The Heard Island Feasibility Test

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In January 1991, the Heard Island Feasibility Test (HIFT) was carried out to establish the limits of usable, long-range acoustic transmissions. Coded acoustic signals transmitted from a source near Heard Island in the southern Indian Ocean were monitored at 16 sites in the North and South Atlantic, the North and South Pacific, the Indian Ocean, and the Southern Ocean. The question posed by HIFT, whether at such global ranges the signals would permit phase-coherent processing and thus yield favorable signal-to-noise levels, was answered in the affirmative. There was no evidence of distress by the local marine mammal population in response to the acoustic transmissions. HIFT was prerequisite to a program for Acoustic Thermometry of Ocean Climate (ATOC). The principal challenges to such a program are discussed.

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The motivation for the Heard Island Feasibility Test (HIFT) arises from the problem of global warming. The release of CO_2 and other greenhouse gases into the atmosphere produces a disturbance in the radiation balance, leading to an expected increase in global atmospheric temperature. The oceans play a vital role in atmospheric greenhouse warming. They provide for storage of heat and greenhouse gases. Without oceans, the atmosphere would be expected to warm at a rate two to three times the rate with oceans, other factors remaining the same.

Any climatic ocean changes are, of course, of interest in their own right. The thermal and dynamical structure of some coupled atmosphere/ocean models[1] undergo drastic changes, such as a virtual cessation of the thermohaline circulation (buoyancy driven as opposed to wind driven), preventing the ventilation of the deeper layers. This could have a profound impact on marine life.

There is a need for testing model predictions with direct ocean measurements. *Local* measurements of ocean temperature are subject to large variability associated with mesoscale eddies. These are associated with temperature anomalies, positive and negative, on scales of 100 days and 100 km, with magnitudes that are several hundred times the expected yearly rate of ocean greenhouse warming. One needs a method for measuring the *average* temperature over large ocean ranges. This requirement can be met by acoustic thermometry, based on two simple considerations: (i) the travel time of sound between two points is a sensitive indicator of the intervening ocean temperature, and (ii) the ocean is a good propagator of sound and so these points can be very far apart.

To be quantitative, we need to make some assertions concerning oceanic greenhouse warming. One thing is clear: A model of uniform downward diffusion of surface heating is totally inapplicable. The process is one of convection involving horizontal and vertical ocean circulation. All global circulation models (GCMs) predict temperature changes that are not uniform and are structured on gyre and basin scales of order 10 Mm (megameters). For optimum detection of climate variability, the array needs to be gyre-scale resolving and mesoscale suppressing. We envision an array of acoustic sources and receivers with typical spans of 5–10 Mm.

For orientation, take as a typical estimate of greenhouse warming 20 m°C/yr (millidegrees per year) at the ocean–atmosphere boundary, decreasing exponentially to 5 m°C/yr at 1-km depth. (The reader must not interpret this model as representing uniform downward diffusion of heat.) Such an estimate is in line with some computer modeling of greenhouse warming; it requires an incremental heat flux into the oceans of 2 W/m^2, which is the estimated perturbation of radiative transfer associated with the enhanced greenhouse gases (the associated atmospheric warming requires only 0.03 W/m^2). Thermal expansion in this scenario yields a rise in sea level of 2 mm/yr, which is not inconsistent with global tide gauge measurements.

What is the expected acoustic signature? Sound speed increases by 4–5 m/s per °C. Taking +5 m°C/yr at the sound channel axis yields −0.1 s/yr for the travel time over a 10-Mm path. In ocean acoustic tomography travel times are measured to a precision of 1 ms, albeit over 1-Mm ranges. For acoustic thermometry we want to achieve a precision of

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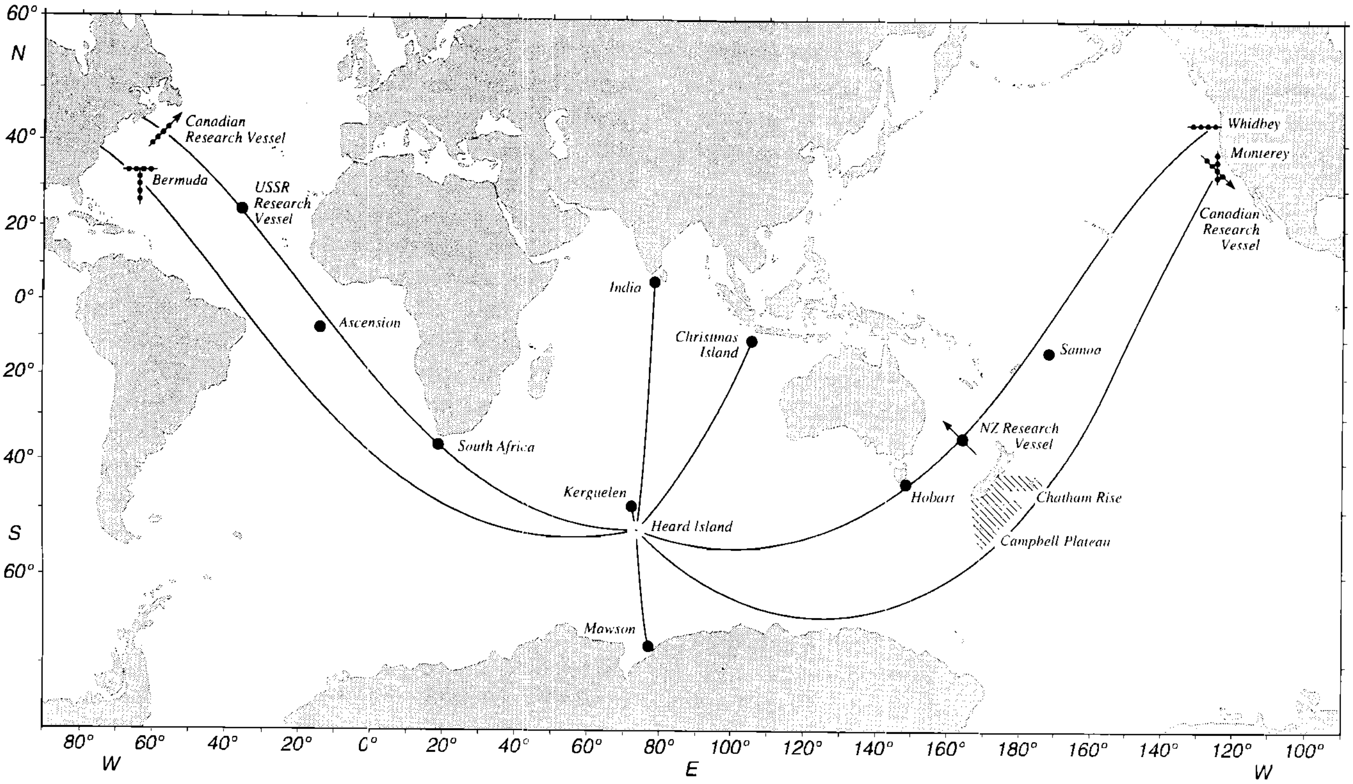

FIG. 1. Ray paths from source to receiver sites are refracted geodesics, i.e., great circles corrected for Earth flattening and horizontal sound speed gradients. The source array was suspended from R/V Cory Chouest 50 km southeast of Heard Island. Single dots indicate sites with single receivers. Dots connected by horizontal lines designate horizontal bottom-mounted arrays, vertical lines designate vertical arrays, and slanted lines designate arrays towed in the direction of the arrow. Signals were received at all sites except for the vertical array at Bermuda (which sank) and the Japanese station off Samoa.

10–50 ms, and this sets the required bandwidth and signal-to-noise ratio (SNR).

HIFT tested whether acoustic propagation through the ocean would support travel time measurements to this accuracy. Coded low-frequency acoustic signals were transmitted from a site near Heard Island in the southern Indian Ocean to the 16 receiver sites in the Indian, Atlantic, and Pacific Oceans indicated in Fig. 1. Signals were detected and travel times measured at distances up to 18 Mm.

The proposed acoustic array will, of course, measure the *combined* greenhouse and ambient climate signals. Their separation constitutes what is perhaps the principal intellectual challenge in this undertaking. Simple frequency and wave-number filtering will not do, as the two signals have overlapping power spectra. But in accordance with ongoing modeling efforts, the *spatial* structure of the ambient and greenhouse signals are not the same. The separation then depends upon a coordinated modeling and observational effort. It is useful to note that, from an oceanographer's point of view, measurements of the ambient background "noise" are at least as interesting as the detection of greenhouse warming. The understanding of gyre and basin scale variability is perhaps the most challenging problem facing physical oceanographers today. Finally, it is important to emphasize that acoustic thermometry addresses the issue of measuring climatic change (ambient or otherwise) in the oceans; it does not tell us anything about the underlying causes and about the effects on the atmosphere.

I. THE HEARD ISLAND FEASIBILITY TEST

The issues in the HIFT were: can signals generated by currently available acoustic sources be detected at ranges of order 10 Mm, can coded signals be "matched filtered" to measure travel time to better than 0.1 s, and can this be done without harm to local marine life?

It was by no means established *a priori* that these issues could be resolved positively. Uncertainties in surface scattering in the first 5 Mm of RSR (refracted, surface reflected) propagation led to estimates of acoustic propagation loss that differed by 60 dB. Signal coherence and resolvability of paths and/or modes were unknown at these ranges. A successful feasibility test was regarded as the necessary (but not sufficient) prelude for Acoustic Thermometry of Ocean Climate (ATOC).

We were fortunate to obtain from the U.S. Navy the use of powerful low-frequency HLF-4 transducers aboard the R/V Cory Chouest. These sources fitted our requirements well except that their operational use was limited to a maximum depth of 300 m. This dictated deployment at high latitude where the SOFAR channel is shallow.

A site near Heard Island (an uninhabited Australian Island discovered in 1853) was found to permit, quite unexpectedly, insonification of both the Atlantic and Pacific Oceans.[2] The acoustic rays emanating from the source site (Fig. 1) are refracted geodesics; i.e., they are approximately great circles, but they allow for the polar flattening of the Earth and for refraction from horizontal gradients in sound speed. More precisely, the rays allow for horizontal gradients at the sound axis. This is the proper limit for low acoustic mode numbers at high frequencies. Heaney *et al.*[3] have extended the construction to any mode number at any frequency; they also allowed for bathymetric refraction. Both have important consequences that are discussed later.

The initial plan depended entirely on existing U.S. Navy bottom-mounted horizontal receiver arrays at Bermuda and on both coasts of North America. While the planning was underway we received word from oceanographic colleagues in many countries that they were prepared to take receivers to sea to listen to the transmitted signals. The final result was that scientists from nine countries collaborated informally but very effectively using a diverse set of receiving systems.

Very late in the planning stage we were notified by the U.S. National Marine Fisheries Service that permits to "take whales" were required (to "take" is defined to include everything from a slight behavioral response to death. As a consequence the Australian authorities requested that we also file for Australian permits. The principal concern was that the acoustic sources were potentially a threat to marine mammals. By this time ships had been scheduled, and receiving equipment had been shipped to our international partners. Postponement was not an option. The R/V CORY CHOUEST, with Munk and Forbes as chief scientists, sailed from Fremantle, Australia on 9 January 1991 with neither U.S. nor Australian permits. These were received a week and a day, respectively, before the scheduled start of transmissions. A second ship, the R/V AMY CHOUEST, was chartered for the biological observations. Under the leadership of Ann Bowles of Hubbs Sea World, a biological party consisting of three Australian and six American observers was assembled. Clearly the conditions were not ideal for the biological add-on to the experiment. It is preferable to conduct some of the surveys from the air, the least intrusive method, but there is no landing strip within 3 Mm of Heard Island. Baseline measurements and the experiment itself were necessarily short term.[4]

Within these experimental limits there was no indication of any harmful effect on the abundant local marine life, although changes in behavior were observed. The most compelling evidence was the absence of sperm whale sonar "clicks" during the transmission period, but there was no accompanying evidence of mammal distress and none of the behavioral changes observed have been associated with long-term effects. We had agreed on a protocol whereby a transmission would be aborted if any marine mammals were within 1 km of the source ship at transmission start time. There was no such instance.

Our plan was to transmit for 10 days, commencing 0000 Greenwich Mean Time (GMT) 26 January 1991 (Australia Day), on a 1-h-on, 2-h-off schedule. Nine ships and six land based sites were standing by worldwide to receive the signals. R. Spindel at the Applied Physics Laboratory of the University of Washington (APL-UW) coordinated communications. The schedule had been "frozen" and distributed to all receiver sites prior to the experiment, with no changes to be made for equipment malfunctioning, bad weather, or other considerations. This was the right decision; it reduced the required communication to tolerable levels. As previously stated, there was considerable uncertainty as to whether the signals would be received at the remote stations. The earliest possible responses were from the two arrays with "real time" processors: Bermuda (manned by K. Metzger) and Whidbey Island near Seattle (manned by T. Birdsall). Both transmissions were at ranges of approximately 18 Mm, one westward, the other eastward, nearly half around the Earth with acoustic travel times of $3\frac{1}{2}$ h.

On the day prior to the scheduled start, technicians aboard the R/V CORY CHOUEST requested a routine 5-min checkout of the sources. Three and one-half hours later the CORY received a message via the APL communications center from an excited Metzger at Bermuda describing an early reception at 57 Hz and asking confirmation that it was from the CORY. Soon thereafter, APL-UW reported that Birdsall at Whidbey Island had confirmed a reception in the Pacific. The question about the adequacy of the source level had been answered, and it was not yet Australia Day!

The scheduled transmissions commenced on time, and other stations soon began to report receptions. On 31 January the CORY encountered a gale with 10-m seas. One suspended source was torn loose and went to the bottom. The others were severely damaged. Fortunately, there had been 35 successful transmissions before this untimely termination.

II. SOURCE AND RECEIVERS

The R/V CORY CHOUEST carried ten HLF-4LL acoustic sources (Fig. 2) manufactured by Hydroacoustics, Inc., Rochester, NY, and the specialized handling equipment that enabled them to be deployed in a vertical array through the ship's center well to the depth of 175 m (the local sound channel axis, Fig. 3). Acoustic energy is generated by driving circular faceplates into vibration with hydraulically controlled pistons. The plates resonated at 57 Hz and provided a bandwidth of about 14 Hz. Each source was capable of transmitting a nominal level of 206 dB *re:* 1 μPa @ 1 m (3.3 kW acoustic).

A vertical array of ten sources with a 3.81-m spacing (0.15 λ at 57 Hz) was used, but only five sources were activated at a time. Overheating of the hydraulic system and possible resonant coupling between sources was a major concern. Indeed, it was not until a November 1990 trial in the Sea of Japan, prior to steaming to Heard Island, that we learned that the sources could be operated continuously for an hour and that five could be operated in parallel, thus providing a maximum transmit level of 220 dB $[206+20\log_{10}(5)]$. *In situ* measurements indicated that source levels of 221 dB were actually obtained.

Receivers at different sites included bottom-mounted hydrophones, either singly or in horizontal arrays, ship-towed horizontal arrays, bottom-moored and ship-suspended vertical arrays, and hydrophones suspended from surface floats (see Table I).

A self-contained receiver and PC-based data processing system was developed to simplify and standardize data acquisition. Sonobuoys, or sonobuoy-like surface floats with hydrophones suspended at the depth of the local sound channel axis, telemetered to ship or shore for recording and pro-

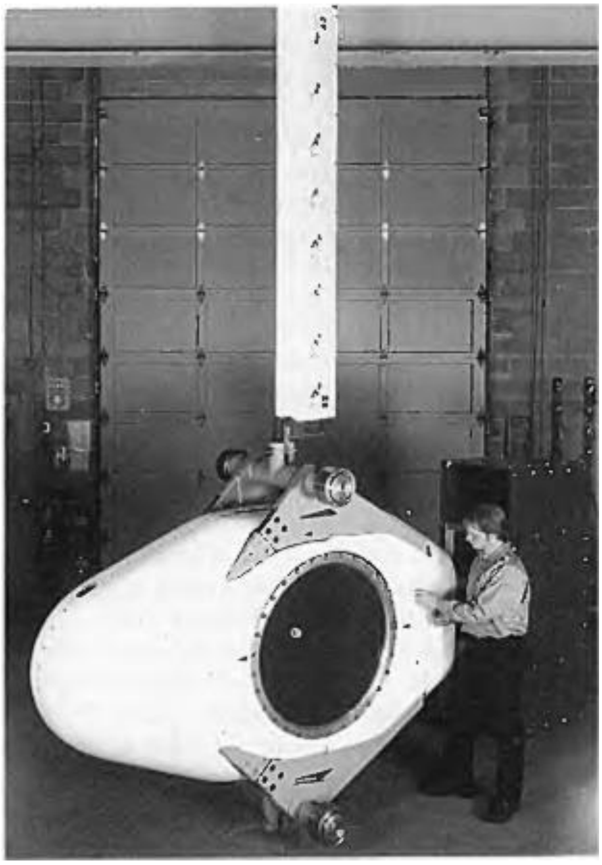

FIG. 2. The HLF-4 acoustic source (courtesy of Hydroacoustics, Inc.). The smooth Fiberglass housing covers most of the transducer mechanical equipment and electrical containers. One of the two exposed circular radiating faces is shown. Ten sources were suspended through the center well of the R/V CORY CHOUEST in a vertical array with 3.81-m element spacing. A maximum of five sources was energized for each hour-long transmission.

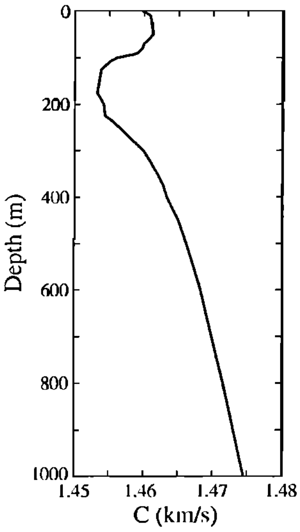

FIG. 3. Sound speed profile at Ascension Island on 26 January 1991. The center of the source array was placed at a depth of 175 m.

TABLE I. Receiving sites for the Heard Island Feasibility Test [surface-suspended systems used a sonobuoy deployment with a radio frequency link; ship-suspended had a cable from the hydrophone(s)].

Receiving site	Country	Receiver type
Ascension Island	U.S.A. (NOAA)	Bottomed, single hydrophone
Bermuda	U.S.A. (U. Mich.)	Bottomed, horizontal array
Capetown, S.A.	South Africa	Ship-suspended, single hydrophone
Christmas Island (Indian Ocean)	Australia	Surface-suspended, single hydrophone
Goa, India	India	Surface-suspended, single hydrophone
Heard Island (R/V CORY CHOUEST)	Australia	Surface-suspended, single hydrophone
Kerguelen Island	France	Surface-suspended, single hydrophone
Krylov Seamount (N. Atlantic)	Russia	Ship-suspended, vertical array
Mawson Station, Antarctica	Australia	Bottomed, single hydrophone
Monterey, California	U.S.A. (MIT, NPS, MBARI, SAIC)	Ship-suspended, vertical array
New Zealand	New Zealand	Hydrophones dropped from moving ship
Samoa	Japan	Ship-suspended, single hydrophone
Tasmania	Australia	Surface-suspended, single hydrophone
U.S. East coast (off Cape Cod)	Canada (DREA)	Towed, horizontal array
U.S. West coast (off San Diego)	Canada (DREP)	Towed, horizontal array
U.S. West coast	U.S.A. (U. Mich.)	Bottomed, horizontal array

cessing at Mawson, Goa, Kerguelen, Christmas Island, Capetown, Bermuda, Tasmania, New Zealand, the U.S. West Coast, and Ascension Island. Detailed descriptions are given in the appropriate papers in this volume.

Receivers of their own design were used by Soviet investigators anchored off the Krylov Seamount in the North Atlantic[5] and by Japanese participants near Samoa. Canadian laboratories towed horizontal line arrays off both coasts of North America.[6,7] A vertical line array was deployed off California.[8] All arrays used multichannel, digital data acquisition.

III. SIGNALS AND SIGNAL PROCESSING: THE STRATEGY

HIFT signal strategy had to take into account the very large uncertainty in the expected propagation loss, stability, and arrival spread. Path lengths ranged from 1 to 18 Mm.

Receivers ranged from simple sonobuoys to horizontal and vertical arrays with significant array gain. Birdsall *et al.*[9] developed the signaling strategy, assembled the data, and subjected it to a summary form of frequency domain processing (we refer to their paper for a detailed discussion). The results provide a basis for further analysis by interested investigators.

The frequency of choice was 57 Hz (to avoid confusion with the ubiquitous 50- and 60-Hz power frequencies). The 18-Mm volume attenuation is 5 dB in the Atlantic waters and 3 dB in the Pacific waters (The corresponding Atlantic attenuation at 100 Hz is 19 dB!) Spatial spreading losses were separately examined by three methods using an improved sonar equation, an adiabatic mode propagation model, and a ray/time front propagation model. Each gave a wide spread of answers. What was needed was the intensity of a resolved arrival, either per ray path or per mode, and not the usual CW transmission loss. In the end a compromise between experience and computation yielded an estimate of 135-dB space-time spreading loss at 18 Mm per observable ray or mode.

Surface scattering was a major consideration. For the first few megameters the propagation was along an upward refracting polar channel (RSR) in a region of notoriously high sea states. At 5-Mm ranges, even very low surface scattering losses accumulate; a loss of just 1.2×10^{-2} dB/km accumulates to 60 dB in the polar channel. Ray model losses for the surface interacting rays varied from 2 dB for 10-m/s winds to 60 dB for 20-m/s winds. The conclusion was that very high sea states would kill the signal. A modal analysis by Baggeroer (personal communication) based upon the Kuperman–Ingenito scattering theory[10] raised similar concerns.

Blockage and refraction by islands, seamounts, and ridges were further important considerations. In the final analysis blockage became a question to be answered by the measurements. Horizontal refraction by horizontal gradients in sound speed was a concern since small angular deflections cause large shifts at long ranges.

We chose three types of signals. The first was a simple cw tone at 57 Hz, which allowed detection by the simplest receiving equipment. It had the highest carrier-to-noise ratio of all the HIFT signals. The second signal type was a three-digit M-sequence with 10 carrier cycles per digit and a 45° phase modulation angle. (M-sequences are standard signals long used in tomography and are likely to be the signal of choice for a long-term ocean monitoring program.[11]) This signal had a period of 0.526 s and a spectral line spacing of 1.9 Hz. It was chosen because it has five principal spectral lines (hence the name "pentaline") with special amplitude properties. The first pair of spectral lines 1.9 Hz from the carrier are roughly 6 dB below the carrier, and the next pair 3.8 Hz from the carrier are about 12 dB below the carrier. This signal allowed a rough estimate of received SNR based only on which lines were present.

The third signal type consisted of four different M-sequences. Their bandwidth and period were sufficient to determine the multipath structure using pulse compression. Each digit consisted of five carrier cycles with sequence durations of 22.4, 44.8, 89.7, and 179.6 s, respectively. We felt that 22.4 s would be sufficient to accommodate the expected time spread in arrival patterns even at the most distant receivers; the longer sequences were insurance.

The requirement was to achieve a 20-dB processed SNR on every significant arrival. This yields a time of arrival precision of one-tenth the nominal resolution of W^{-1} (W is bandwidth), and an insignificant false alarm probability. A basic transmission duration of 1 h was chosen, long enough to provide significant gain, yet short compared to a tidal cycle. On the basis of past experience (though at higher frequencies and shorter ranges) we anticipated being able to achieve 50 s of coherent processing, followed by incoherent processing. These preliminary estimates, made in January 1989, yielded a processed output quality of 10 dB for a single hydrophone at 10 Mm—not good enough. But the far stations had long horizontal arrays that would raise the level by at least 10 dB. An additional gain of 14 dB along the axis could be expected by energizing five sources in parallel, thus achieving well over the 20-dB SNR design goal.

A primary goal was to learn about the phase stability of the recorded arrivals. The signals were designed to give information for integration times as short as 20 s. To our surprise (and delight) we were able to coherently process for up to a half hour at 5 Mm range.

During the 6 days of the test, 35 out of a possible 48 transmissions took place. We refer to Ref. 9 for information on the 16 receiver sites, ranges, and travel times, and on the data acquired at the receiver sites for each of the accomplished 35 transmissions.

IV. RECORDS BY SINGLE RECEIVERS AND FIXED ARRAYS

Some receptions by fixed receivers are presented to give the reader a feel for the quality of the data. More detailed discussions are found in other papers of this volume.

Examples of the three types of signals are shown in Fig. 4. The recorded spectra are nearly perfect replica of the theoretical spectra (apart from the 60-Hz contamination); only the pedestals at the foot of the pentalines give evidence that this is a display derived from measurements. The onset of reception is abrupt, whereas the shutoff lingers suggesting reverberant energy extending beyond the 60-min transmission. This is particularly evident for the M-sequence.

At Ascension Island, 9.2 Mm from the CORY CHOUEST, signals were received on single, bottom-mounted hydrophones located at sound channel axis depth (about 800 m) or deeper. These hydrophones are part of the U.S. Air Force's Missile Impact Location System (MILS). SNRs in a 1-Hz band ranged from 19 to 30 dB and averaged about 16 dB (all referenced to a transmit level of 220 dB). Figure 5, based on data taken by Palmer and his collaborators,[12] compares an ideal (simulated) pentaline transmission to an actual reception. Two periods of 0.53 s each are shown. The experimental spectrum was produced by incoherently averaging 500 spectra, each of which was constructed with a 4.49-s data record. Figure 6 from Georges and collaborators[13] shows matched filtered 255-digit (22.4-s) M-sequence receptions on four hydrophones, taken 24 h apart. For any one hydrophone,

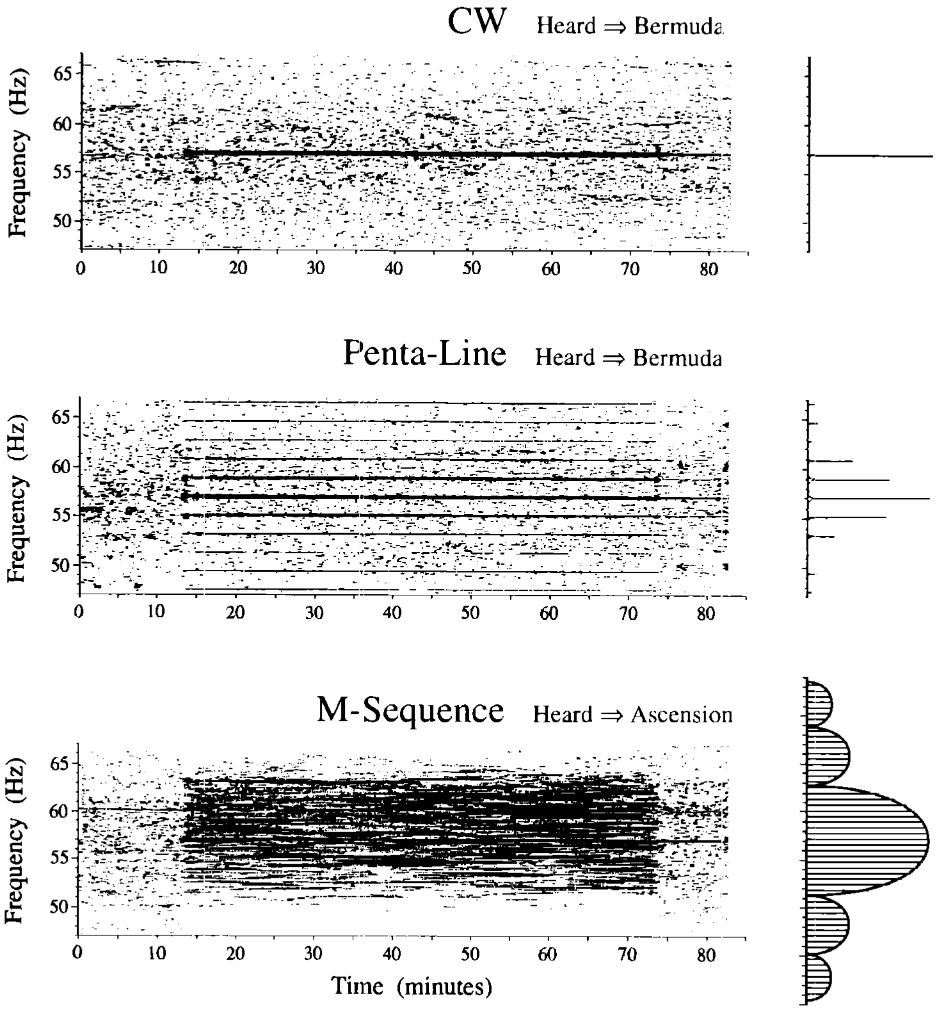

FIG. 4. Three types of HIFT signals as received at Bermuda (range 16 Mm, travel time 2.95 h) and at Ascension Island (9.2 Mm, 1.71 h). Note the 60-Hz interference line for the M-sequence, and the 57-Hz carrier "afterglow" from scattered arrivals. Spectra of the entire 60-min record are shown to the right.

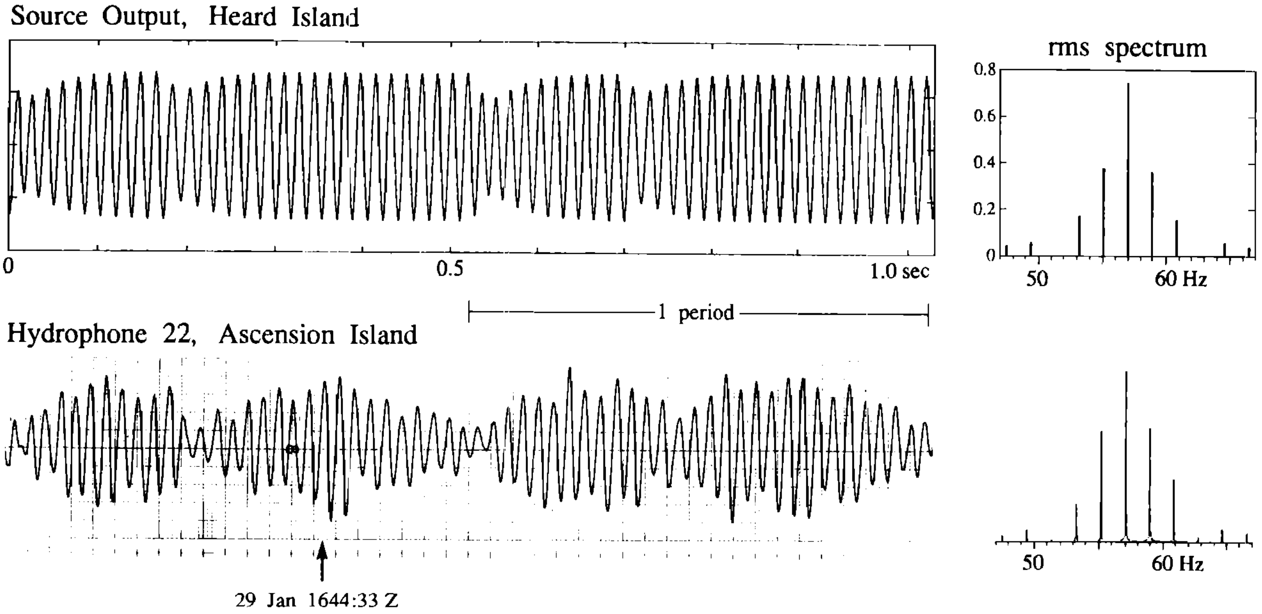

FIG. 5. An example of the pentaline signal in the time domain. Two periods of the 0.53-s sequence are shown. The upper panel shows a simulated signal and its spectrum; the lower panel gives the measured reception and the spectrum computed using 37 min of data.

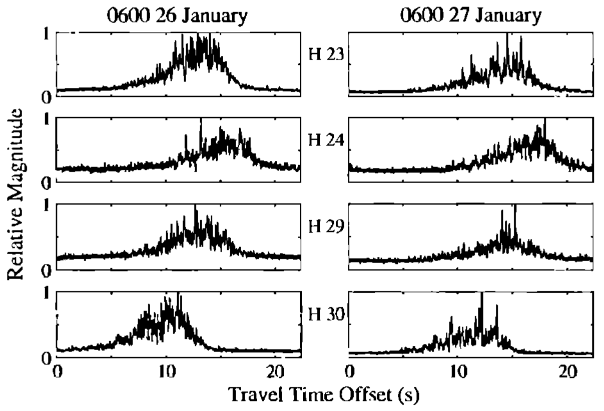

FIG. 6. Arrival pattern at four Ascension hydrophones recorded 24 h apart. Each panel is a 60-min incoherent average of a match-filtered (pulse compressed) 255-digit M-sequence. See Birdsall and collaborators[9] for details.

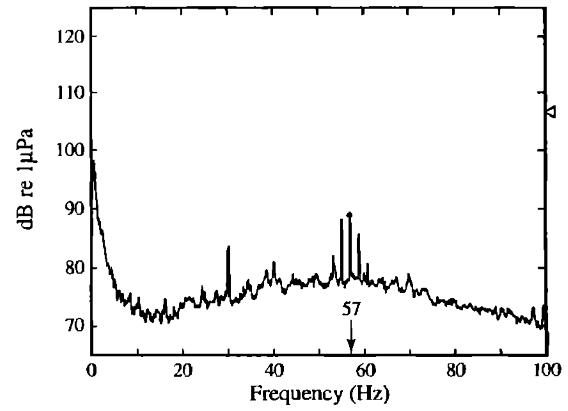

FIG. 8. Spectrum of pentaline signal at the Krylov Seamount.

the arrival patterns differ from day to day. H23 and H24 are within a few kilometers, yet the arrival patterns from a single transmission differ distinctly. This suggests that the source motion by 3 nautical miles (5.6 km) during a transmission run may contribute significantly to any decorrelation.

Figure 7 shows an interesting display of received signal and out-of-band noise on Krylov Seamount in the Eastern North Atlantic 12.5 Mm and 2.32 acoustic hours from Heard Island,[5] as function of the number of sources that were transmitting. Another example from this data set (Fig. 8) is the output of a spectrum analyzer during the reception of a pentaline signal. The five spectral lines are clearly visible.

Measurements taken off South Africa,[14] though closer to the source than Ascension, were generally of poorer quality (Fig. 9). The highly variable ocean hydrography associated with the Aguhlas Front and the extreme sea conditions (10-m swells) led to difficulties in deploying a hydrophone in an optimum location at sound channel axis depth.

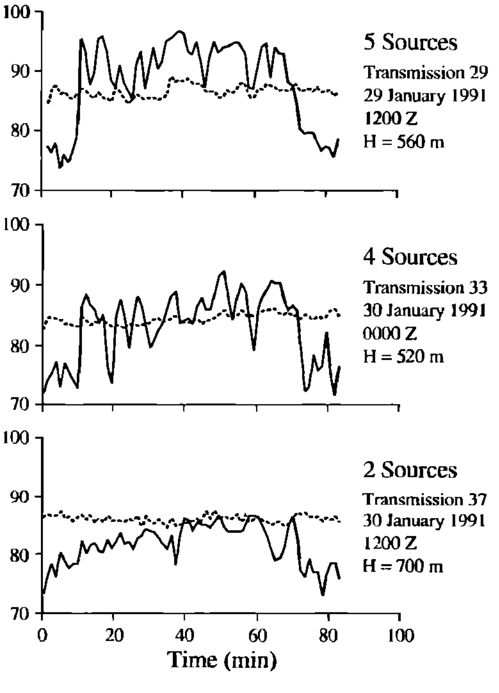

FIG. 7. Reception of the 57-Hz cw signal at Krylov Seamount in the Eastern North Atlantic.[5] Solid line is signal power; dotted line is noise power density averaged over adjacent frequency bands in units of dB *re:* 1 μPa/$\sqrt{\text{Hz}}$. The signal-to-noise ratio degrades as the number of operative sources decreases.

A final example of data collected on a single, surface-suspended hydrophone is shown in Fig. 10. The top panel displays the incoherent 41-min average with excellent SNR. Comparison with the computed arrival pattern will be discussed later. The general conclusion is that single hydrophones can provide significant information.

V. RECORDS BY TOWED AND VERTICAL ARRAYS

Both towed arrays and vertical arrays were deployed during the HIFT to measure spatial properties of the HIFT signals as well as to provide array gain.

A. Canadian towed arrays

We were fortunate to have the participation of Canadian towed arrays from DREA (Defense Research Establishment Atlantic)[6] and DREP (Defense Research Establishment Pacific).[7] While designed for higher frequencies, both arrays

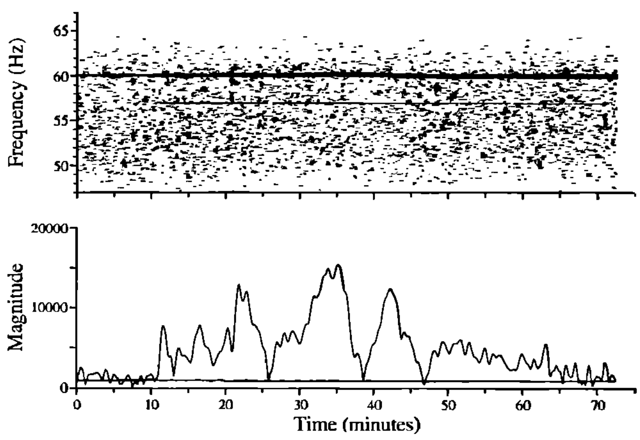

FIG. 9. The cw transmission received by the ship-suspended hydrophone off Capetown, S.A. (The line at ≈60 Hz is noise from the ship's electrical power.)

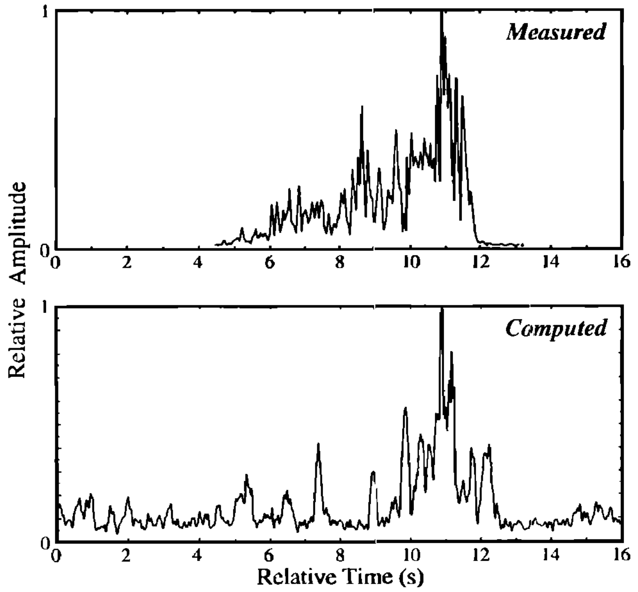

FIG. 10. Comparison of measured and computed arrival patterns at Christmas Island. The measured pattern is an incoherent average of 110 contiguous receptions (41 min) of a pulse compressed 255-digit M-sequence received on a surface-suspended hydrophone. The bottom panel computed by McDonald *et al.*[17] uses 30 modes and 21 frequencies spanning from 52 to 62 Hz.

were very capable at HIFT frequencies; a large number of sensors and digital recording capability provided significant array gain.

The DREA towed array was deployed at depth between 100 and 200 m southeast of Cape Cod with unique opportunity to record signals on both sides of the Gulf Stream. The intensity of receptions varied with position consistent with hypotheses about bathymetric blockage by South America and mid-ocean islands. Figure 11 shows the estimated transmission loss as a function of position relative to the northern boundary of the Gulf Stream. Losses are approximately 135 dB south of the boundary and decrease (the intensity increases) by 10 dB toward the north as the SOFAR axis shoals to the array tow depth.

Along the West Coast, the DREP towed array was deployed off Monterey and San Diego, based upon the predictions of Chiu *et al.*[15] In addition, we had available a U.S. Navy bottom-mounted horizontal line array and the vertical array off Monterey. Analyses were made difficult by large transmission losses, typically 140–150 dB, with signal levels of order 70 dB and SNR of -15 to -10 dB per Hz (single phone cw).

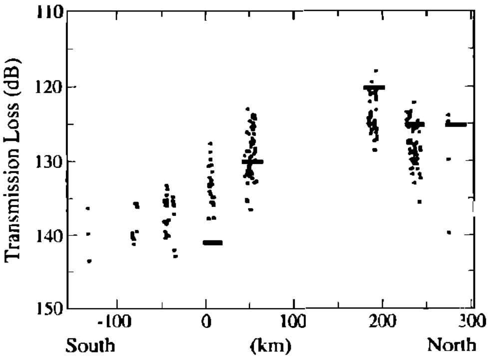

FIG. 11. Transmission loss (increasing downward) as function of position relative to the northern boundary of the Gulf Stream off Newfoundland[7] at a range of 16.8 Mm.

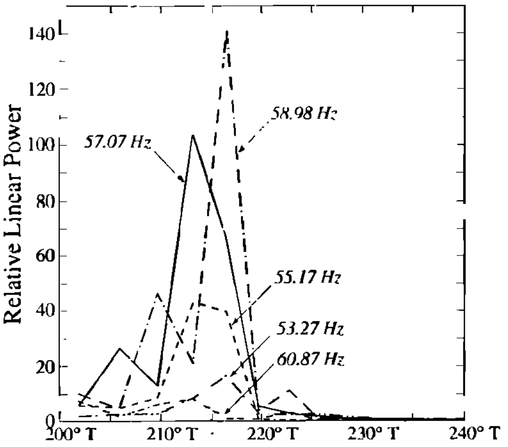

FIG. 12. Relative power as function of arrival bearing angle off California[6] for the pentaline transmission 1500Z 29 January 1991.

One of the speculations about global acoustics concerns horizontal refraction and multipaths,[16,3] so measuring arrival power versus bearing was one of the principal goals for the towed array. Figure 12 plots power as a function of bearing for one of the pentaline transmissions to the DREP array[6] towed at a depth of 300 m. There is a faint suggestion of horizontal multipath, but because of the low SNR the bearing and sidelobe variability can be equally well accounted for by noise effects.

B. Monterey vertical array

The vertical distribution of signal power is a major issue in the use of global acoustics to monitor ocean climate. In the HIFT two vertical arrays were deployed to measure the modal distribution of the received signals.[8] One array was placed off Bermuda, but unfortunately it sank and no data were recovered. The second array, off Monterey, had 32 hydrophones with 45-m spacing covering the water column from 345 to 1740 m. It was tethered to the R/V POINT SUR.

The expectation prior to the HIFT was that all but the lowest-order modes would be strongly attenuated and the signals at long range would consist only of the gravest one or two SOFAR ducted modes. Several indications from the vertical array suggest that this is not the case. First, signal power is detected at depths up to 1700 m, which requires mode 6 or higher to be present. Second, an estimate of the vertical distribution of signal power can be found by measuring the frequency-vertical wave-number spectrum of the array data (Fig. 13). There are several peaks in the 57-Hz frequency band (slightly downshifted for Doppler). The separation in wave number of these peaks suggests up/down power up to at least mode 7. Unfortunately, the low SNR on the California coast limited the resolution of the wave-number spectra.

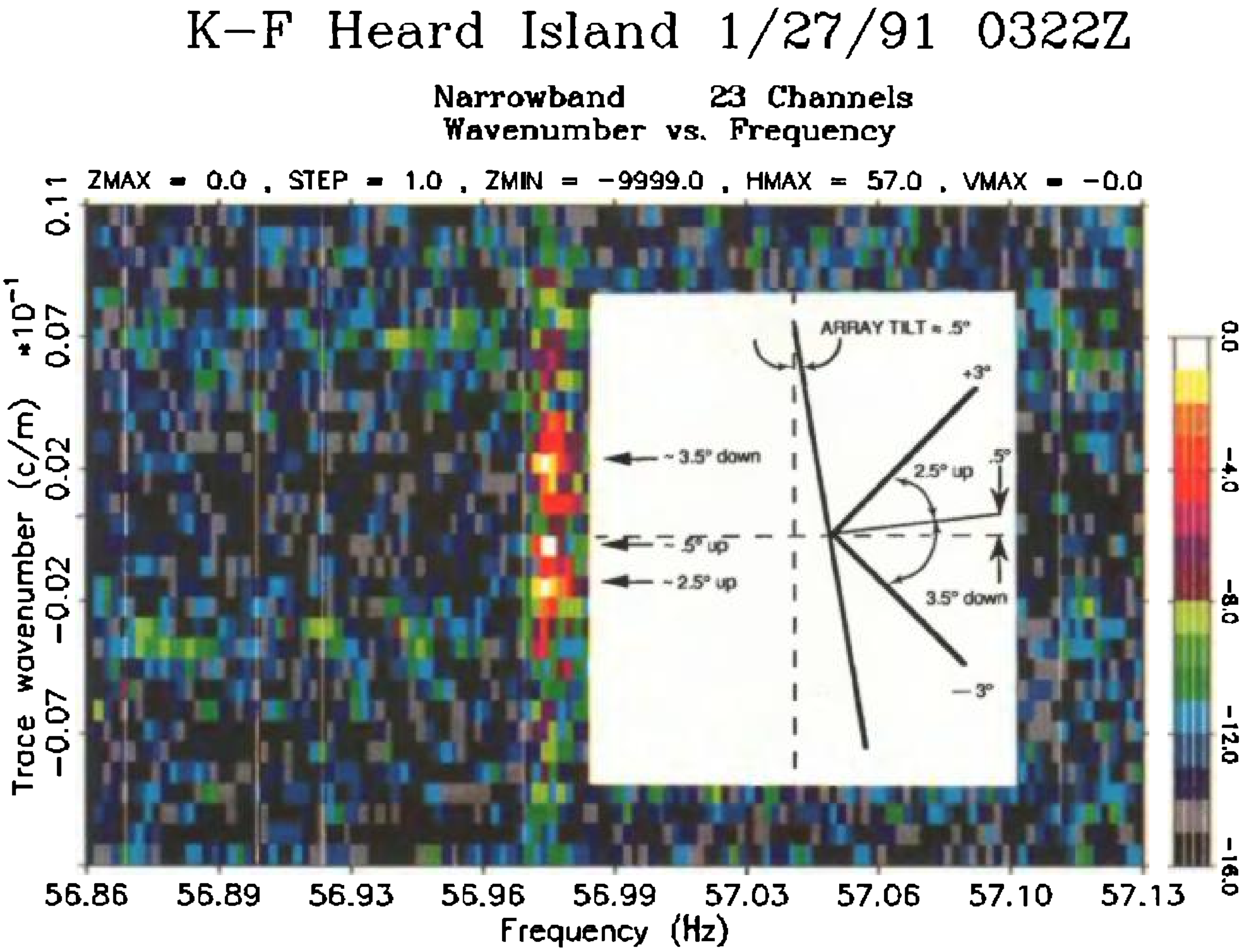

FIG. 13. Frequency wave-number spectrum for a cw signal recorded at the vertical array off Monterey.[8] An intensive band centered at 56.97 Hz (down Doppler) has peaks at vertical wave numbers of approximately −0.002, 0.000, 0.002, and 0.003 cycles/m. The spread in vertical wave numbers suggests the presence of modes up to mode number 7.

VI. PROBLEMS OF GLOBAL ACOUSTICS

HIFT has raised a series of issues largely ignored in the usual propagation experiments but critical to propagation on a global scale. Very few of the issues are "solved" in the HIFT papers, but the results obtained have suggested a strategy for future work.

A. Refracted geodesics

It has long been appreciated that the departure of the Earth from spherical shape is associated with a significant departure of geodesics (shortest distance between two points on a spheroid) from great circles. The departure increases sharply as one approaches antipodal ranges, and for points separated by exactly 180° there are, of course, an infinite number of great circles. In preparing for HIFT the computed ray paths were *refracted* geodesics, that is, they allowed for horizontal gradients in sound speed in addition to Earth flattening;[2] however, refraction was computed only for the horizontal gradients at the depth of the sound axis.

Heaney *et al.*[3] generalized the foregoing treatment by computing the refracted geodesics separately for each mode. (In this sense, the pre-HIFT axial calculations constitute the limit of low mode numbers and high frequencies.) More importantly, the Heaney constructions allowed for refraction by bottom topography, in addition to the effects of sound speed gradients and Earth flattening. The general statement governing refraction is that acoustic paths are repelled by shallow depths, high sound speed (warm water), and high latitudes. We refer to McDonald *et al.*[17] for a discussion of these issues.

Over a flat bottom the separation in horizontal paths for low and high modes (or for axial and steep rays) is small as compared to the horizontal dimensions of the ocean temperature structure. Accordingly different modes measure nearly the same ocean structure. The situation may be quite different when one considers the combined effect of thermal and bathymetric refraction. Quite small differences in horizontal deflection may lead to grossly different bottom interactions and accordingly widely separated paths, so that different modes may sample quite different ocean regions. This appears to have been the case for at least one of the HIFT transmission paths.

B. Launch angles

One of the anticipated complications of HIFT was that the source ship moved at about 3 knots into the prevailing

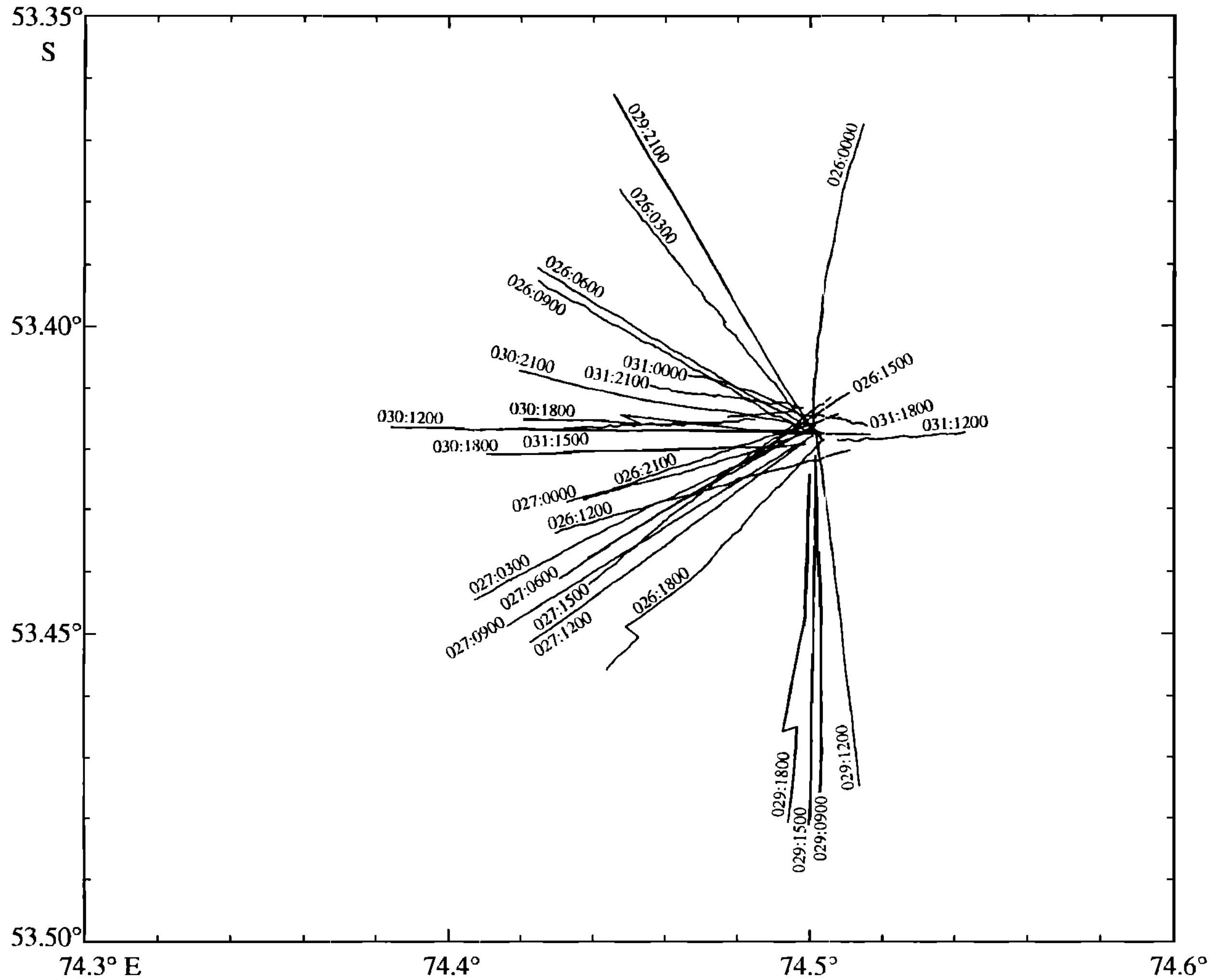

FIG. 14. GPS tracks of transmission runs at stated yeardays and start times. Starting point was kept as close as possible to 53.42° S, 74.5° E. All runs were on automatic pilot at 3 kn heading into the wind and waves.

wind and sea and induced a Doppler shift in the carrier frequency. This was removed early in the processing of received signals. To our surprise, even a *variability* in the ship's motion by a few percent as detected by Global Positioning Satellite (GPS) measurements was in excellent agreement with a slight Doppler variability.[18] This is perhaps the most vivid demonstration of phase-coherent processing at megameter ranges.

An unexpected bonus occurred from knowing the precise Doppler shift for each reception. When combined with GPS navigation data from the R/V Cory Chouest, the observed Doppler shift allowed us to calculate horizontal launch angles from the source toward individual receivers.[19] These angles were consistent even though the ship's course differed widely for different transmission runs (Fig. 14). Under the conditions of HIFT, Doppler-derived launch angle could be computed to an accuracy of ±0.1°. (The accuracy could be further improved in future experiments.) From Heard Island to Ascension Island, the Doppler-derived azimuth was 268.06°±0.1°, compared to 266.05° for the refracted geodesic launch angle of mode 1 at 57 Hz. The conclusion is that the *a priori* estimate of the ray path was correct.

For comparison we note that the computed Ascension launch angle for the axially refracted geodesic is 260.18° and for the unrefracted geodesic it is 265.91°.

C. Tasman blockage

The situation is altogether different for the eastward path to the American West Coast.[20] One of the earliest confirmations that the signals from Heard Island had crossed the Pacific was from Whidbey Island. Calculation of the refracted geodesics from Heard Island through the Tasman Sea to this facility predicted receiver azimuths of 230°–235°; beamforming at Whidbey Island indicated that the signals arrived from 20° further south, 215°. Using the Doppler-derived launch azimuth technique discussed earlier, we found that the signals arriving at Whidbey left Heard Island at an azimuth of 130°, not 115° as derived for the Tasman geodesic. Evidently the acoustic path went south and east of New Zealand through the "Polynesian window." A similar situation was found off the coast of southern California, where Heard and Chapman[6] towed a horizontal line array and measured an arrival angle of 214° consistent with the Polynesian window.

These results raise two questions: (i) Do refracted paths through the Polynesian window exist? (ii) Can one account for the absence of the "direct"path through the Tasman window? The answer to the first question is "yes." McDonald *et al.*[17] (their Table I and Fig. 5) list Polynesian paths to Monterey and southern California with moderate bottom losses; however, the computed signal intensity is larger for the Tasman path than for the Polynesian path. One can only surmise that the bottom losses were unexpectedly higher for the Tasman path and they rapidly increased for receiver locations to the north of Oregon. With regard to the second question, Forbes[20] suggests that the Tasman path was blocked by the ridges that lie in the northeastern sector of the Tasman Sea, between New Zealand and Fiji (and Samoa). The New Zealanders did receive strong signals in the center of the Tasman Sea, but the Japanese, listening near Samoa on the "downstream" side of the Lau Ridge, did not receive any of the HIFT signals. The rugged bathymetry that intrudes into the SOFAR channel near Fiji, Tonga, and Samoa appears to have severely attenuated the HIFT signals.

D. Differential Doppler

In megameter-range tomography, ray tilt is routinely measured by a short vertical array and has proven very useful in viewing the arrival pattern in tilt-travel time space. In the normal SOFAR sequence, the early arrival of steep rays is followed by the late arrivals of flat rays. Dzieciuch and Munk[21] suggest that *differential* Doppler can be used to measure vertical tilt of rays even with a single hydrophone. For a horizontally moving source, steep rays should experience a smaller Doppler than flat rays. (The dependence of Doppler upon the projection of the ship's course onto the horizontal launch azimuth has already been discussed in Sec. VI B.) It was found that differential Doppler for the 5-Mm transmission to Christmas Island does not follow the normal SOFAR sequence. However, the differential Doppler is not inconsistent with transmission through a sharp (nonadiabatic) front separating a polar surface duct from a temperate interior sound channel. Moreover, a moving source is associated with the creation and destruction of eigenrays at a rate comparable to what is observed. This raises the issue whether the transmission from a moving source through a sharp front might be responsible for some of the observed complexity of the arrival pattern. The following topics deal with theoretical efforts to explore this issue.

E. Ray propagation through a front

For orientation consider the situation in Fig. 15. The solid line corresponds to an axial (near-surface) polar ray that is converted at a discontinuous front into a fairly steep temperate ray. The dashed ray is axial in the temperate ocean, and a fairly steep RSR ray in the polar ocean. The path for each of these two rays consists then of two sectors: a slow axial sector and a rapid nonaxial sector. The sequence of arrival of these two rays (or of any other rays) is not obvious; it depends, among other considerations, on the relative length of the polar and temperate sectors, the ray tilt at the front (here set to zero), and the sound-speed profiles. The figure is a convenient caricature to portray an essential element of the Heard Island transmissions through the Antarctic Circumpolar Convergence (ACC).

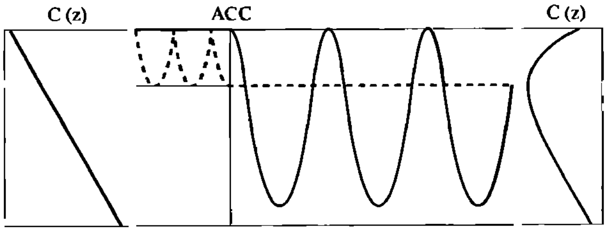

FIG. 15. Cartoon for a transition from RSR to RR propagation across the Antarctic Circumpolar Convergence (ACC). The temperate sound-speed profile (right) is associated with an interior sound channel; the high-latitude sound-speed profile (left) is associated with an axis along the surface. Dashed and solid lines represent limiting rays that are axial at temperate and polar latitudes, respectively.

F. Mode propagation through a front

The most detailed discussion of modal propagation is given in the paper by McDonald *et al.*[17] Their final result for Christmas Island is reproduced in Fig. 10 (bottom). Given the lack of synoptic information about sound speed along the path, this is as close as we can get to a comparison between measured and computed transmissions. The temporal spread and pulse shape are in reasonable accord. The calculations appear to capture the complexity in the arrival structure, but not the details.

Mode coupling is strong (we refer to the figures in Ref. 17). For the transmission to California, with an initial condition of mode 1 excitation only, the energy is redistributed over the New Zealand plateau among approximately the first eight modes. Past Chatham Rise, most of the energy is in modes 3 and 5. With a multimodal initial condition of modes 1–25 appropriate to a point source at 175 m depth, there is a modest exchange of energy until the New Zealand plateau, when modes above 9 disappear, with only a moderate redistribution thereafter. The result is consistent with the finding of Baggeroer *et al.*[8] using the vertical array off Monterey, California.

Shang *et al.*[22] have also used a modal decomposition to simulate some of the HIFT transmissions. They find strong coupling at the ACC. The computed spread for the lowest six modes is consistent with the measured spread. The authors emphasize that the relation between arrival time and frequency is not simple and monotonic, and it is possible to have multiple arrival peaks for any one mode, and a reversal in the expected order of mode arrivals.

We make no attempt here to compare the different approaches. There is agreement that mode coupling across the ACC is an important consideration that needs to be taken into account for any interpretation of the observations. The ACC is associated with a change in the shape of the sound-speed profile, a transition from a surface duct to an internal duct. The corresponding ray transformation is from RSR to RR. Similarly, an intense warm eddy can split the SOFAR sound channel into a dual channel, and such a change in shape is accompanied by severe mode coupling, as expected.

G. Random field coupling

We need to be concerned also with mode coupling due to short scale inhomogeneities. A case in point is that of a horizontally homogeneous sound channel with a weak superposed field of mesoscale eddies. The analogous problem of mode coupling by an internal wave field has been studied by Dozier and Tappert.[23,24] Their calculations indicate strong mode coupling between neighboring modes at distances of order 1 Mm. It is important that these problems be studied. Topological fronts, such as the ACC, can perhaps be avoided in future ATOC transmissions, but there is no way of escaping the ubiquitous presence of the mesoscale and internal wave fields.

VII. ACOUSTIC THERMOMETRY OF OCEAN CLIMATE (ATOC)

HIFT (planned for 10 days, carried out for 5 days) was, of course, never intended to address problems of climate variability. Upon returning from Heard Island, planning was initiated for obtaining the appropriate climate-oriented time series of acoustic travel times. The ATOC program did not get underway until early 1993.

Heard Island is not a candidate site for ATOC. It is too inaccessible, and its unique dual-ocean access is not appropriate for climate studies. We will concentrate on 5- to 10-Mm ranges; these appear to be acoustically feasible, and they are the appropriate scale for the study of climate variability. The reduced ranges permit sources of less intensity than those used for the HIFT.

Building on the experience gained from HIFT, we have designed and built sources of lower intensity (195 dB *re:* 1 μPa @ 1 m) and somewhat higher frequency (60–90 Hz) than those used for the global transmissions. At temperate latitudes where the sound channel axis is near 1 km, the intensity in the biologically important upper ocean will be reduced by more than 30 dB relative to HIFT.

The plan is to deploy two acoustic sources, one for transmission from Hawaii into the northern Pacific, the other for transmission from California northwestward into the North Pacific and southwestward toward a receiver at New Zealand. For receivers we shall again depend on the cooperative use of the bottom-mounted horizontal arrays at U.S. Navy NAVFAC stations. In addition we shall deploy several large-aperture vertical line arrays that were designed to resolve vertical modes up to mode 10. This is in response to the HIFT result that a major effort to understand the modal distribution is required for the interpretation of long-range transmissions. We regard this as an interim measure; in the long run we expect to depend upon simple, inexpensive autonomous receivers.

A crucial problem that has not been resolved by HIFT is the resolution, identification, and stability of individual features in the arrival pattern. It was necessary, if only for reasons of safety, for the R/V CORY CHOUEST to be underway during transmissions, headed into the winds and sea. Ship-towed arrays and surface suspended hydrophones were also in motion. We attribute some of the complexity in the HIFT arrivals to this motion and have designed ATOC for a fixed-geometry. Crossing the Antarctic Front must be a major contributor to the complexity of HIFT arrivals, and accordingly we have chosen more benign paths for ATOC. B.E. McDonald (personal communication) has suggested that mode coupling, once properly understood, may provide an opportunity (rather than a liability) for gaining range-dependent information.

Topographic blocking and scattering is a major problem. Sound is refractively repelled from shoaling water, and there are acoustic multipaths associated with islands, seamounts, and other topographic features. This has, of course, long been known, but was driven home by the unexpected West Coast arrival through the Polynesian window, which owes its existence to bathymetric scattering. We have placed a great effort in selecting ATOC paths that are as free as possible from bathymetric effects. It may be possible to identify stable scattered arrivals to provide temperature information along additional paths. HIFT records typically show a 15- to 20-min "afterglow" following the transmission, see Fig. 4.) For this and other reasons it would be worthwhile to include a moving cw source interlude in the proposed fixed geometry transmissions; this will provide very precise information on launch angle and help in the identification of scattered paths.

We do not view acoustic thermometry as a stand-alone methodology for monitoring ocean climate variability. For example, satellite altimetry with its fine horizontal resolution at the ocean surface nicely complements the acoustically derived information of the ocean interior.[25] The interaction with ocean modeling and prediction is of particular importance. The forthcoming ATOC measurements will provide the opportunity for interaction with an ongoing real-time modeling effort.

While the initial phase of ATOC concentrates its efforts in the Pacific, the long-term objective is to deploy sources and receivers in all the world's oceans. Plans are now being formulated in cooperation with several nations for monitoring the Atlantic, Indian, and Arctic Oceans.

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