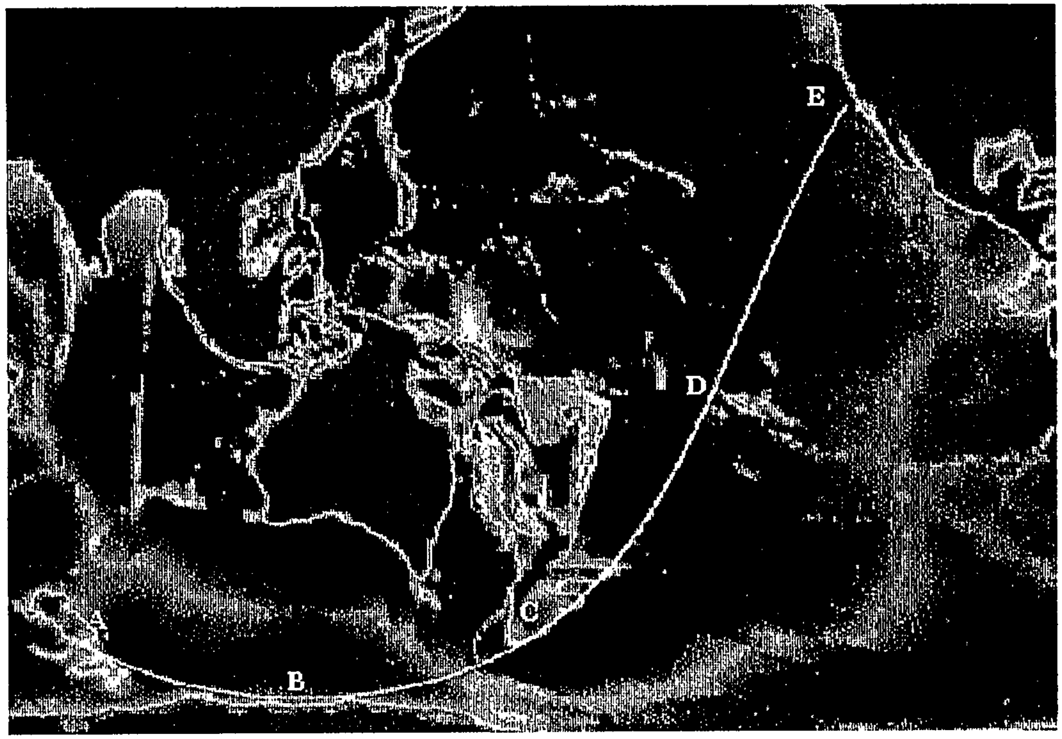


FIGURE 11c

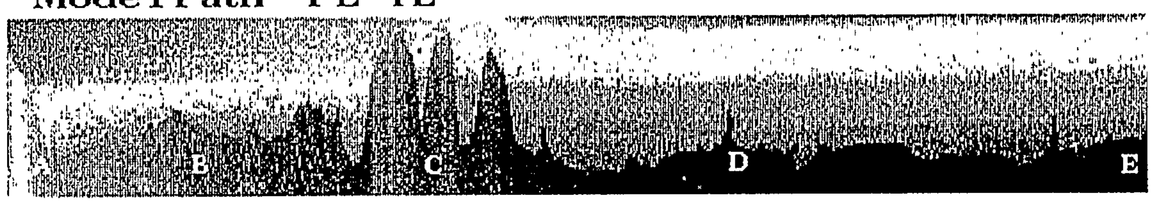
Data set 01270222 (transmitted 1/27 0000)
Signal arrival at 740 seconds.
Mode Coefficients for Modes 1-7

Heard Island – California
PE Calculation
Point Source Excitation

Mode 1 Path



Mode 1 Path PE TL



Modal Excitation vs Range

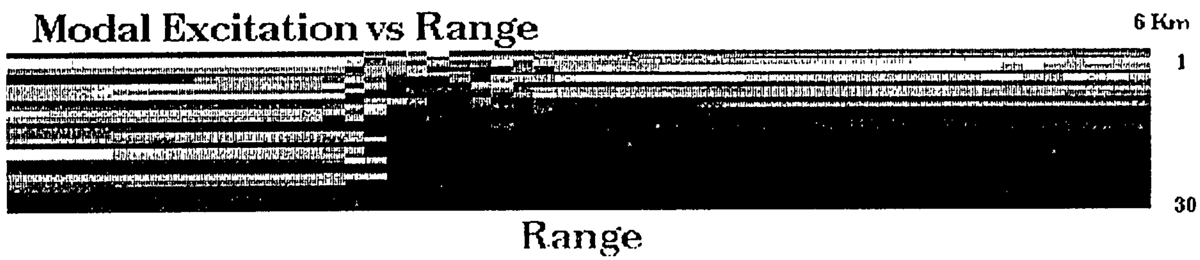


FIGURE 12

R92-16
April 1991

BERMUDA GLOBAL WARMING ARRAY

RECOVERY REPORT

Prepared by

Science Applications International Corporation
MariPro Operation
1522 Cook Place
Goleta, CA 93117

TABLE OF CONTENTS

LIST OF FIGURES

1.0 INTRODUCTION

The purpose of this report is to document the efforts to date (26 March 1991) required to recover the Heard Island acoustic array and associated hardware.

2.0 BACKGROUND

The global warming (Heard Island) array was deployed using the Bermuda Biological Station for Research (BBSR) vessel R/V WEATHERBIRD II on 28 January 1991. At deployment the position was approximately 32^0 00.49'N and 64^0 04.27'W in a water depth of approximately 4,460 meters (14,630 feet). After completion of the Heard Island experiment the array was released from its mooring. The releases appeared to be functioning properly and seemed to release as commanded but the floats never appeared on the surface. Upon further acoustic ranging it was determined that the releases were tethered to the bottom as shown in Figure 2.0-1 at a height of approximately 1,500 meters (5,000) feet from the bottom (3,000 meters from the surface). As indicated in the figure most of the array hardware was believed to be somewhat stretched out on the bottom.

The main purpose of this recovery exercise was to recover the data from the recording device. The array and associated hardware, while important, were considered to be of secondary priority for this effort.

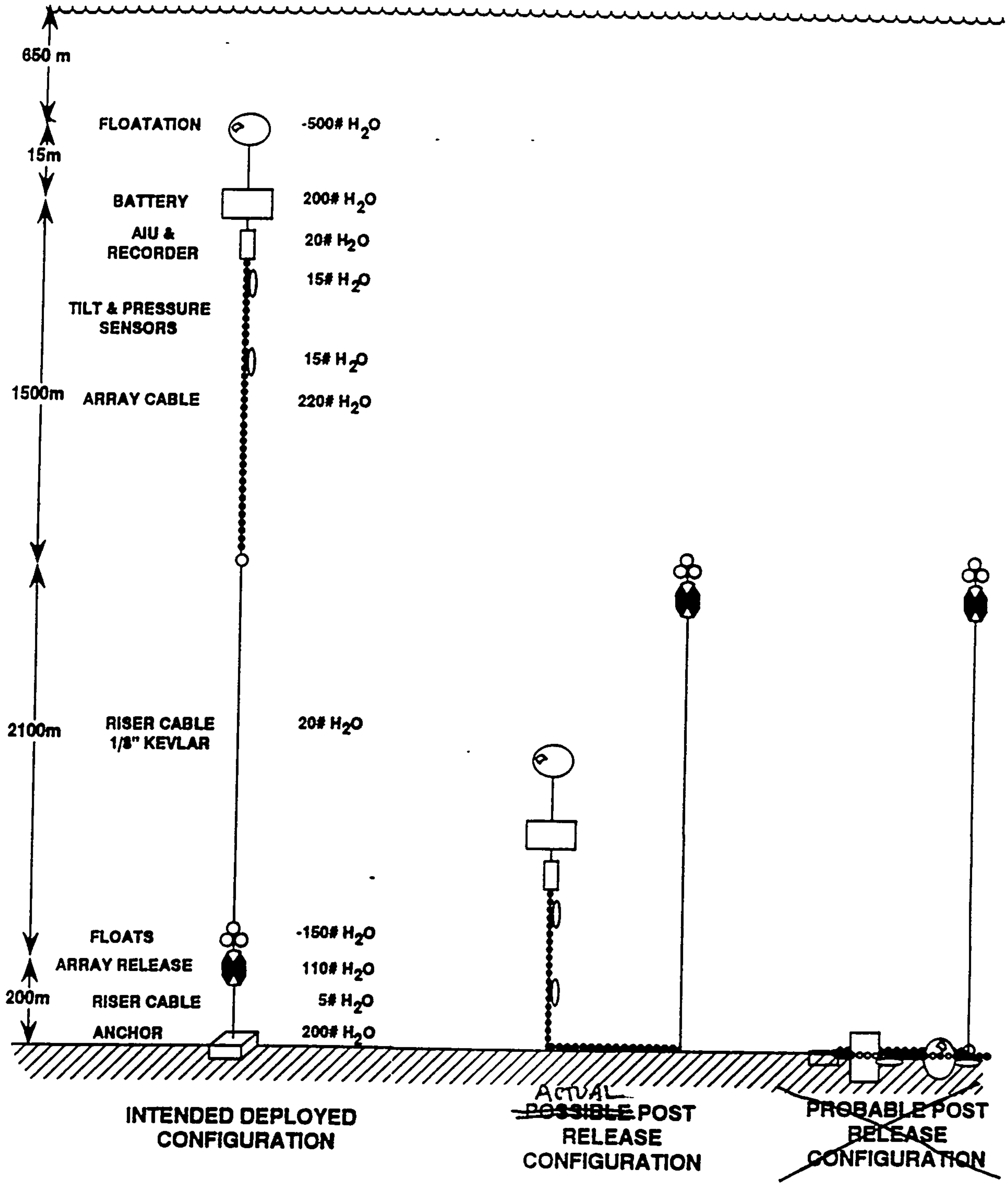
3.0 MOBILIZATION

The following hardware (a detailed list is contained in Appendix "B") was obtained and shipped to the BBSR:

1. Winch, grappling gear and associated hardware shipped from SAIC/MariPro.

2. 25K feet (7,620 meters) of 1/4 inch kevlar shipped from the manufactures distributor.

The tracking system, INS system and Benthos equipment were all hand carried to the BBSR. Due to a work slowdown at the Bermuda dock the winch and kevlar was not delivered to the BBSR until Monday 18 March. A Friday delivery of the equipment would have enabled mobilization that would have allowed the weekend to be spent at sea performing recovery operations. (Even if all the equipment had been loaded the weather conditions on Saturday and Sunday would have made recovery operations difficult). Upon delivery of all equipment the winch was mounted in place, the Trackpoint mount was welded in place and the kevlar was wound onto the winch. The INS system was checked out and interfaced as required. All grappling hardware was assembled and rigged prior to departure.



HEARD ISLAND BDA ARRAY CONFIGURATION

FIGURE 2.0-1

4.0 RECOVERY EXERCISE

Two sperate sea trips were made in attempting to recover SAIC's Heard Island array (Appendix "A" is a summary of the recovery exercise daily log). The first trip was on Monday and Tuesday, 18 and 19 March 1991. The location of the releases indicated after the last recovery attempt did not appear accurate. The ships crew had taken further Benthos readings on subsequent cruises and had obtained a new position which (after ranging with the deck box) turned out to be more accurate. The R/V WEATHERBIRD II sailed to the updated known location of the acoustic releases and array, 32^0 00.49'N 64^0 04.27'W. The Benthos deck unit confirmed the slant range to the releases was approximately 3,000 meters, which agrees with the slant range as originally provided. The weather deteriorated constantly during this first effort and it was only possible to make one grappling run (run 1) in a SE to NW direction (as planned). Run 1 was not successful. Due to the weather, and vessel scheduling conflicts, the ship returned to BBSR on Tuesday afternoon.

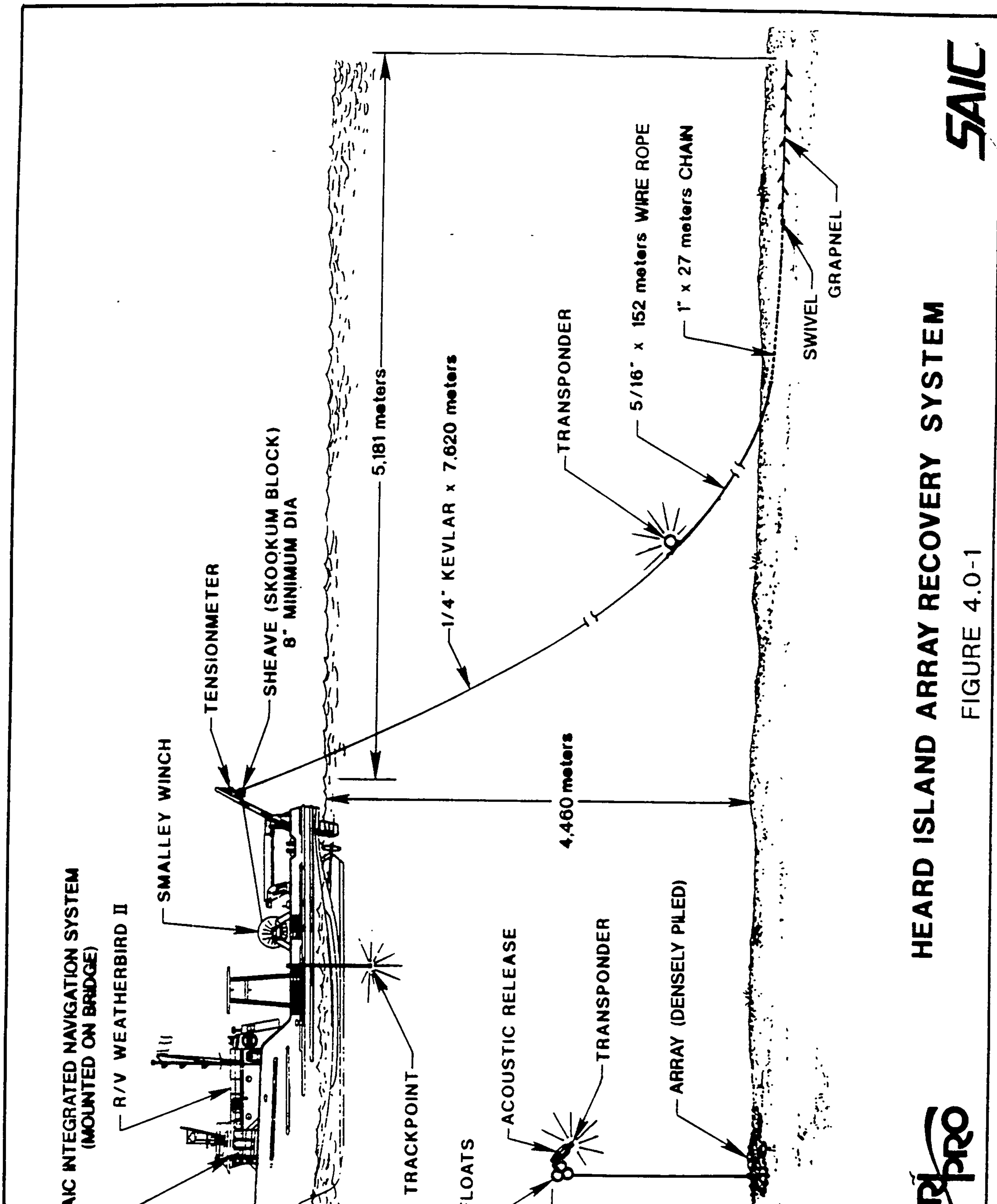
The second trip was made on Friday, Saturday, Sunday and Monday, 22 - 25 March 1991. The location of the releases and the array was pinpointed using the Benthos deck box and the INS system to obtain a hyperbolic fix. Several slant ranges and their respective geographic positions were obtained and fed into the INS system which then calculated an accurate release position (± 3 meters). Using this method, it was determined that the actual position of the releases was 32^0 00' 20.087"N and 64^0 04' 39.492"W. This position was 3,200 meters South of the previous position at a depth of 1,985 meters.

Figure 4.0-1 shows the new configuration of the array as well as the array recovery system. Run 2 was made in a NW to SE direction through the above position with negative results. The release position was re-checked and found to be: 32^0 00' 23.843"N and 64^0 04' 37.251"W (124 meters NNE of position 2). Run 3 was made through the position in a E to W direction, again, with negative results.

The release position was re-checked and found to be: 32^0 00' 19.243"N and 64^0 04' 38.299"W (41 meters SE of position 3). It is interesting to note that all the positions of the release lie along a basically N/S line within a few hundred meters.

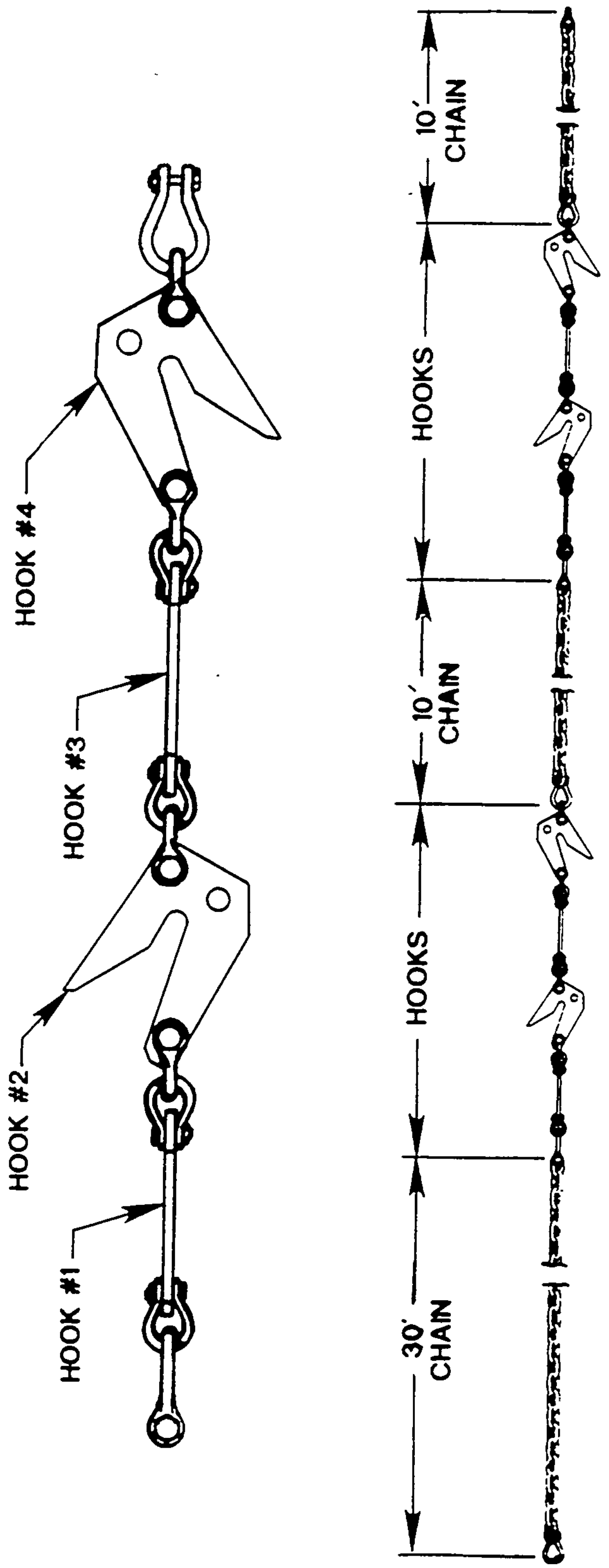
Prior to the start of the fourth run all the available hooks were added to the grapnel. This was done because it was thought that the 1-1/8" stud link chain may have been pushing the array into the bottom and the additional hooks would increase the probability of dragging the array out of the mud. While trying to deploy the grapnel for run number 4 the wire rope parted and all hooks were lost. Fortunately it was possible to fabricate a new grapnel system utilizing the spare length of stud link chain. Figure 4.0-2 is a detail of the original grapnel and Figure 4.0-3 is a detail of the grapnel fabricated while at sea. Figure 4.0-4 are photographs of both the original grapnel as well as the grapnel fabricated at sea.

Figure 4.0-5 are photographs of the winch used for the recovery exercise and the winch in operation at sea.



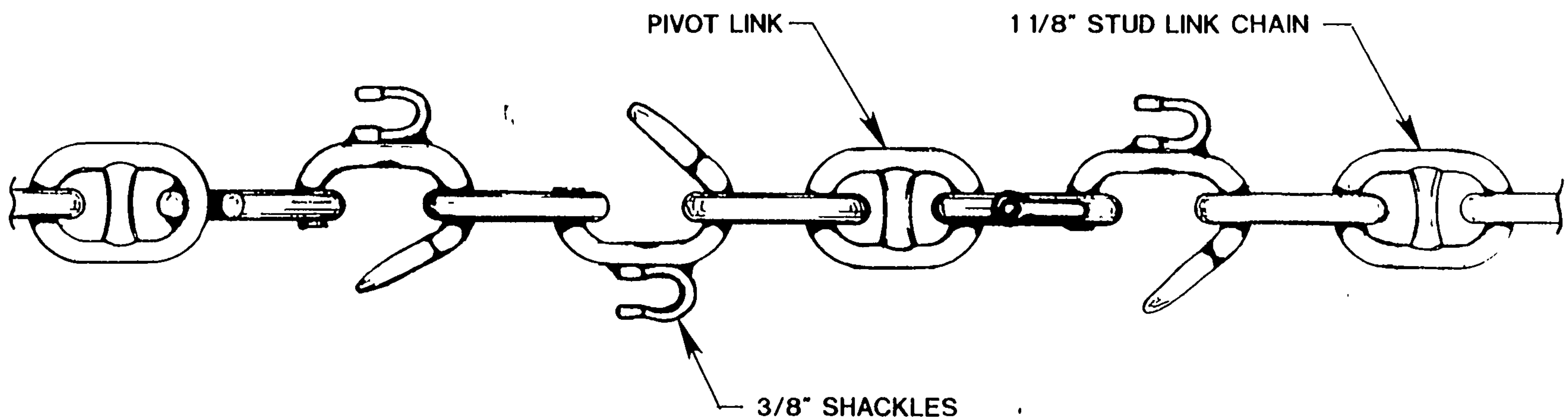
HEARD ISLAND ARRAY RECOVERY SYSTEM

FIGURE 4.0-1



GRAPPLING SYSTEM

FIGURE 4.0-2



GRAPNEL FABRICATED WHILE AT SEA

FIGURE 4.0-3

ORIGINAL GRAPNEL ON DECK PRIOR TO DEPLOYMENT

CONFIGURATION OF GRAPNEL FABRICATED WHILE AT SEA

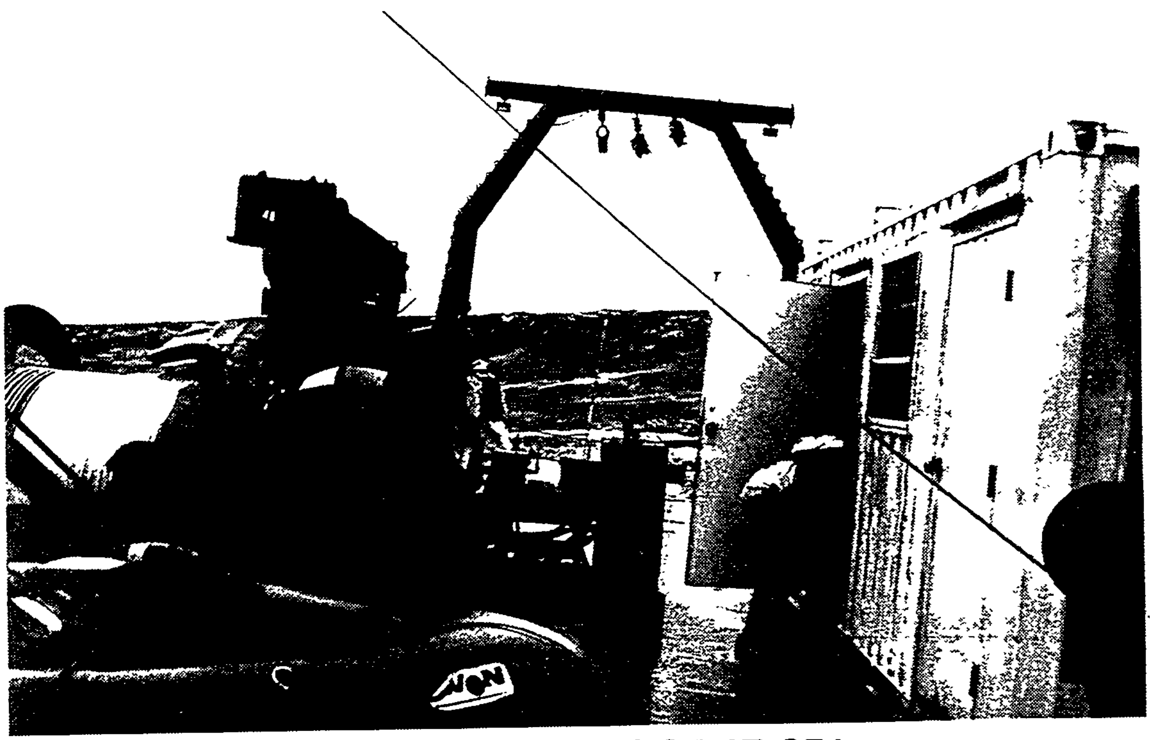
MARIPRO

GRAPNEL SYSTEMS

FIGURE 4.0-4

SAIC.

RECOVERY WINCH WITH 7,620 meters OF 1/4" KEVLAR
152 meters OF 5/16" WIRE ROPE AND 2 SHOTS
(54 meters) OF 1-1/8" STUD LINK CHAIN



GRAPPLING EXERCISE AT SEA
(ANOTHER NICE DAY IN BERMUDA)

MARIPRO

WINCH AND AT SEA OPERATIONS
FIGURE 4.0-5

SAIC

Run 4 was made in a ENE to WSW direction. Run 5 was made in a SSW to NNE direction, and run 6 was made in the opposite direction of run 5. All of these runs produced negative results. A re-check of the release position showed them at: 32^0 00' 21.825"N and 64^0 04' 39.231"W (185 meters N of position 4).

A final run (run 7) was made from E to W at a very slow, and difficult to control, speed. A positive "Hookup" was made to something, but was subsequently lost. A last re-check of the release position was 32^0 00' 19.899"N by 64^0 04' 37.152"W at a depth of 1985 meters.

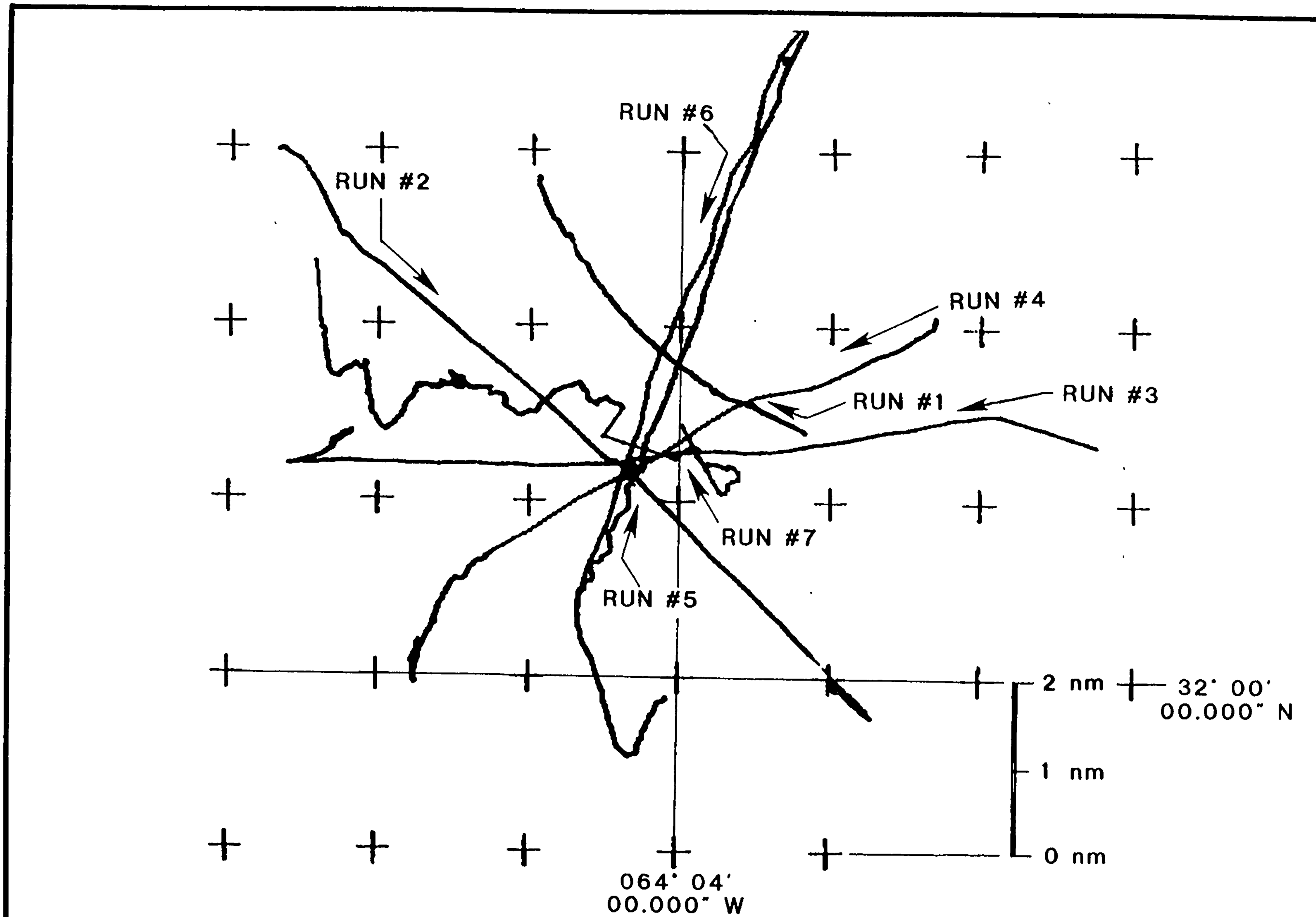
Figure 4.0-6 is a composite of the ship's track for the seven runs made during the recovery exercise. After several of the runs, the location procedure was repeated to insure that the releases and array had not been disturbed during that particular recovery attempt. It is felt that a sufficient number of runs were made in the array location that if the array were stretched out as originally thought the grapnel would have hooked it. Due to the condition of the grapnel upon each recovery (hooks polished and covered with mud in spots) it was determined that the grapnel was on the bottom. Given this information it is thought that the array must be in a small pile on the bottom.

5.0 CONCLUSIONS

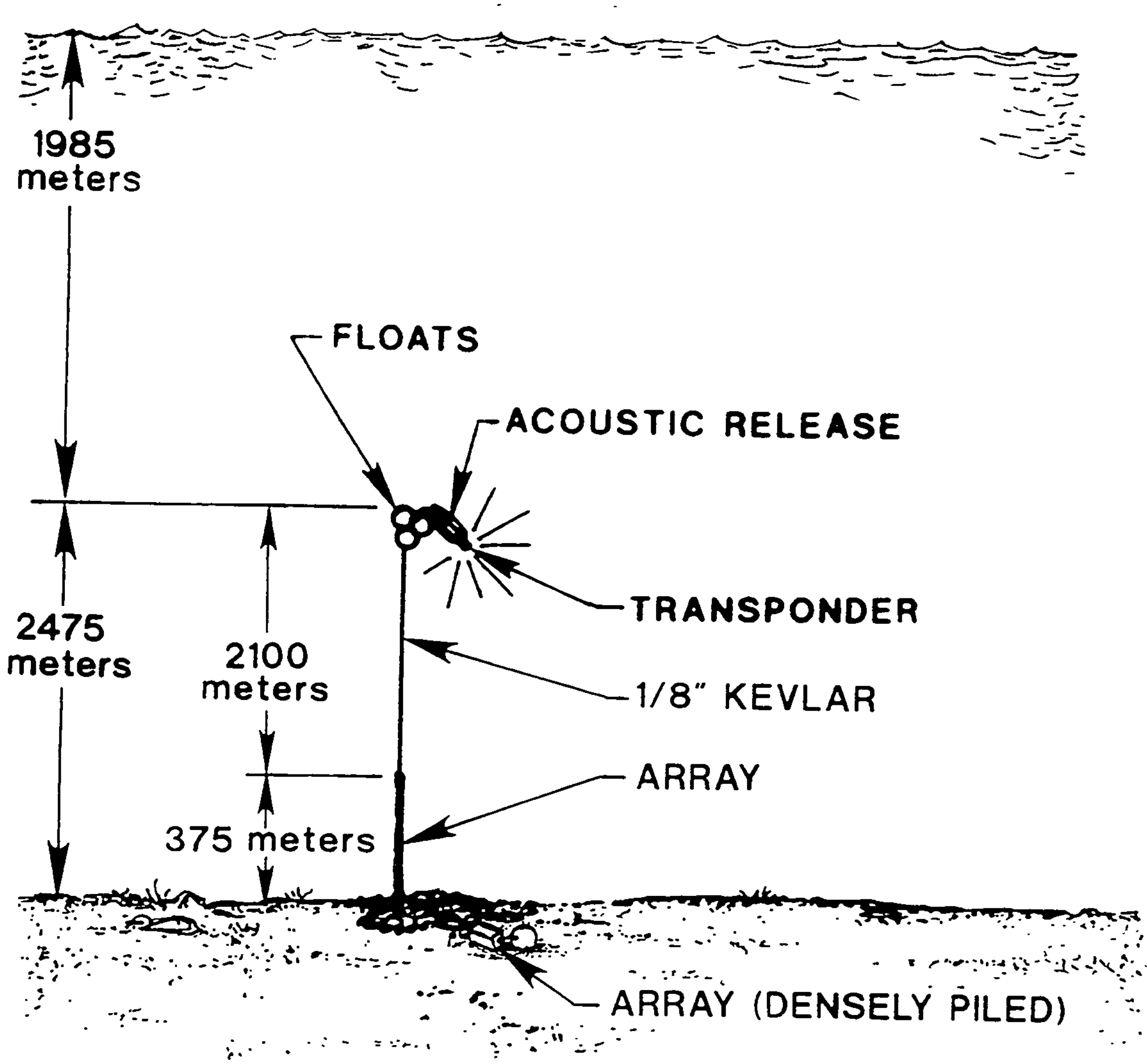
It is the opinion of the SAIC/MariPro participants in this recovery attempt that when the array was first installed, it sank directly to the bottom as soon as the safety float on the surface was punctured. This resulted in the array being concentrated in a small area around the anchor and not stretched out as originally thought. Figure 5.0-1 indicates the probable array position on the bottom.

When the acoustic releases were triggered for recovery, they ascended toward the surface until the added accumulated load of the 1/8" kevlar and the array matched the reserve buoyancy of the release's flotation. This depth was originally reported as 1,500 meters off the bottom (3,000 meters from the surface). As a result of actual measurement with the Benthos deck box it has subsequently been determined that the releases had ascended to approximately 2,500 meters off the bottom (1,985 meters below the surface). The new position of the releases and the array is 32^0 00' 19.899"N and 64^0 04' 37.152"W ($\pm$ 0.91 meters).

During run #2 and #7 tension increased on the tension meter and solid "pulses" in the kevlar indicated a positive "hook-up" to something on the bottom, but when the hooks were recovered, they were empty. Speed is a critical factor to the grappling exercise. Due to the local weather conditions the speeds utilized were as low as possible, however, they may not have been slow enough. Also the weather conditions did not allow for optimum Trackpoint performance. The grapnel transponder and the releases could not be adequately tracked simultaneously to provide a clear "picture" of their relative positions to one another. Once the grapnel transponder was out of the 45^0 cone tracking all but disappeared. The releases could only be intermittently tracked when the vessel was directly over them.



SHIPS TRACK,GRAPPLING RUNS 1-7
HEARD ISLAND ARRAY RECOVERY OPERATIONS
3/19/91 - 3/24/91
FIGURE 4.0-6



ACTUAL POST RELEASE CONFIGURATION

FIGURE 5.0-1

6.0 RECOMMENDATIONS

If another attempt is made to recover the Heard Island array it is the opinion of SAIC/Maripro that the following changes and improvements to the procedure and equipment should be effected.

The Trackpoint system performance was less that expected as it was configured. In order to get useful tracking data from the XT6000s at ranges in excess of 3,000 meters, a higher output beacon must be obtained. This is the best way to go and past experience with increasing transponder source levels for the Trackpoint system has greatly improved range capabilities. The depth of the Trackpoint hydrophone needs to be increased by 3 or 4 meters to get it further away from surface/ship noise.

The number and configuration of grapnel hooks needs to be increased. It is felt that 1 shot of 1" or larger chain with an in water weight of approximately 1,000 - 1,500 pounds will keep the weight of the system to acceptable levels as well as provide sufficient grapnel performance.

Decreasing the scope of the grapnel to approximately 6,400 meters and keeping the vessel speed at .5 to 1 knot will help to keep the grapnel transponder in the 45^0 cone as well as provide greater feedback when something is hooked.

At the conclusion of this recovery effort it was felt that with one more day the system could have been recovered. If the above changes are made it is the opinion of SAIC/MariPro that there is a good possibility that Heard Island array could be recovered. The vessel is presently available the last week in August should another attempt be made.

APPENDIX "A"

RECOVERY EXERCISE DAILY LOG

MONDAY 18 MARCH (Weather: 10 - 15 foot seas wind up to 40 knots)

1600 After all hardware had been loaded on board and tested the ship got underway for the recovery site. On the way out the kevlar was again wound off the drum and re-coiled on the winch under tension, using approximately 1,000# of chain.

2300 Arrived at the given location of the releases and array obtained during the previous recovery effort. This position differed from the location the ships crew had obtained the week before (both taken with LORAN). The Benthos system was used to range on the releases and they were found to be at a slant range of approximately 6,052 meters. It was decided that the position obtained by the ships crew was the correct one and the vessel re-located to the new position. Upon ranging the release were found to be at slant ranges of approximately 3,000 meters. The vessel was positioned approximately 5 miles South East of the release location and the grapnel deployed.

TUESDAY 19 MARCH (Weather: 15 - 20 foot seas wind up to 50 knots)

0030 Begin run number 1. Deployment took approximately 1 hour. At the end of the wire rope and the beginning of the kevlar a benthos expendable transponder was attached. During deployment constant attempts were made to track both the expendable as well as the acoustic releases with limited success. The best that could be accomplished was approximate positions of these devices which were fixed on the INS system.

After complete deployment the vessel proceeded down the track at approximately 1-1/2 knots. The vessel passed somewhat to the North of the release position. Due to the lack of grapnel tracking data it is impossible to determine exact CPA. The gear of the winch was adjusted to provide greater pulling power upon recovery. The disadvantage is that it will take longer to recover.

0500 Start recovery of grapnel system at 5 miles North West of array position.

0730 Grapnel on deck with no array.

1030 The weather continued to deteriorate and another run was not possible. The releases were ranged on to confirm that their position had not changed.

1100 R/V WEATHERBIRD II underway towards Bermuda.

1600 Arrived Biological Station (Winds gusting 55 - 60 knots).

WEDNESDAY 20 MARCH (Weather: 10 - 15 foot seas wind up to 40 knots)

0900 Returned to vessel to make plans for next recovery effort. The following items were learned on the initial effort:

1. The Trackpoint was not able to track the grapnel as required.

2. The position of the releases were not as thought.

3. The grappling speed needs to be slower.

4. One of the expendable transponders needs to be trackable with the Benthos deck box if the Trackpoint is not able to track it.

As a result of the above Jeff Bodsford was contacted at ORE to see if he had any ideas about increasing the range of the Trackpoint. He indicated that to maximize system range, keep the pulse width and the interrogate time up. The system was already interrogating at 10ms with a 5-10 second rep rate so it was felt that optimal performance, given the conditions, was already being obtained.

Robert Catalino at Benthos was also contacted and he gave instructions on changing the interrogate frequency of the XT6000.

Software was obtained to get a hyperbolic fix on the releases using slant ranges and known positions. This was loaded onto the INS computer and checked out.

The vessel was committed until Friday the 22nd. The ship would only be available tonight for maybe 10-12 hours (enough for one run) but the weather was the same as it had been the previous day, so it was decided to wait until Friday.

FRIDAY 22 MARCH (Weather: 3 - 5 foot seas wind up to 15 knots)

0900 Arrived at the ship and began preparing for sea. The XT6000 was modified so that it could be interrogated at 12Khz with the Benthos deck box.

1120 Underway to the array site. While underway it was noticed that the shackle holding the Skookum block and the tension meter had worked loose. This was repaired however since it was not a safety shackle and a large enough safety shackle was not available it was thought that this would be a recurring difficulty.

Using the software loaded into the INS system a hyperbolic fix was obtained on the releases. The depth of the releases appears to be 2,000 meters. The position is 32^0 00' 20.087N 64^0 04' 39.492"W.

1930 Begin run number 2. The vessel was positioned 10,000 meters North West of the release position and the grapnel was deployed. Both of the XT6000s were attached to the end of the wire rope (beginning of Kevlar). Both of the XT6000s were operating as expected. The tension meter read approximately 500# during the deployment and increased to 1,000# once grappling began. The Trackpoint was able to track the grapnel until approximately 3,000 meters of water depth. At this point both of the transponders became erratic and tracking was spotty at best. The Benthos deck box was still getting repeatable results out to approximately 6,000 meters of slant range.

2225 Ship passed over the release position and continued on heading 135^0 True. Due to the loss of Trackpoint data the last known positions for the releases and the grapnel were utilized for navigation purposes. It was estimated that the grapnel was approximately 6,000 meters behind the vessel.

SATURDAY 23 MARCH (Weather: 5 - 7 foot seas wind up to 15 knots)

0000 Grapnel passes over the releases. Grappling continued for approximately another 1,000 meters just to be sure.

0100 Begin recovery of grapnel. During the recovery tensions were seen to go from 2,000 - 2,500 pounds. It appeared like there might be something in the grapnel.

0325 Grapnel on deck with no array. The XT6000 that had been modified had approximately 1 cup of water in it. The XT6000 was dismantled cleaned and packed back up. It will need a new battery and circuit card.

0440 Ranged on the releases to get a better fix. It appears that they have moved approximately 124 meters to the NNE, new location 32^0 00' 23.843" N 64^0 04' 37.251"W. The INS system was again utilized to get a fix.

0545 Begin run number 3. The grapnel was deployed. The drum of the winch is beginning to buckle under the stress of the kevlar at recovery tensions. It is thought that there must be some elasticity in the jacket that is causing this as the kevlar is not supposed to stretch.

The XT6000 was tracked on the way down but tracking becomes muddy at the 3,000 meter point as it had in previous runs.

0655 Grapnel on bottom.

0810 Vessel passed over the releases.

0950 Grapnel at approximate release location. As before the run continued for another 1,000 meters to assure that the grapnel passed over the releases.

1045 Began recovery of grapnel. There did not appear to be any additional tension besides the weight of the grapnel itself. The weather began to deteriorate a bit.

1055 Halted recovery to grapple for a few hundred more meters.

1250 Grapnel on deck with no array. The grapnel was secured and the vessel proceeded to the release point again to confirm release position.

1355 New release location 32^0 00' 19.243"N 64^0 04' 38.299"W, approximately 41 meters SE of position at beginning of run number 3.

1430 It was thought that the grapnel might be passing over the array but the 1" anchor chain might be burying the array before the hooks have a chance to grab it. It was decided to added the back up grapnel to the system to increase the chance of hooking the array.

1450 The shackles on the miller swivel hung up in the Skookum block as it was going over. In attempts to free the swivel the 5/16" wire rope was stressed excessively and the wire parted causing the loss of all grappling hardware.

1500 Using the spare chain a new grapnel was fabricated, the wire rope was re-terminated and the grapnel prepared for deployment.

1745 Begin run number 4. Due to the decreased weight of the grapnel the gear was again switched on the winch to increase it's speed. The grapnel was lowered over as before and tracking was again possible until approximately 3,000 meters. This time all efforts were made to keep the ship in position and the grapnel was lowered almost straight down.

2230 The grapnel passed over the releases (the ship had passed over the releases at approximately 2000 hrs). The tension was observed to build approximately 200 - 300# pounds but due to the weather conditions it was difficult to tell if it was truly increased tension or just the surge of the ship and the weight of the grapnel.

2330 Grapnel on deck with no array. Returned to release location and confirmed position again. Once on location performed drift check. The weather continued to deteriorate.

SUNDAY 24 MARCH (Weather: 8 - 10 foot seas wind up to 20 knots)

0001 Continued drift check (020^0 True at 1 knot) because the next attempt would be made at the lowest possible speed.

0130 Begin run number 5. Re-position vessel up-wind (SSW) and begin deploying grapnel.

0140 Hydraulics not operating properly. Stopped lowering and changed fuel filters on engine and resumed lowering grapnel.

0300 Grapnel on bottom at a depth of approximately 4,244 meters (as per Trackpoint). It was possible to track the XT6000 better because the grapnel was lowered straight down and the transponder stayed in the 45^0 cone better.

0530 Finish run number 5. No tension increases were observed.

0550 Begin partial recovery of kevlar. Executed a 180^0 turn to start run number 6.

0700 Begin run number 6. The plan on this run was to try and en-circle the release position and hopefully wind up the array and releases in grapnel system.

0745 Complete deployment for run number 6.

0845 Vessel at release location.

0915 Slowed vessel to 1 - 0.5 knots to allow grapnel to settle to the bottom.

1130 Completed run number 6 and begin to recover grapnel.

1310 Grapnel on deck again with no array.

1330 Locate releases again to ascertain position. New release position 32^0 00' 21.825"N 64^0 04' 39.231"W approximately 185 meters N of position at the end of run number 5.

1420 Start deployment East of release position for run number 7. The XT6000 was tracked to approximately 3,400 meters of water before loss of track.

1445 GPS quit updating.

1510 GPS back on line.

1520 Grapnel on bottom. While GPS was out the vessel had drifted quite a bid off track and attempts were made to correct position, at less than 1.0 knots of ship speed.

2145 Tension increased to > 1,000#. At this time the distance from the vessel the releases was approximately 6,000 meters so the position was correct. Due to the increased drag the vessel was not responding to rudder inputs so the ships speed was decreased and the drag line went slack.

2250 Began recovery with no increased tension.

MONDAY 25 MARCH (Weather: 8 - 10 foot seas wind up to 20 knots)

0001 Grapnel on deck with no array.

0010 Trackpoint hydrophone and all equipment secured. Vessel proceeding to release location to ascertain position.

0140 Completed location experiment and it was determined that releases were still in the same basic location of 32^0 00' 19.899"N by 64^0 04' 37.152"W at a depth of 1985 meters.

0150 Underway for Biological station.

0700 Arrive Biological station and begin de-mobilization.

De-mobilization was continued until Monday afternoon and again on Tuesday morning. All equipment requiring shipment was packed and made ready for return to CONUS.

APPENDIX "B"

DETAILED SHIPPING LIST

SHIPPING LIST

DESCRIPTION	NUMBER
Grapnel (Small)	4 sets
Grapnel (Large)	2 sets
Tension Meter	2 units
Hydraulic motor	1 complete
Hydraulic hoses	1 set
Shackles	1 set (Assorted)
Salvage floats	1 lot
Wire rope, 5/16" X 500'	1
Chain, 1" X 50'	1
Chain, 3/4" X 20'	1
Swivels	2
Block, Skookum	1
Kevlar, 1/4" X 25,000'	1