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ANALYZING THE DYNAMICS OF DOLPHIN BIOSONAR BEHAVIOR DURING SEARCH AND DETECTION TASKS

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1. INTRODUCTION

The bottlenose dolphin (*Tursiops truncatus*) uses biological sonar to efficiently navigate, forage and monitor its surroundings in the very shallow water. In that difficult acoustic environment, the propagation of sound is degraded by variable boundary and volume conditions. These variable conditions combine with the animal's dynamic biosonar output and movements to produce a set of complicated sonar problems that are not well understood. Learning how the dolphin solves these problems would provide basic knowledge and aid the design of artificial sonar and navigation systems. Past research has considered separate components of the dolphin's biosonar system. By design, these experiments control extraneous variables by having the animal and targets in relatively fixed positions and simplify the sonar problem by using targets in the water column. While these studies provide valid psychophysical measurements in laboratory-like surroundings, such designs fail to elicit the range of abilities that are likely used in more variable and complex situations. There, combinations and interactions of the components can enhance the animal's performance in ways that are not predictable from the characteristics of the individual components. For example, when detecting an object on the bottom, the extraction of the signal from the bottom-scatter may be facilitated by a combination of movements to improve the aspect angle, grazing angle and distance as well as adjustments of biosonar's transmit frequency and amplitude to better match the bottom, object and aspect. Such combinations and dynamic adjustments play a roll in biosonar performance but, it is not likely that these behaviors will be observed in repetitive static conditions. Fortunately, the measurement of complex biosonar behaviors is yielding to advances in compact measuring and recording devices that can be adapted to the dolphin and harsh marine environment. The work to be reported uses such tools as well as new concepts and procedures to measure and analyze dynamic biosonar behavióг. The biosonar search and detection task is used as the prototype problem since it requires the exercise of many biosonar abilities at once while lending itself to a discrete-trials paradigm that facilitates systematic analyses. Also, other sonar problems, such as object-discrimination, can be incorporated into that paradigm. For bottom-objects, an open ocean field is used to provide a realisitic space for biosonar search and detection. Multiple object positions are used to randomize the objects' 3-D aspect and background that would otherwise provide extraneous cues for detection and identification.

2. BACKGROUND

Of the dolphin's various acoustic emissions, the broadband pulses and hearing that are used for biosonar have received the most attention. The transmitted pulse is a damped sinusoid wave of 30-100 microsec duration with 2-7 excursions and energy located between 30 and 130 kHz. Typically, peak frequencies are found at 40-60 kHz and 100-120 kHz. Pulses may have peak-to-peak SPL's of from 170 dB to over 225 dB re:1µPa at 1 m with a peak-frequency in the lower, the upper or, with a bimodal spectrum, in both ranges depending on the situation. The 3 dB bandwidth can vary from less than 40 kHz with a single peak to over 100 kHz when both peaks are prominent.

When echolocating a specific object, the animal emits a train of a few to hundreds of pulses, each of which is emitted following the receipt of the echo from the previous pulse. That is, the inter-pulse-interval is gated by the travel time of the pulse to and from the farthest area of interest plus a small delay between the reception of an echo and the subsequent pulse. The output power and frequency are under voluntary control of the animal [1] with the highest SPL recorded being 227 dB or, in equivalent energy-flux-density, about 167 dB [2].

The directed transmit beam is symmetric about the head-axis in the horizontal plane but elevated about 5 deg up from the axis of the skull in the vertical plane [3]. The near- to far-field transition occurs at just over .5 m from the tip of the rostrum [4] and the 3 dB beamwidth is about 10 deg in both the vertical and horizontal planes. While the width is inversely related to frequency, the average beam has been found to have a directivity index of 25.8 [2]. Measurements of the waveform that are taken beyond +/- 5 deg of the beam's axis in the vertical and beyond +/- 10 deg in the horizontal show considerable distortion relative to those made on the major axis. Off-axis measurements above the major axis contain complicated components that are probably due to internal reflections in the head while those below show a shift toward lower peak frequencies [5].

As with the transmit beam, the receiver beam is directional with a width that is inversely related to frequency and approximately in the same alignment with the skull. However, its 3 dB beamwidth is considerably wider both in the vertical plane - 30, 28 and 17 deg for 30, 60 and 120 kHz respectively - and the horizontal plane - 59, 32 and 14 deg for 30, 60 and 120 kHz respectively [6]. The directivity index for the highest frequency -120 kHz - is only about 20.8 dB compared to the 25.8 dB of the more directional average transmit beam [2].

3. 2-DIMENSIONAL DYNAMIC SCAN

In the first stage of analysis, the head-azimuths and range-gated pulses of the dolphin were recorded as it scanned a large field outside of its enclosure for the presence or absence of objects in the water column. The measurements included the test object's location, the animal's location, the animal's head-azimuth at each pulse and the interpulse intervals. Controls were used to insure that the animal approached each scan of each session with no extraneous cues to the presence or absence of the object and, when present, its location. In this way, the animal developed its own scan strategy. In the tests reported, it achieved better than 90 percent accuracy.

The animal's 20 x 20 ft test-enclosure with wide-mesh wire sides and bottom was open to a bay. The test-object was a 10 or 12 in stainless steel sphere of slight negative buoyancy that was suspended 1 m below the surface from a small flotation collar and a vertical sighting stick (Fig 1.A). Fig 1.B shows the relative positions of the enclosure, action field, animal trainer (TR), computer operator (OP) and a bearing-taker at a surveyed site on an adjacent pier (BT). Trial-by-trial placement and recovery of spheres in the field was done by three paddle-board riders. Each was equipped with a sphere and float and was required to be near an assigned float - either SA, SB or SC - during each trial. Their constant positions during trials were ignored by the animal. In order to achieve rapid random placement and recovery of a sphere and reduce the requirements for accurate placement by the paddlers, each paddler was made responsible for a group of nearby sectors - paddler SA for sectors 1-4, paddler SB for 5-8 and paddler SC for 9-12. Before each trial, a sector number and a present-absent indicator were signaled. The paddler who was assigned that sector would move to any position in it and, on object present trials, quietly place his sphere and return to his station. The other two would move to any one of their sectors and return to their stations. On object-absent trials, all paddlers moved to any one of their sectors and returned without placing a sphere. Any sphere remaining from a previous trial would be recovered at this time. The exact position of the sphere (+/- 1.5 yds) was determined by the bearing-taker who used an optical range and bearing finder to fix the location of the sighting-stick above the sphere. The animal's position was known to within +/- 3 yds by his habit of always scanning from the seaward end of the enclosure. The sequence of trial-types was quasi-random with a 50:50 ratio of present to absent trials while the sector sequence for object-present trials distributed the spheres randomly with respect to area in a session. There were 36 trials per session and 1 session per day.

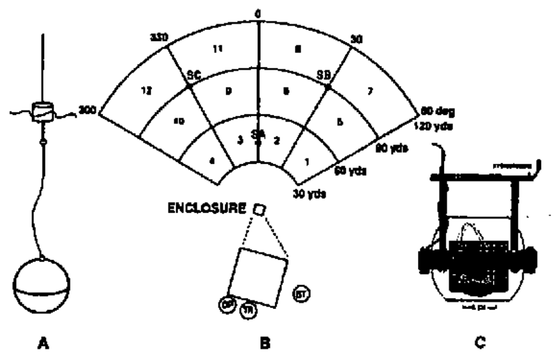

Figure 1 Sphere, 2-D action field and bite-plate assembly

The head-azimuth and interpulse intervals were recorded with an instrumented bite-plate (Fig. 1.C), a microprocessor and a lap-top computer. A dental impression of the animal's upper jaw was used to make the bite-plate. A custom fit carbon-fiber base with a hole for each tooth allowed the plate to be very thin and strong. A soft rubber negative impression, bonded to the base, cushioned the teeth and gums at every point and distributed the clenching and torquing forces evenly over the mouth. The plate acted as a stereotaxic device in that it and any attached instruments were reliably positioned relative to the skull. An added advantage of the impression bite-plate was that any release and recovery of the plate resulted in improper alignment that was apparent when the animal delivered the plate at end of a scan. A polycarbonate frame around the plate held a simple hydrophone and four small vertical struts that rigidly supported a housing with a compass. The quality of the hydrophone and its position were not critical as the high power close to the melon reduced the need for amplification and allowed a relatively high threshold for triggering a level-shift-detector. A fluxgate compass (KVH-314) was vendor-modified to eliminate damping and provided update at 10 Hz with +/- .5 deg static accuracy. The update values lagged the real headings by about 100 ms and all azimuths were regressed in time by that amount. Custom gimbals held the compass and aligned it with the enclosure. A sighting line on the bite-plate allowed field calibration with known survey points.

A tether with power and data lines from the compass and hydrophone was connected to a battery powered microprocessor (New Micros 64HC12 100-Squared) that was, in turn, connected to lap-top PC computer on the rear walkway of the floating test-enclosure. In the processor, a recycling timer triggered the highest priority interrupt every ms that caused a clock in RAM to be incremented by one. The hydrophone's output was connected via an amplifier, a level-shift detector and a Schmitt trigger to the next lower priority interrupt of the processor. The compass automatically produced a new azimuth value every 100 ms that was captured in a processor counter. A circuit detected the completion of each new update and triggered the lowest priority interrupt that caused the processor to store the newest azimuth. The rising edge of each biosonar pulse would trigger a hydrophone-interrupt that would cause the newest azimuth to be stored with the current RAM-clock value into a circular queue. A foreground routine continuously unloaded the queue over a serial line to the lap-top computer that displayed and recorded the data. Keyboard commands from the lap-top were sent over the same serial line to setup, start and stop operation of the controller. Final sphere locations that were recorded by the bearing taker were later entered by hand. The controller was programmed in New Micros Max Forth and assembly language while the lap-top was programmed in APL*PLUS/PC.

The paddlers set the field before each trial while the animal was held at the rear of the enclosure. With the paddlers at their stations, the animal was given the bite-plate and released to scan. Data acquisition started at this time and, on object-present trials, the sphere's position was determined by the bearing taker. If the animal returned and touched an underwater paddle on an object-present trial or returned directly to the handler on an object-absent trial, it was immediately rewarded with three small fish and the trial was ended. Incorrect responses were followed by a 1 min time-out and repeat scan until a correct response would end the trial and produce a full reward. Only the initial scan of a trial was recorded. Later, with responses distributed evenly between alternatives, the reward following a correction response was reduced to a single fish. Any fish remaining were fed to the animal one-half hour after the session. Consistent handling throughout and, on object-absent trials, pseudo fixes and pseudo sphere placements were used to eliminate correlation's between extraneous stimuli and the presence of an object.

Fig 2. shows the notation for data representation and a typical scan on an object-present trial. The notation plots a sonar "distance-point" along the azimuth of the animal's head at one half the distance that the pulse energy would travel between the preceding and current pulses. In the polar diagram, the animal's enclosure appears as a square on the baseline and the action field is enclosed in dashed lines. Successive distance-points are connected by solid lines and any point that would fall beyond 150 yds is plotted at that distance. The sphere's location is represented by an "X". The animal adopted a right-to-left search pattern on all trials so the first point of the scan appears on the right of the diagram.

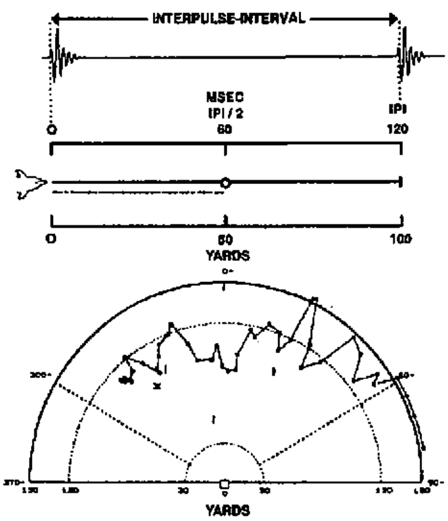

Figure 2 Data notation and example trial

The initial analysis looked for the effects of learning on the scan pattern. Fig 3. shows the median distance-point at each 3 deg increment taken from 36 consecutive object-absent trials over two sessions (i. e. scans not interrupted by the detection of spheres). Also plotted are the mean starting and ending points with standard deviations and the distribution of spheres on 90 object-present trials. Although the random distribution of spheres with respect to area was not completely successful, there was sufficient variability to cause the animal to spread its pattern to the periphery except on the center axis. There, the animal detected the lack of targets and adapted its scan accordingly.

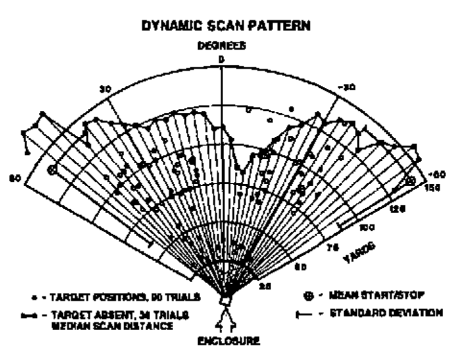

Figure 3 2-D median scan pattern

The position and variability of the mean start and stop points almost guaranteed that, allowing for beam width, neither would spheres be missed nor energy wasted. Another analysis looked for spatial correlations between clusters of distance-points and the location of spheres with the aim of predicting a sphere's location from the pattern features. The correlations were not as high as expected since, on 20 percent of the correct detection trials, the animal made only a single pulse on the approximate azimuth of the sphere. Further analysis of head motion as a function of azimuth revealed that, toward the end of the scan, more lengthy hesitations always occurred at the azimuth of the sphere than elsewhere. Using that azimuth, all distance-points within several degrees were analyzed and a single reference point was determined that correlated most highly with the location of the target. With the hesitation-azimuth and simple linear prediction from the correlation between the reference points and spheres, it was possible to predict the locations of most reported spheres to within +/- 10 yds as shown in Fig 4. Other analyses examined the number of pulses placed on an object as function of its distance as well as the variability of the delay between the receipt of an echo and a subsequent pulse. The average angular separation between successive pulse-azimuths is also being studied as a measure of the functional beamwidth.

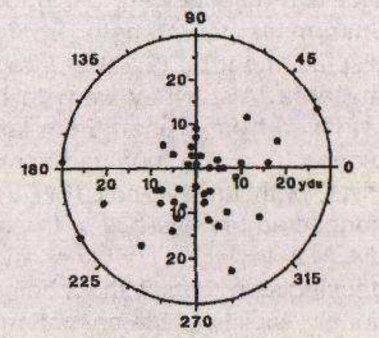

Figure 4 Prediction accuracy

4. 3-DIMENSIONAL DYNAMIC SCAN

In the second stage, more complete measurements were made while the animal searched for and detected objects on the bottom in an open-ocean field. Here, the object's location, animal's location, head-azimuths and interpulse intervals were measured as well as the roll and pitch of the skull, the depth of the head and the time-waveform of each emitted pulse. A session consisted of the animal following a guide boat to each of 36 different locations or "stations" in 35 to 45 ft of water and performing a trial at each station. A trial consisted of the animal searching the surrounding bottom for the presence or absence of objects that had been positioned within an 80 yd radius of the station's center. As before, objects were placed at only half of the stations in a quasi-random sequence and, where present, they were distributed randomly with respect to the area of the circle. The field of stations was located about 3 NM South of Coronado Island in San Diego and is illustrated in Fig 5. The design of the field allowed the stations to be traversed in up to 4 different patterns or sequences in a week and the distribution of present and absent stations as well as the position of objects were randomized once a week. Station centers were 240 yds apart to create a wide object-free area about the station that, with practice, provided unambiguous feedback to the animal regarding the distance to be scanned.

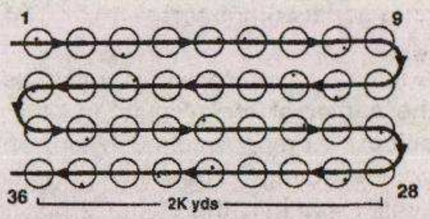

Figure 5 Open ocean field

The test-objects were designed to hug the bottom and have strong uniform target-strength from any aspect angle while resisting displacement by the strong swell surges and large mats of kelp in the area. Also, they were to be easily and accurately placed and retrieved from a boat. Each target had the upper half of a foam tri-plane (10 in dia) mounted on a circular steel plate (23 in dia, .25 in thick) with an eye-bolt (Fig 6). A monofilament line (250 lb test) connected the eye-bolt to the tip of a small pencil shaped float (1 in dia, 12 in len). The line and float threaded their way through passing kelp mats without being snagged while presenting minimum sonar visibility to the animal and allowing easy placement and retrieval from the surface. A crew of two could set, check or clear the field of 18 targets in about 1 hr using the navigation system to be described.

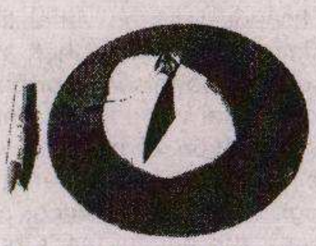

Figure 6 Target tri-plane and float

The stations, objects and animal were located in reference to a 9-channel Trimble 4000DS DGPS that provided the boat-mast's position (+/- 1 m) every second. Its output and that of a fluxgate compass (KVH C100) in the bow were taken to a navigation computer with daylight display on the boat-driver's console. The computer (embedded PC) combined the DGPS and compass headings with the station and target locations to present an earth-referenced overhead graphic of the stations and test-objects from any field-position at any magnification. A graphic icon represented the boat's real-time position and heading in the field and a slug-trail visualized the track - an aid in estimating set and drift at low speeds. Also displayed in digital format were the boat's current heading, speed, distance-to-station, longitude, latitude and rectangular coordinates in yards relative to the field's origin. Finally, it provided the boat's heading, satellite's time and GPS position on a serial output port at 1 Hz. The unit was programmed in Visual Basic and assembly language.

A station was located by keying its number into the navigation computer. That station appeared in the center of the display and the boat-icon was used by the driver as a guide to station. Test-objects were positioned by lowering the object to the bottom at the desired coordinates while compensating for the lowering point's offset from the mast at the immediate boat-heading. In a similar manner, the animal's position was taken to be at a point about 3 yds off the cut-out of the boat's left gunnel - the animal's estimated average position during a scan. The animal had been trained with a light harness and training tether to scan the field while remaining within a small circle in close proximity to the boat. The tether had a low-strain break-away link at its connection to the harness that either the animal or handler could easily break. As such, the tether served only to guide and not to restrain the animal. The animal quickly learned to do a circular scan within the length provided by the trainer without pulling on the line.

As in the 2-D scan, the bite-plate assembly used a dental-impression plate and underslung instrument pack but, here, the unit was untethered, battery-powered and of higher capacity. Fig 7 shows the unit and components for measuring azimuth, attitude, depth and biosonar output. The hydophone (B&K 8103) was fixed in the centerline about .55 m ahead of the tip of the upper rostrum and about 4 deg down from the axis of the transmit beam as measured by Au

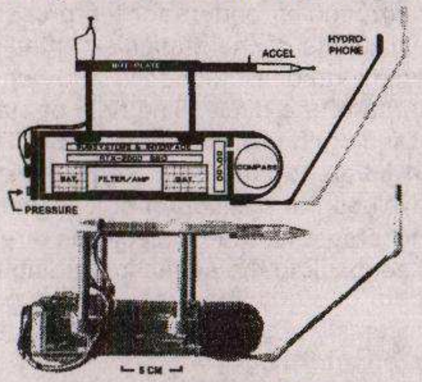

Figure 7 Instrument pack on bite-plate assembly

[2]. A hollow carbon fiber strut held the phone rigidly without oscillation and enclosed its cable. The phone and strut had a cross-section area to the transmit and receive beams of less that .5 deg in the horizontal plane. Inside the instrument pack, the hydrophone line went to an amplifier and dual 6 pole Butterworth filter circuit of our own design with a 4.5 kHz high- and 180 kHz low-pass cut-offs. The output was split to a level-shift detector - a pretrigger circuit connected to the processor's highest interrupt line - and to the input of a 20 microsec delay circuit. Three accelerometers (Sunstrand 2180) with adjustable sensitivity were mounted to the frame on mutually orthogonal axes - one in the plane of the frame at its forward tip and other two at the rear on either side and outboard of the animals head. This external outboard arrangement was used to support other prototype subsystems that are not reported here. Finally, a pressure gauge (Entran EPNM-A38A) was fit into the removable rear wall of the instrument pack.

The main compartment of the pack held a single board computer, interface board, filter-amplifier circuit, power conditioners and 1.8 Ah, Ni-MH battery. A forward extension held a fluxgate compass (KVH C100) in custom gimbals that allowed +/- 80 deg rotation in each axis. The compass's own mircroprocessor was located on the main interface board. Compass updates occurred at 10 Hz and were requested and read by the main processor over a RS-232 line from the compass. A custom tap on the compass circuit and a counter in the main processor were used to detect the availability of each new update thus allowing the main processor to request and receive new updates with a constant time lag and minimum overhead. As in the 2-D case, updated azimuth values lagged real headings by about 100 ms and were regressed in time by that amount. Azimuth values were also conditioned to remove single point discontiuities and smoothed with a 300 ms moving average.

The single board computer (Silicon Composers Fox) had a 10 Mhz RTX-2000 processor, 512 KB SRAM, a serial port and the Forth language in ROM. The processor's ASIC bus was routed to the interface board where various circuits were attached. A 2 Mhz 12 bit A/D converter with an internal sample-and-hold circuit (Datel ADS-117MM) and a fast 8 channel multiplexer (Datel MX-826MM) were used to select and convert the analog inputs from the accelerometers, pressure gauge and hydrophone. There are spare channels and speed for future extensions. The speed of the processor allowed for the acquisition of data from the A/D to the internal stack of the processor at rates up to 2 Mhz for bursts of up to 240 values. Its deterministic execution prevented any jitter. The 12 V battery was converted to +/- 15 V and 5 V with dc converters (Pico IRF15D and LRF5S) and filtered to minimize noise and spikes before distribution.

The rising or falling edge of each biosonar pulse would cause the pre-trigger circuit to trigger the processor's highest interrupt. Its routine would digitize 128 successive samples of the animal's biosonar pulse at .9 Mhz. Upon completion, the value of a 1 ms clock in RAM was added to the samples and the data were moved to the first empty one of two RAM buffers. A recycling 1 ms timer triggered the next lower priority interrupt. At each time-out, it incremented the RAM-clock, pushed the contents of any filled data buffers into a main data queue and decremented a counter. On every tenth count (10 ms) it would fetch the most recent azimuth (maintained by a foreground routine), digitize the outputs of the accelerometers and pressure gauge, push them all to the main data queue and reset the counter. The foreground routine fetched compass updates and handled incoming commands from the serial port when it was connected to another computer for programming and data transfer. All programs were written in SC/Forth.

The data from the navigation computer and the animal's instrument pack were brought together in the topside computer - a battery powered PC with a hard disk, daylight display and splash proof keyboard in a waterproof case. A serial line from the navigation computer provided the DGPS position, boat heading and satellite time continuously while a second serial line with a pluggable connector provided communication with the animal's instrument pack for programming, controlling the unit and uploading data.

Between stations, the animal followed the boat while carrying a soft bite-plate that was designed to minimize scanning while in transit. At station, the animal offered this plate to the trainer. Simultaneously, the computer operator started the topside computer which began recording DGPS coordinates, boat-headings and satellite times from the navigation computer and issued a start command to the animal's pack via a serial line. With both data acquisition computers synchronized and running. the serial line to the animal's pack was unplugged and the bite-plate was placed in the animal's mouth. On cue, the animal scanned the station and returned to either touch a ball on the left gunnel to report a detected object or go directly to the trainer to report an empty station. The same response criterion, rewards, time-outs and correction procedure were in effect as in the 2-D study. When the animal returned the bite-plate assembly, it was immediately plugged into the topside computer. A key command stored the collected navigation data, stopped the animal's acquisition program and initiated a transfer from the queue of the animal's pack to the topside computer. Movement to the next station began as soon as the animal had been rewarded.

For each pulse, a 3-D "distance-point" is plotted on the head-axis at one half the distance that sound would travel between the preceding and current pulse. The head-axis is derived from the head's azimuth, attitude and altitude over the bottom with tide taken into account. The head-axis does not represent the physical beam-axis but, is highly correlated with it. Ongoing analysis will establish their relationship as in the 2-D case. As before, successive distance-points are connected by a solid line. A second 3-D point, the "bottom-intercept", may be plotted on the same axis to mark the intercept of the head-axis with the bottom. The top panel of Fig 8 shows the 3-D geometry where a distance point falls well beyond the bottom-intercept - a condition that indicates the interrogation of a bottom-object.
When the positions are reversed, interrogation of an object in the water-column is indicated.

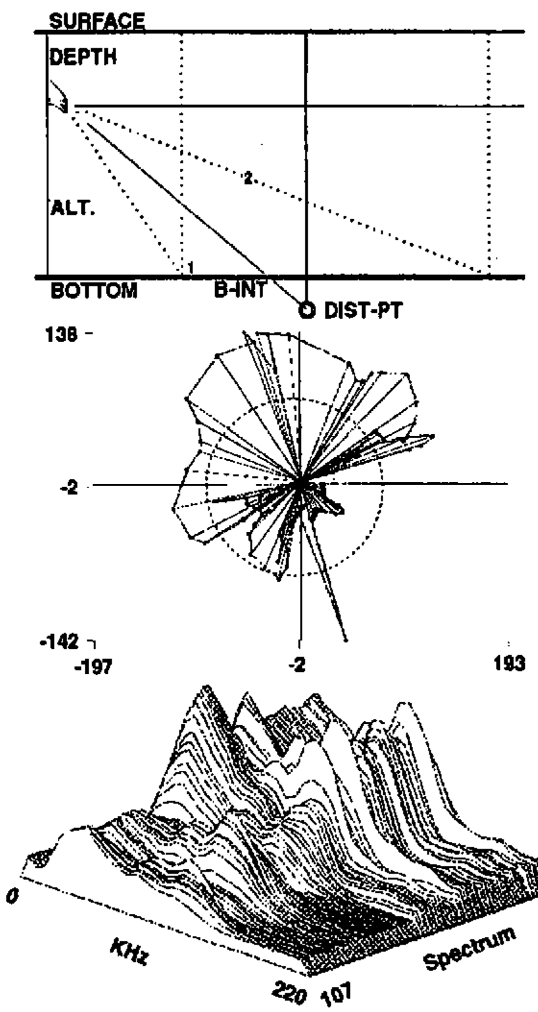

Figure 8 3-D notation, example trial and spectra

The center panel shows initial data with a 2-D projection of a scan on an object-present trial as viewed from above. The boat and animal are in the center of the 160 yd diameter circular station. The animal began a counter-clockwise scan at about 75 deg (true) and hesitated on one nearby foreign object before scanning on the test-object at about 175 deg and 20 yds from center. When collated over many trials, this 3-D data allows the functional beam axis and width to be estimated during both the search and target-identification portions of the scan. A 3-D waterfall plot of pulse-spectra appears in the lower panel and shows considerable frequency and amplitude variation in the scan. Ongoing analyses are examining the data for reliable correlations between such modulations and the variables of the field. Also included, is the use of the empirical data as a basis for testing a variety of hypotheses about the functional parameters of the biosonar system. Finally, another analysis examines the pulse-waveforms of the scan without reference to external events. Recording the pulse of a moving animal from a fixed position relative to the skull eliminates any subtle shifts of the beam between pulses and between scans. Initial examination of the waveforms suggest that two separate waves are being combined but, further analysis is required to eliminate alternative explanations.

5. CONCLUSIONS

The methods reported here provided new basic knowledge and demonstrated the feasibility of measuring the dynamics of dolphin biosonar behavior in large open-water fields. The 2-D study demonstrated the importance of the animal's recent history of detections on its current scan pattern while also allowing inferences about other major features of biosonar behavior such as the echo-pulse interval and ensonification intensity. The 3-D study confirmed those findings in an open-ocean scenario with more difficult bottom targets and extended the analysis to include more complete descriptions of the animal's orientation and spectral content of the bisonar emissions. Ongoing analyses will determine, with more accuracy, the distribution of biosonar energy during the search and detection portions of the scan as well as any modulations of the animal's biosonar output that it may have been using to enhance performance. The hardware and procedures that were used in these studies had to accommodate a wide range of parameter values and their rates of change that were initially unknown. With the understanding that was gained in these first studies, future development can select more efficient components and better tailor the procedures to the task. Also aiding in this development is the continuing improvement in electronics and sensor designs that allow further reductions in size and power requirements. Anticipated extensions of these analysis will seek to measure the animal's 3-D translation during "free-roaming" open ocean searches and the spectral composition of echoes returning along the axis of ensonification.

6. REFERENCES

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